GEOLOGIC HAZARDS AND LAND-USE PLANNING: BACKGROUND, EXPLANATION, AND GUIDELINES FOR DEVELOPMENT IN DAVIS COUNTY IN DESIGNATED GEOLOGIC HAZARDS SPECIAL STUDY AREAS

by

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UTAH GEOLOGICAL AND MINERAL SURVEY
a division of
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FORWARD

Beginning in 1985, the Utah Geological and Mineral Survey sponsored the Wasatch Front County Hazards Geologist Program which utilized federal funding to place geologists in local-government planning departments in Wasatch Front counties. One of the purposes of the program was to aid cities and counties in land-use planning as it relates to geologic hazards. To accomplish this, the county geologists prepared maps showing geologic hazards, and descriptive texts explaining the hazards and use of the maps in planning. Texts were prepared jointly by the three county geologists, and vary only slightly from county to county. This Open-File Report presents the text completed for Davis County. Each chapter addresses a specific hazard, and chapters can be separated and used individually if preferred. Maps are not included in this report, and must be obtained from the Davis County Planning Department. Recommendations regarding use of the maps and requirements for site investigations and disclosure included in this report (see Table A-1, p. A-2) are specific to Davis County for use in conjunction with their Subdivision Ordinance. Geologic-hazards maps available from Davis County include the incorporated areas, and these maps, as well as this report, are adaptable for use by cities in Davis County in their ordinances.

CONTENTS

INTRODUCTION

Geologic hazards (earthquakes, landslides, debris flows, rock falls, flooding, and shallow ground water) are important factors to be considered prior to development in order to protect the life and property of the people of Davis County. In areas subject to geologic hazards, the County may require that special studies be performed and reports submitted to its planning department which identify hazards and, if necessary, recommend measures needed to mitigate them. The County may require this for unincorporated areas under the Davis County Subdivision Ordinance, section 3-3-3 (7), and most cities have the authority to do likewise under existing zoning, hillside protection, or subdivision ordinances or development codes.

Geologic hazard special study areas in Davis County, including incorporated areas, have been mapped and these maps are available through the Davis County Planning Commission. A separate set of maps on 1:24,000 scale U. S. Geological Survey topographic quadrangles has been prepared for each hazard. These maps don't show actual hazard areas but rather show areas where a potential hazard exists, and where special studies should be performed prior to planning commission approval or issuance of a building permit as outlined in table A-1. The special studies may: 1) show that no hazard is actually present; 2) recommend measures needed to mitigate the hazard (for example setbacks, engineered protection); or, 3) recommend that the site is not suitable for the proposed use. Such reports will then be reviewed by the planning commission and their designees, and revised if necessary, depending upon review comments. The planning commission will then either approve or deny the proposed development.

Details of the types of studies required are outlined in the following chapters. Each chapter describes a separate hazard and its effects, discusses how the special studies area maps were prepared and should be used, and outlines the scope of site investigations (special studies) generally needed to satisfy ordinance requirements. Special studies need only address the specific hazards shown on the maps. For example, if the area is in both a surface fault rupture and debris-flow special study area, studies addressing these hazards are required, but special studies addressing other hazards such as rock fall, landslides, or liquefaction are not required. However, it is prudent for all developers and their consultants to be aware of all hazards and recognize that special study area maps are generalized maps and hazards may exist that are not shown on these maps.

ACKNOWLEDGEMENTS

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Table A-1. Recommended requirement for site-specific investigations for various geologic hazards and classes of facilities proposed for Davis County, Utah.

		FACILITY CLASS			
Hazard	Special study zone or potential hazard area	Essential facilities, lifelines, special- and high-occupancy buildings	Industrial and commercial buildings (other than high-occupancy)	Residential subdivisions	Residential single lots
Surface fault rupture	In	Yes	Yes	YES	YES
	Out	Yes	No	No	No
Tectonic subsidence	In	Yes	No*	No*	No*
	Out	No	No	No	No
Liquefaction	High and moderate zones	Yes	Yes	No*	No*
	Low and very low zones	Yes	No	No	No
Landslides	In	Yes	Yes	Yes	Yes
	Out	Yes	No	No	No
Debris flows	In	Yes	Yes+	Yes+	Yes+
	Out	Yes	No	No	No
Rock fall	In	Yes	Yes	Yes	Yes
	Out	Yes	No	No	No
Stream flooding	Zone A: 100-year flood plain	Yes	Yes	Yes	Yes
	Other zones (B and C, etc.)	Yes	No	No	No
Lake flooding	Below 4,217 feet in elevation	Yes	Yes	Yes	Yes
	Above 4,217 feet in elevation	No	No	No	No
Dam failure inundation	In	Yes	No*	No*	No*
	Out	No	No	No	No
Shallow ground water	In	Yes	Yes	Yes	Yes
	Out	Yes	No	No	No

*Appropriate disclosure should be required.

+If a debris basin is present above the site, debris-flow special studies are not required; it is advised that Davis County Flood Control be contacted regarding adequacy of debris basins.

SURFACE FAULT RUPTURE

INTRODUCTION

Surface faulting has been identified as a potential hazard in Davis County, Utah. This chapter of this paper is an effort to address the problems associated with surface faulting, to suggest investigation methods, and propose certain mitigation procedures. Much of the specific information on faults is from various studies by the U.S. Geological Survey and the Utah Geological and Mineral Survey. Nelson and Personius (1990) have prepared maps to show the known areas in Davis County where a hazard exists from surface fault ruptures. The purpose of this chapter is to discuss the nature of the surface fault rupture hazard, its potential consequences, and to give recommendations regarding the use of the maps and how the hazard should be addressed in land-use planning, development, and regulation. This work is one of several translated documents addressing natural hazards which are designed for planners and other decision-makers who have a limited geology background.

Davis County is in north-central Utah and along the base of the central portion of the Wasatch Range. The range and the adjoining basin, of which Salt Lake Valley is a part, are the result of millions of years of faulting which caused the mountains to be uplifted and the basins to be downdropped along the Wasatch fault zone. Although no surface ruptures have occurred along this fault zone in historical time, evidence gathered from detailed geologic studies of existing scarps indicates that large-magnitude earthquakes and accompanying surface ruptures have occurred repeatedly within the past 10,000 yr and earlier.

Earthquakes are generated by movement along faults at depth. During large-magnitude earthquakes (Richter magnitude 6.5+), ruptures generally propagate to the surface as one side of the fault is uplifted and the other side downdropped (figure B-1); the resulting (normal) fault scarp has a near vertical slope. Broad subsidence of the valleys accompanying surface faulting may affect areas several miles away from the fault. These effects are not considered here, but are covered in a separate chapter entitled "Tectonic Subsidence".

CHARACTERISTICS OF THE WASATCH FAULT ZONE

The Wasatch fault zone (WFZ) extends from near Malad City in southern Idaho to Fayette in central Utah, a distance of about 213 mi (Machette and others, 1989). The fault zone trends roughly north-south and dips steeply to the west as shown in figure B-2. The Wasatch fault zone is not a single fault plane, but is a zone of deformation containing many individual subparallel faults. Where the zone intersects the surface, it commonly consists of one main down-to-the-west fault with a disturbed area, generally to the west on the downthrown side, as much as several hundred feet wide, or possibly a series of down-to-the-west faults. This disturbed area, commonly termed the zone of deformation, contains small cracks and tilted or displaced blocks and may include a graben that is bounded on the west by a scarp formed by a down-to-the-east (antithetic) fault (figure B-2).

The entire length of the Wasatch fault zone is not expected to rupture in any one earthquake. Instead, discrete segments of varying lengths rupture independently. Originally, 6 segments were proposed, but more recent studies indicate there may be as many as 10 or 11 (figure B-3; Schwartz and Coppersmith, 1984; Machette and others, 1987; Machette and others, 1989). The most important aspect of the concept of segmentation is that segments control the length of the expected surface rupture, the starting or stopping points of ruptures, and place physical constraints on the maximum magnitudes of potential earthquakes.

Several different analyses of the history of the WFZ suggest a surface-faulting event occurs every 200 to 415 yrs. From a study which considered the number of surface-faulting earthquakes on the original six segments over the past 8,000 yr, Schwartz (1988) suggests that such earthquakes occur on the average every 200-400 yr, and studies which assessed 10 or 11 segments arrived at a similar recurrence of 340-415 yr (Machette and others, 1989; W.R. Lund

Wasatch Fault Zone

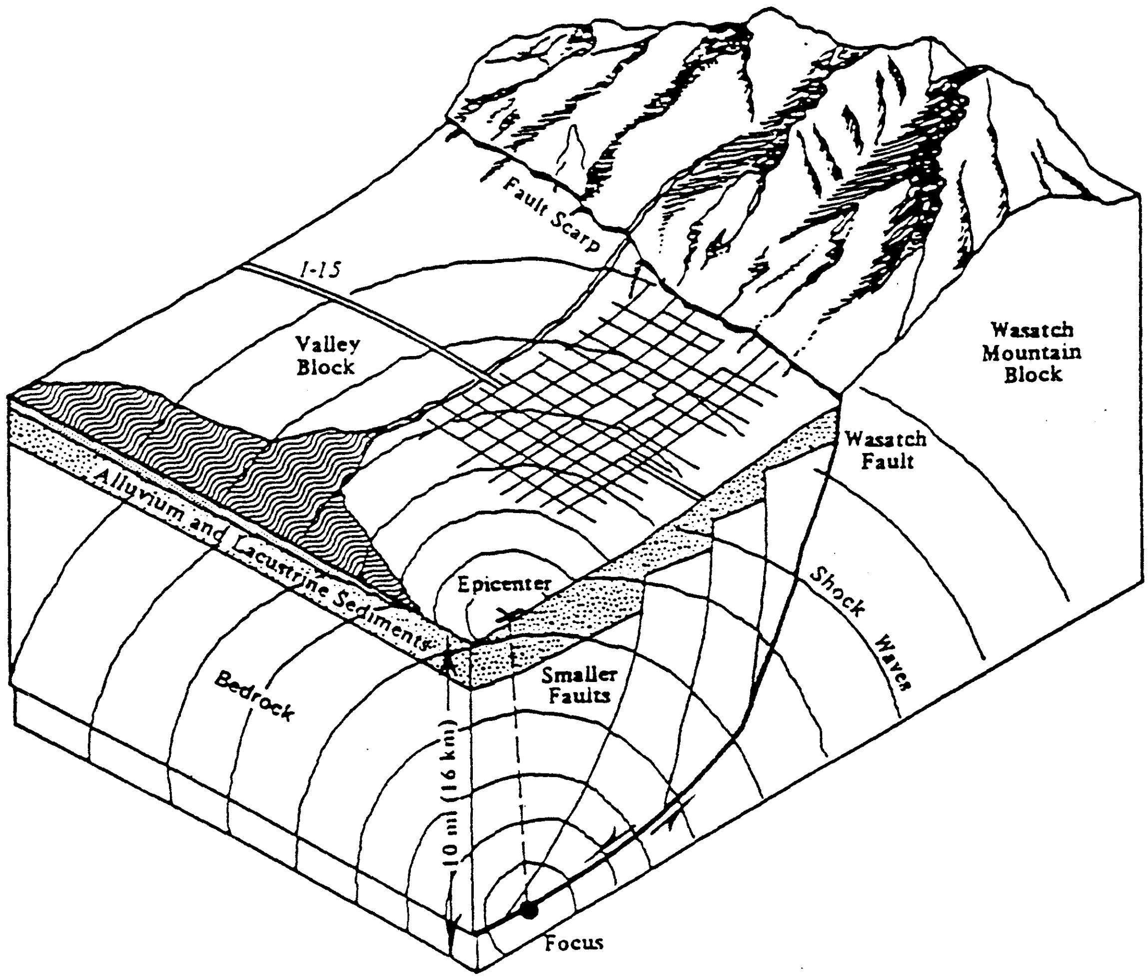

Figure B-1. Schematic diagram of the Wasatch fault zone showing the relation of the epicenter to the focus and the trace of the surface rupture (fault scarp). The plane of the fault probably dips at 50-60 degrees toward the valley. The epicenter of the earthquake is located in the valley (downthrown block), not on the trace of the surface rupture. Adapted from a special poster by the Utah Museum of Natural History.

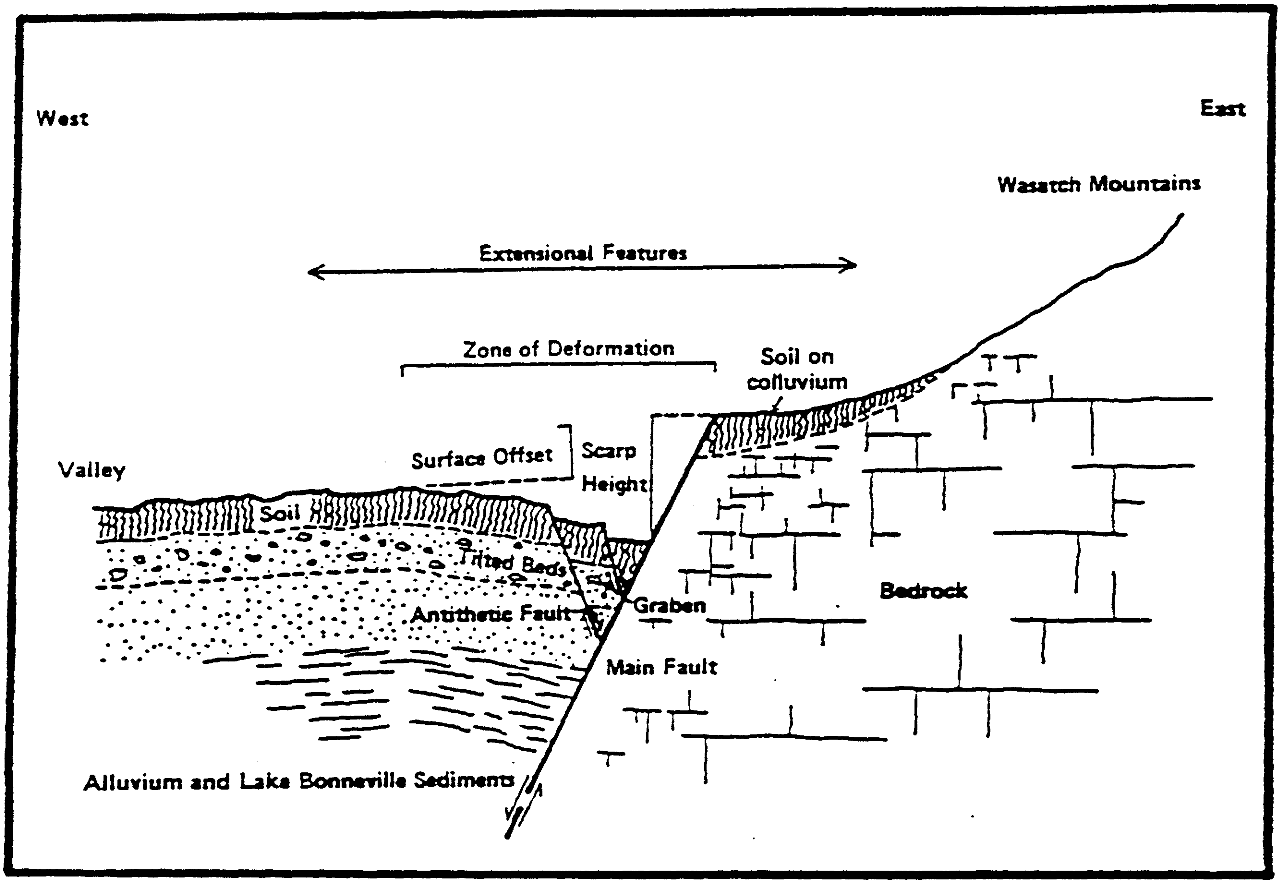

Figure B-2. Schematic diagram of a normal fault showing features typical of the Wasatch fault zone near the ground surface. Sketch is not to scale, but surface offset is usually about 6 to 9 ft. Note that the scarp height is commonly greater than the surface offset.

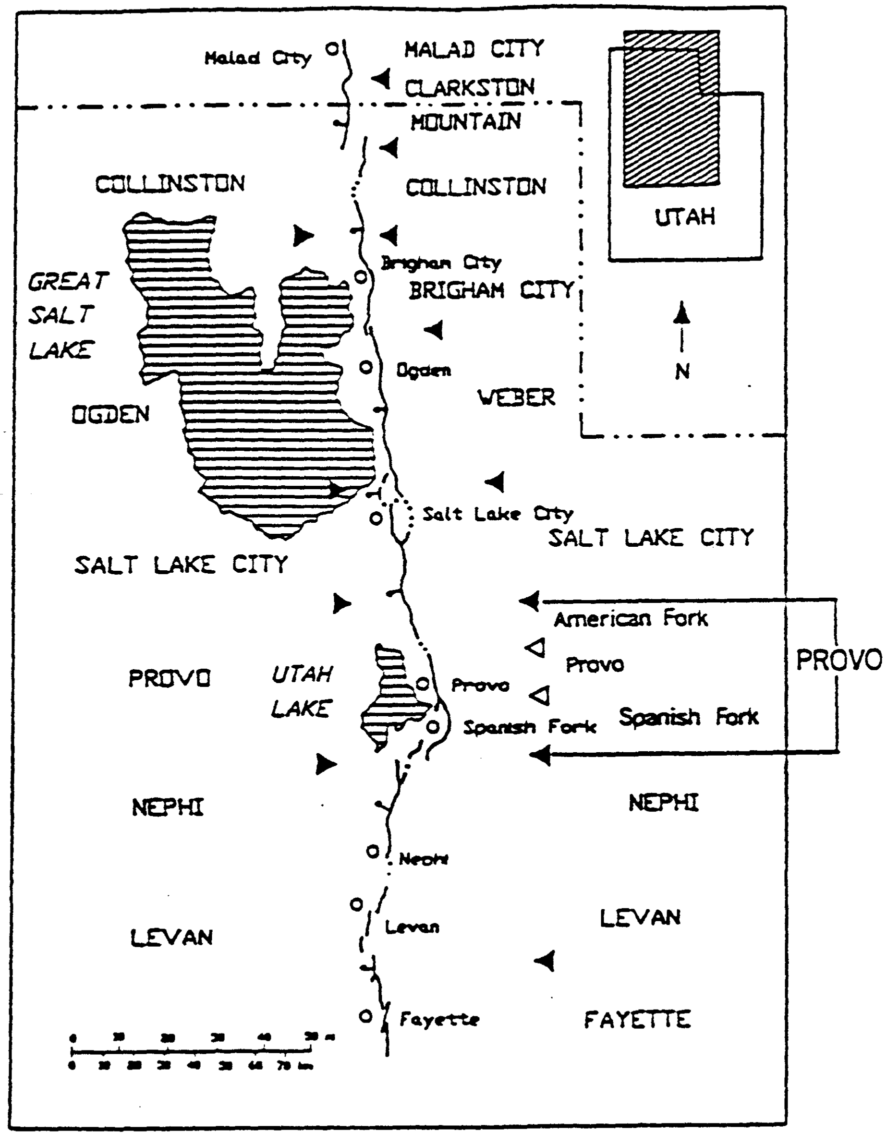

Figure B-3. Map showing the boundaries and names of the Wasatch fault zone segments. Segment boundaries are noted by solid arrows. The left column is from Schwartz and Coppersmith (1984) and the names on the right are from Machette and others (1989). The total number of identified segments has increased from 6 to 10, possibly 11, depending on the persistence of the subsegment boundaries (represented by hollow arrows). Adapted from Machette and others (1989).

oral commun., 1988). The most recent rupture along the Wasatch fault zone may have occurred on the Nephi segment in Juab County, between 300-500 yrs ago (Schwartz and Coppersmith, 1984), although Jackson and Ruzicka (1988) suggest that this event may have occurred 500 or slightly more years ago.

Davis County contains two of the segments defined by Machette and others (1989) (figure B-3). From north to south, these segments are the Weber segment and the Salt Lake City segment. Details of segment length, average recurrence, and age of last movement are given in table B-1. The average recurrence interval on the Salt Lake City segment (table B-1) is estimated at around 4,000 yr (Schwartz and Lund, 1988). Estimates for the average recurrence interval of surface faulting on the Weber segment range from 500-1,000 yr (Swan and others, 1980) to 3,000-4,000 yr (McCalpin and others, in prep.).

The Weber segment is 38 mi long and extends from the southern edge of the Pleasant View salient near North Ogden, where it overlaps the Brigham City segment, to the northern edge of the Salt Lake salient near North Salt Lake, where it overlaps the Warm Springs fault of the Salt Lake City segment. A trenching study near Fruit Heights (Kaysville site, table B-1) indicated that the most recent surface faulting on the southern portion of the Weber segment occurred between about 700 and 1,000 yrs ago (McCalpin and others, in prep.). Studies of an exposure near the mouth of Garner Canyon in North Ogden (Nelson and others, 1987) and trenches (East Ogden site, table B-1) just north of Ogden Canyon (Nelson, 1988) also indicate that the last major surface-faulting event on the segment occurred prior to about 1,100 yrs ago; there is some evidence, however, for a possible small event occurring prior to about 600 yrs ago at the East Ogden site (Nelson, 1988). One surface-faulting event between 2,000 and 3,000 yrs ago in the northern portion of the Weber segment at the Garner Canyon and East Ogden sites (Nelson and others, 1987; Nelson, 1988; McCalpin and others, in prep.) did not occur in the southern portion at the Kaysville site. This indicates that surface-faulting events may not always cause ground displacement over the entire length of the Weber segment (McCalpin and others, in prep.), which is the longest of the Wasatch fault segments. There is evidence for 5-6 surface-faulting events during the last 12,000 yr at the Kaysville trench site. Average ground-surface displacement along the main trace of the fault at the Garner Canyon exposure was 4.6 ft (Nelson and others, 1987); at the Kaysville site average ground-surface displacement along the main trace of the fault was 5.9-7.2 ft.

The Salt Lake City segment is 29 mi long (Machette and others, 1989) and extends from the western edge of the Salt Lake salient to the Traverse Range salient at Corner Canyon (Machette and others, 1987). A trenching study near Sandy (Dry Creek site, table B-1) indicates that the most recent surface faulting on the Salt Lake City segment occurred less than 1,130 to 1,830 yrs ago, and that there have been three surface-faulting events on the segment during the last 8,000 to 9,000 yr (Schwartz and Lund, 1988). Average displacement at the Dry Creek trench site was 13-16 ft (Schwartz and Lund, 1988). The Warm Springs fault, the northernmost portion of the Salt Lake City segment, has not been studied in detail.

On individual segments of the Wasatch fault zone, ruptures may occur from every few hundred to a few thousand years. Detailed studies on the central segments of the fault zone indicate periods between surface-faulting events range from less than 1000 yr to over 3,000 yr with an individual segment average of 2035 to 2070 yrs (Machette and others, 1989). However, it must be understood that the data are incomplete, imprecise, and that events do not necessarily occur at regular intervals; recurrence on individual segments is quite variable (Schwartz, 1988). Thus, considering the previously mentioned recurrence interval, 200 to 400 yr for all segments, and the time since the most recent event (300 to 500 yr), earthquakes may be expected somewhere along the WFZ at any time.

There is some evidence that earthquakes on different segments may cluster in time and occur so closely together that they appear as one event in the geologic record. If clustering occurs, groups of earthquakes with very short time-intervals (possibly weeks, months or years) between events could occur sequentially along the WFZ. If this occurs, then the average recurrence calculated for the entire fault (200-400 yr) could be misleading, and events

WASATCH* FAULT SEGMENT	LENGTH* SURFACE TRACE (mi/km)	RECURRENCE INTERVAL (Average, yr)	DISPLACEMENT PER EVENT (ft/m)	AGE OF MOST RECENT SURFACE FAULTING (yr ago)	REFERENCES
Brigham City	24.9/40.0	1500-2200	6.6/2.0	about 3600 (3100-4100)	Machette and others, 1989; Personius, 1990
Weber	37.9/61.0	1400 (East Ogden site)	4.6/1.4 (Garner Canyon)	<1100, possible small event <600 (East Ogden site)	Nelson, 1988; Nelson and others, 1987; McCalpin and others, 1990
		3000-4000 (Kaysville site)	5/9-7.2/1.8-2.2 (Kaysville site)	700-930 (Kaysville site)	
Salt Lake City	28.6/46.0	4000 (3000-5000)	13-16/4.5-5.0	<1130-1830	Schwartz and Lund, 1988

*All segment names and length data were taken from Machette and others, 1989.

Table B-1. Data for the Wasatch fault zone in Weber and Davis Counties. Segment names, lengths, recurrence intervals, displacement, and age information is taken from the references given, and should be consulted for detailed explanations of the derivation of each parameter.

may have occurred in more closely spaced clusters with larger periods between clusters. This, however, would not change the recurrence estimates for earthquakes on individual segments.

Other faults, perhaps capable of surface rupturing, occur in Davis County, including faults inferred to occur along the margins of Antelope Island. These faults do not pose a surface-fault-rupture hazard to urbanized areas of Davis County, but further work is needed to define recurrence intervals because ground shaking from an earthquake generated by these faults would significantly affect Davis County.

CONSEQUENCES OF SURFACE FAULT RUPTURES AND REDUCTION OF HAZARDS

Studies along the Wasatch fault zone have indicated that during a "characteristic" earthquake which produces surface faulting, offsets of 6 ft or more (average 6.6 ft) may occur on the main trace of the fault zone (Schwartz and Coppersmith, 1984). This offset will result in formation of a near-vertical scarp, generally in unconsolidated surficial deposits, that begins to ravel and erode-back to the material's angle of repose (33-35 degrees) soon after formation. Antithetic faults west of the main trace may also form, generally exhibiting a lesser amount of offset, but sometimes as much as several feet (figure B-2). The zone between these two faults may be complexly faulted and tilted with offset along minor faults of several inches or more. An example of this is the graben at the Kaysville trench site near Fruit Heights. In some cases, a broad zone of flexure may form west of the main fault in which the surface is tilted downward toward the fault zone. An example of this warping is preserved south of the mouth of Hobble Creek in Utah County where back tilting extends over 650 ft from the fault with a maximum dip of 3 degrees to the east.

It is difficult, both technically and economically, to design a structure to withstand 6 ft or more of offset through its foundation. Thus, avoidance of the main trace of the fault, and preparedness to respond and rebuild, are the principal reduction techniques that can be taken reasonably.

In some areas, adjacent to the main trace but still within the zone of deformation, avoidance may not be necessary. Less damaging (smaller) offsets and tilting may occur and structural measures may be taken to reduce casualties and damage. However, structural damage may still be great, and buildings in the zone of deformation may not be safe for occupants following a large earthquake.

USE OF SENSITIVE AREA OVERLAY ZONE MAPS

The U.S. Geological Survey (Nelson and Personius, 1990) has prepared a map that shows the main traces of the Wasatch fault zone in Davis County. This map is presently in preliminary form at a scale of 1:50,000, but clearly indicates the areas where surface-fault-rupture hazards need to be considered. This map has been used as the basis to prepare the sensitive area overlay zone maps. The sensitive area overlay zone follows the mapped trace of the Wasatch fault zone, and is about 500 ft wide on the upthrown and downthrown sides of the outermost fault scarps along the Weber segment. The purpose of this zone is to delineate areas where site-specific investigations addressing surface-fault-rupture hazards are recommended. Because the fault maps used to delineate these zones were prepared at a scale of 1:50,000 (1 in = 0.79 mi), they are not detailed enough to delineate all fault traces and zones of deformation at a particular location, thus site-specific investigations are recommended in the study zone.

SCOPE OF SITE INVESTIGATIONS

The scope of site investigations will vary depending on the proposed land use, nature of faulting, and amount of preexisting disturbance of the surface. Prior to construction, a geotechnical report delineating the location of the faults and a suggested setback distance may be required. At undisturbed sites, the initial phase of the surface-faulting investigation should include mapping and topographic profiling of all suspected faults and scarps. Mapping consists chiefly of identifying fault scarps or other fault-related geomorphic features based on interpretation of aerial photographs and detailed field investigations. Topographic profiles (two dimensional cross-sections) of fault scarps should be made to define the fault-related features, which are usually apparent from these profiles. Profiles should extend several hundred feet on either side of the main fault scarp in order to provide the basic information needed to define standard fault setbacks.

In disturbed or geologically young areas, such as an active stream flood plain or farmed areas, the surficial material may be regraded or less than 10,000 yrs old, and of sufficient thickness to conceal older faulted deposits and faults. These areas would require that site-specific studies contain recommendations for setback distances derived from projections of faults on adjacent property through the study area. If setback distances cannot be determined from projections, then trenching may be done to a depth that encounters undisturbed material which is older than 10,000 yr, to determine if faulting had occurred.

A study by McCalpin (1987) indicates that faults are commonly located at the midpoint of its scarp. It is recommended that structures be set back a minimum of 50 ft from the midpoint of the scarp (figure B-4A), if the scarp angle does not reach 30 percent. If the scarp slope is 30 percent or greater, then the setback should be taken from the 30 percent slope break at the top and bottom of the scarp (figure B-4B). By following these recommendations, we should be able keep structures from straddling the main, and potentially most dangerous trace of the fault, but it will not remove them from the entire zone of deformation. If profiles indicate that backtilting, secondary faulting, or graben-bounding antithetic faults are present and a wide zone of deformation exists, a 50-ft setback should be taken from the outermost antithetic fault (figure B-4C) or, in areas of flexure and backtilting, from the area where the original pre-fault surface slope is regained. It is recommended that construction in the zone of deformation not be allowed unless detailed studies involving trenching are performed to define the hazard. Fault-trench investigations are used to accurately locate, characterize, and in some cases, date past events at a specific location and to delineate the zone of deformation. Based on data from trenches, further recommendations can be made for variances from these minimum setback guidelines.

At sites within suspected fault zones where the surface is disturbed and the causative faults cannot be located on the basis of surface evidence, trenching of proposed locations of structures is recommended. In some cases, it would be advisable to offset trenches (along the strike of the fault) from actual building foundations to avoid adversely affecting soil foundation conditions with trench backfill. Utah Geological and Mineral Survey Miscellaneous Publication N (Utah Section of the Association of Engineering Geologists, 1987) lists guidelines for performing surface-fault-rupture investigations and preparing reports; it should be consulted prior to performing such studies. Recommendations include consulting the county to further clarify the scope of investigation and types of information that should be obtained from such a study. Once site-specific reports have been completed, they should be reviewed by the county and any problems discussed and resolved prior to submittal to the planning commission for approval.

The information in this paper is the most accurate available as of August, 1989. Much surface-fault-rupture research is being conducted along the Wasatch Front, and the text which accompanies the surface-fault-rupture sensitive area overlay zone maps will be updated periodically as necessary. New and more accurate fault locations will also be added to the accompanying maps as the locations become available. The text and maps are kept on file at the Davis County Planning Office.

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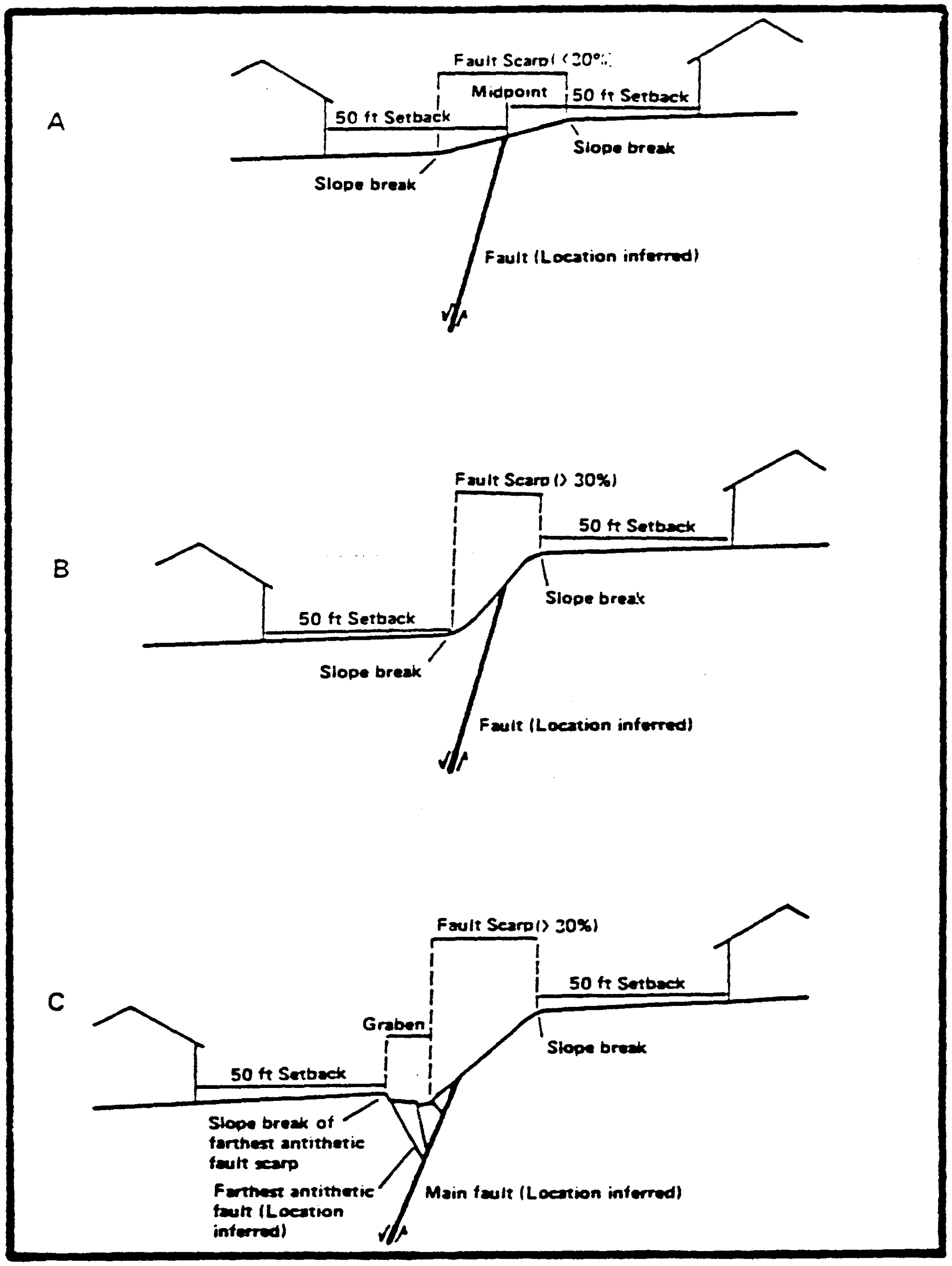

Figure B-4. Schematic diagram of recommended minimum setback distances relative to fault scarps in areas where trenching studies are not performed. Recommended setback distances are A. 50 ft from the midpoint of a scarp that does not have a 30 degree slope; B. 50 ft from the top and bottom slope break on a scarp which has 30 degrees or more slope; and C. for scarps where a graben is present, 50 ft from the 30 percent slope break at the top and 50 ft from the farthest antithetic fault scarp.

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TECTONIC SUBSIDENCE

INTRODUCTION

Tectonic subsidence is the warping, lowering and tilting of a valley floor that accompanies surface-rupturing earthquakes on normal (dip slip) faults such as the Wasatch fault zone. Subsidence occurred during the 1959 Hebgen Lake, Montana, earthquake and the 1983 Borah Peak, Idaho, earthquake, and geologic evidence (the eastward shifts of the courses of the Jordan and Bear Rivers, the anomalously low altitude of the Gilbert Shoreline, etc.) indicates that tectonic subsidence has occurred during prehistoric earthquakes along the Wasatch Front (Keaton, 1987). Inundation along the shores of lakes and reservoirs and the ponding of water in areas with a shallow water table may be caused by tectonic subsidence. Also, tectonic subsidence may adversely affect certain structures which require gentle gradients or horizontal floors, particularly wastewater-treatment facilities and sewer lines (Keaton, 1987). In this chapter we discuss the consequences of possible tectonic subsidence in Davis County and make recommendations concerning the use of hazard maps for mitigation of subsidence hazards in land-use planning.

CHARACTERISTICS OF TECTONIC SUBSIDENCE

Tectonic subsidence, also termed seismic tilting, occurs during large magnitude earthquakes (> M 6.5) generated along normal faults which have accompanying deformation or displacement at the ground surface. The extent of seismic tilting is controlled chiefly by the amount and length of surface displacement, and normally occurs only along the portion of the fault that experienced surface deformation. The area of subsidence is controlled by the length of the fault rupture and subsidence should extend only a short distance beyond the ends of the fault rupture.

The Wasatch fault zone (WFZ) consists of 10 to 11 distinct segments which probably break independently (Machette and others, 1989). The primary WFZ segment in Davis County is the Weber segment which has a length of about 38 mi, the longest of the WFZ segments (Machette and others, 1989). The northern end of the Salt Lake segment (the Warm Springs fault) extends into southern Davis County along the western edge of the Salt Lake Salient (Machette and others, 1989). Southern Davis County could experience tectonic subsidence should surface faulting occur on either segment.

The probability of tectonic subsidence occurring is the same as a large earthquake (> M 6.5). The average composite recurrence interval for large earthquakes on the WFZ is 340 to 415 years, however, for any given individual segment, the average recurrence interval is 2035 to 2070 years (Machette and others, 1989). Due to the dispersion in the timing of events and the catastrophic losses which will occur during a large magnitude earthquake, the most conservative estimate, 340 to 415 years, should be used. This figure becomes even more significant when the timing of the most recent event, about 400 years ago (Machette and others, 1989), is considered.

Two earthquakes have occurred in the northern Basin and Range which are models for the WFZ; the largest is the 1959 M_s 7.5 Hebgen Lake, Montana, earthquake (Doser, 1985). The area of tilting, measured perpendicular to the fault, extended up to 10 mi from the fault at Hebgen Lake (Meyers and Hamilton, 1964). The amount of subsidence at Hebgen Lake (up to 20 ft) (Keaton, 1987) is larger than that expected for the 'characteristic earthquake' (Schwartz and Coppersmith, 1984) of the Wasatch Front and was not used as a direct analog for the Davis County area. The maximum ground-surface displacement due to surface-fault rupture at Hebgen Lake was about 20 ft, whereas the WFZ has an expected offset of 6 to 9 ft (Schwartz and Coppersmith, 1984). Also, the hazard maps for Davis County will show average expected offset for the WFZ, not the largest displacement which has occurred locally. The second earthquake model, the 1984 Borah Peak event, also formed subsidence (up to about 4.3 ft) extending up to about 9.3 mi from the fault; insufficient benchmark distribution eliminated evaluation of the distance of tectonic subsidence parallel to the fault (Keaton, 1987).

The expected area of subsidence for the WFZ extends for about 10 mi west of the fault zone with the majority of the deformation within about 3 mi (Keaton, 1986). The maximum amount of subsidence should occur at the fault and decrease gradually away on the downdropped valley block (Keaton, 1986).

Tectonic subsidence may cause flooding (Smith and Richins, 1984; figure C-1). The amount of inundation along shorelines will depend upon lake levels at the time of the event. The Bay Area Refuse Dump could be inundated due to tectonic subsidence. I-15 near Centerville could also be flooded if tectonic subsidence occurred when Great Salt Lake was above its historic high. Several zones of flooding have been delineated by Keaton (1986) for Great Salt Lake which correlate to lake elevations of 4200, 4205, 4210, and 4215 ft (1280, 1282, 1282, and 1285 m). These elevations represent a reasonable range of lake-level fluctuations (Keaton, 1986) because the lake has been as low as 4191 feet in 1963 and as high as 4211.85 feet in 1986 and 1987 (U.S. Geological Survey records). Also plotted on the maps are areas where the ground water may pond in the event of seismic tilting. Ground water was considered to be three feet from the ground surface prior to subsidence.

MITIGATION

The two major types of hazards associated with tectonic subsidence are tilting of the ground surface, and flooding from lakes, reservoirs, or shallow ground water (figure C-1). Because subsidence may occur over large areas (tens of square miles), it is generally not practical to avoid the use of potentially affected land except in narrow areas of hazard due to lake shoreline flooding. For gravity-flow structures such as wastewater-treatment plants that are within areas of possible subsidence, it is advisable to consider the tolerance of such structures to slight changes in gradient. Some structures may have to be releveled after a large-magnitude earthquake. Critical facilities which contain dangerous substances should have safety features to protect the structure, its occupants, and the environment, from both tilting and flooding.

Flooding problems along lakes from tectonic subsidence can be reduced using standard techniques. Structures can be raised above expected flood levels and dikes can be built. Land-use regulations around lakes or reservoirs can prohibit or restrict development in a zone along the shoreline that may be inundated. A buffer or safety zone of several feet of elevation above projected lake levels could be adopted to protect against natural rises from wet periods, storm waves, and earthquake-induced seiching, as well as hazards associated with tectonic subsidence.

Rises in the water table accompanying tectonic subsidence may cause water to pond, flood basements, and disrupt buried facilities, chiefly along a 3 mi wide zone adjacent to the fault (Keaton, 1987). In addition, shallow ground-water conditions may be located in areas where earthquake-induced liquefaction could also occur, which may compound mitigation problems. In areas of shallow ground water or standing water, structures can be elevated and basements floodproofed.

USE OF HAZARD MAPS

Keaton (1986) has mapped the areas of potential tectonic subsidence along the Wasatch fault zone in Davis County and estimated the amount of tilting and flooding. This mapping is based on a theoretical model and must be considered preliminary and approximate. Tectonic subsidence is a poorly understood phenomenon along the Wasatch Front, and these maps represent an initial attempt to depict the nature and extent of the hazard. The principal application of the maps is to make land-use planners and other users aware of the hazard and to indicate those areas where further study may be necessary. Site-specific tectonic subsidence studies are recommended only for critical facilities in areas of potential lake-margin and ponded shallow ground-water flooding. However, certain vulnerable facilities such as high-cost wastewater-treatment plants and hazardous-waste facilities should also consider potential tilting. It would also be prudent to consider this hazard for other types of

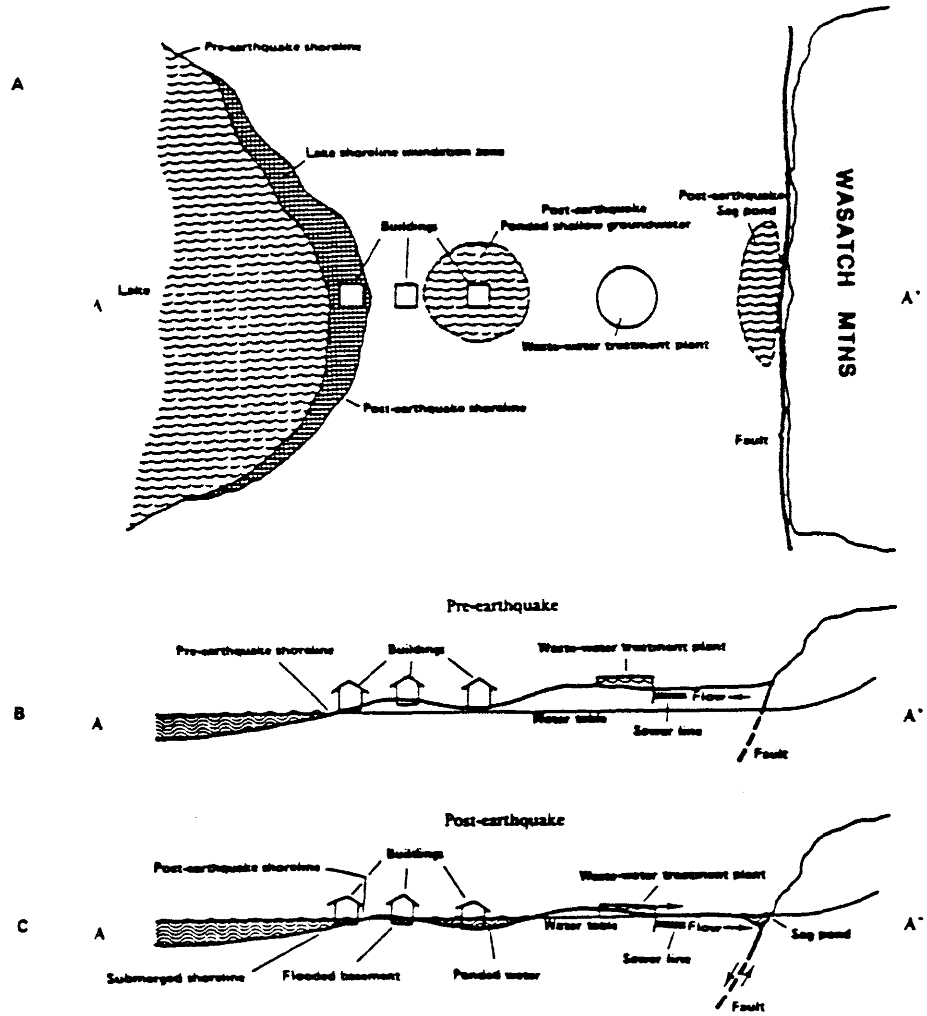

Figure C-1. A) Map (not to scale) showing surface-fault rupture and tectonic subsidence accompanying a hypothetical earthquake along the Wasatch fault zone. Areas that may be inundated after an earthquake are shown with a boxed pattern. A cross-section view between points A-A' is given as a reference in parts B and C to show the possible effects from tectonic subsidence. B) Cross-sectional view between points A-A' from part A showing an imaginary plane (water table) at its pre-earthquake position. Buildings and a waste-water treatment plant are represented to illustrate some of the possible effects of tectonic subsidence. Subsidence would probably not be uniform as depicted in this figure. Also, a majority of the deformation would most likely occur adjacent to the fault and total effects may extend over a much wider area. C) Cross-sectional view between points A-A' from parts A and B showing potential post-earthquake effects from tectonic subsidence. Note the areas of lake flooding as well as flooding from shallow ground water. Gravity-flow systems such as wastewater-treatment plants may experience problems from reversed flows.

development within the area of potential subsidence and take precautions.

SCOPE OF SITE INVESTIGATIONS

Site-specific studies of tectonic subsidence hazard should determine the depth to ground water and site elevation with respect to projected lake and ground-water levels. These results would then be compared to expected amounts of subsidence shown on the map by Keaton (1986). Recommendations regarding hazard reduction should be based on the extent of flooding or ground tilt indicated. These reports will be reviewed by the county. The hazard maps of Keaton (1986) will be amended as new and more accurate information becomes available.

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LIQUEFACTION

INTRODUCTION

Earthquake ground shaking causes a variety of phenomena which can damage structures and threaten lives. One of these is termed soil liquefaction. Ground shaking tends to increase the pressure in the pore water between soil grains, which decreases the stresses between the grains. The loss of intergranular stress can cause the strength of some soils to decrease nearly to zero. When this happens, the soil behaves like a liquid, and therefore is said to have liquefied. When liquefaction occurs, foundations may crack; buildings may tip; buoyant buried structures, such as septic tanks and storage tanks, may rise; and even gentle slopes may fail as liquefied soils and overlying materials move downslope.

The potential for liquefaction depends both on soil and ground-water conditions, and on the severity and duration of ground shaking. Soil liquefaction most commonly occurs in areas of shallow ground water (less than 30 feet) and loose sandy soils such as are found in western Davis County. In general, an earthquake of Richter magnitude 5 or greater is needed to induce liquefaction (Kuribayashi and Tatsuoka, 1975, 1977; Youd, 1977). For larger earthquakes, liquefaction has a greater likelihood of occurrence and will occur at greater distances from the epicenter (the point on the earth's surface directly above the focus of the earthquake). Earthquakes of Richter magnitude 7.0-7.5 are the largest expected along the Wasatch front (Schwartz and Coppersmith, 1984), and during such earthquakes liquefaction has occurred up to 170 miles (1977 Romanian earthquake, magnitude 7.2) from the epicenter (Youd and Perkins, 1987).

Anderson and others (1982) have produced maps depicting liquefaction potential for Davis County. It is the purpose of this chapter to discuss the nature of the liquefaction hazard, its potential consequences, commonly used techniques to reduce the hazard, and to give recommendations regarding how these maps should be used by Davis County and its cities for land-use planning.

NATURE OF THE LIQUEFACTION HAZARD

Liquefaction itself does not necessarily cause damage, but it may induce ground failure of various types which can be very damaging. Four types of ground failure commonly result from liquefaction: 1) loss of bearing strength, 2) ground oscillation, 3) lateral spread landslides, and 4) flow landslides (Youd, 1978a, b; Tinsley and others, 1985). Youd and others (1975) relate these types of ground failure to the slope of the ground surface (table D-1).

Table D-1. Ground slope and expected failure mode resulting from liquefaction (modified from Youd, 1978a; Anderson and others, 1982).

Ground Surface Slope	Failure Mode
Less than 0.5 percent	Bearing Capacity
Less than 0.5 percent, liquefaction at depth	Ground Oscillation
0.5 to 5.0 percent	Lateral Spread Landslide
Greater than 5.0 percent	Flow Landslide

Loss of bearing strength beneath a structure can occur during earthquake ground shaking when the underlying soil liquefies and loses strength (Tinsley and others, 1985) in areas where slopes are generally less than about 0.5 percent (Anderson and others, 1982) (figure D-1). The soil mass can then deform allowing buildings to settle and/or tilt (Tinsley and others, 1985). Buoyant buried structures such as gasoline storage or septic tanks, may float upward in liquefied soils (Tinsley and others, 1985). Among the more spectacular examples of a bearing capacity failure was the tilting of four four-story buildings, some as much as 60 degrees, in the Kwangishicho apartment complex during the 1964 Niigata, Japan, earthquake (National Research Council, 1985). Buried septic tanks rose as much as three feet during the same earthquake (Tinsley and others, 1985).

Ground oscillation takes place when liquefaction occurs beneath the ground surface below soil layers that do not liquefy, and where slopes are too gentle for lateral displacement to occur (Tinsley and others, 1985). Under these conditions, "liquefaction at depth commonly decouples overlying soil blocks, allowing them to jostle back and forth on the liquefied layer during an earthquake" (National Research Council, 1985; figure D-2). The decoupled layer vibrates in a different mode than the underlying and surrounding firm ground, causing fissures to form and impacts to occur between oscillating blocks and adjacent firm ground (National Research Council, 1985; Tinsley and others, 1985). Overlying structures and buried facilities can be damaged due to this type of ground failure as a result of ground settlement, the opening and closing of fissures, and sand boils which commonly accompany the oscillations (Tinsley and others, 1985).

Where the ground surface slope ranges between 0.5 and 5.0 percent, failure by lateral spreading may occur (Anderson and others, 1982). Lateral spreads occur as surficial blocks of sediment are displaced laterally downslope as a result of liquefaction in a subsurface layer (National Research Council, 1985, figure D-3). The surface layer commonly breaks up into blocks bounded by fissures which may tilt and settle differentially with respect to one another (National Research Council, 1985). The ground surface can be displaced laterally several yards, perhaps tens of yards, depending on soil and ground-water conditions and the duration of earthquake shaking (Tinsley and others, 1985). As shown in table D-2, significant damage to structures may result from lateral spreading.

Lateral spread landsliding can be especially destructive to pipelines, utilities, bridge piers, and other structures with shallow foundations (Tinsley and others, 1985). Lateral spread landslides with ground displacements of only a few feet caused every major pipeline break in San Francisco during the 1906 earthquake (Youd, 1978a); hence, liquefaction was largely responsible for the inability to control the fires that caused 85 percent of the damage to the city (Tinsley and others, 1985).

Table D-2. Relationship between ground displacement and damage to structures (from Youd, 1980).

Ground Displacement	Level Of Expected Damage
Less than 4 in.	Little damage, repairable
4 in. to 1 ft	Severe damage, repairable
1 ft to 2 ft	Severe damage, non-repairable
More than 2 ft	Collapse, non-repairable

Where ground surface slopes are steeper than about 5.0 percent, slope failure may occur in the form of flow landslides (Anderson and others, 1982) (figure D-4). Flow failure is the most catastrophic mode of liquefaction-induced ground failure (Tinsley and others, 1985). Flow landslides are comprised chiefly of liquefied soil or blocks of intact material riding on a liquefied layer (National Research Council, 1985). Flow failures can cause soil masses to be displaced tens of yards, and under favorable conditions, flow failure has displaced materials miles at relatively high velocities (Tinsley and others, 1985). Extensive damage due to flow landslides occurred in the cities of Seward and Valdez, Alaska, during the 1964 Alaska Earthquake (Tinsley and others, 1985). A flow landslide during the 1906 San Francisco earthquake knocked a power-house near the Mount Olivet Cemetery from its foundation (Youd, 1973).

REDUCTION OF LIQUEFACTION HAZARDS

Earthquake-induced soil liquefaction or liquefaction-induced ground failures have the potential to cause damage to most types of structures. Structures that are particularly sensitive to liquefaction-induced ground failure

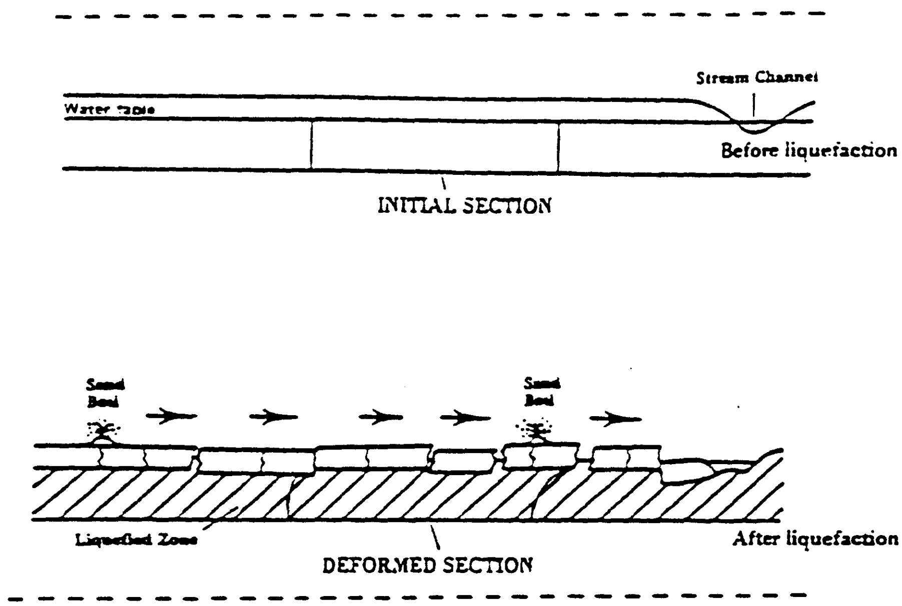

Figure D-3. Diagram of a lateral spread. Liquefaction occurs in the cross-hatched zone (Youd, 1984, in National Research Council, 1985). The ground surface slopes slightly to the right.

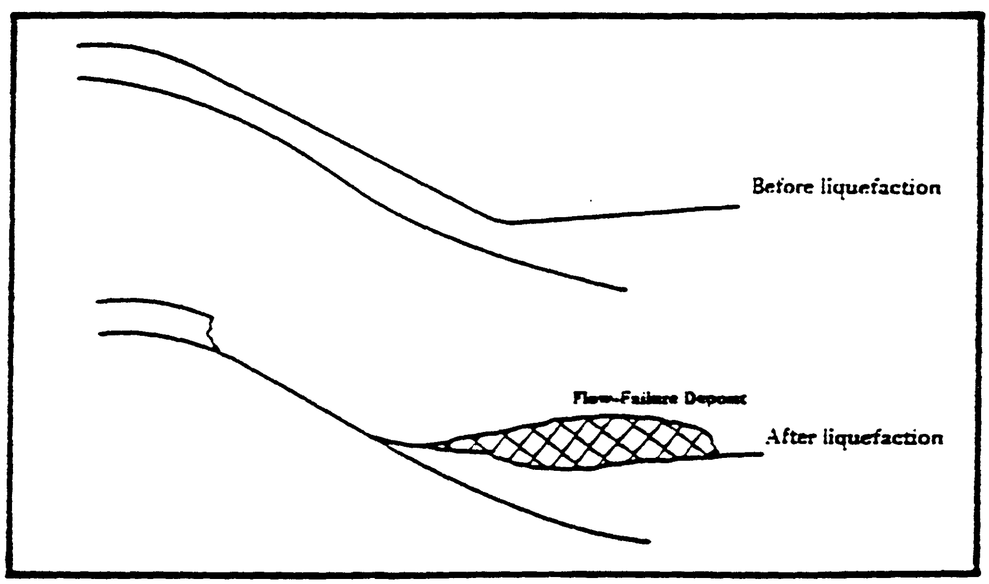

Figure D-4. Diagram of a flow failure. Liquefaction beneath the ground surface causes a loss of shear strength, allowing the soil mass to flow down the steep slope (Youd, 1984, in National Research Council, 1985.

include: buildings with shallow foundations, railway lines, highways and bridges, buried structures, dams, canals, retaining walls, port structures, utility poles, and towers (National Research Council, 1985). The National Research Council (1985) identifies several alternative approaches that can be taken if earthquake-induced liquefaction is determined to be a threat to existing or proposed structures. For an existing structure the choices include: 1) retrofitting the structure and/or site to reduce the potential for liquefaction-induced damage, 2) abandoning the structure if the retrofit costs exceed the potential benefits derived from maintaining the structure, or 3) accepting the risk.

Possible actions which may be taken if a liquefaction hazard exists at the site for a proposed structure include: 1) improving site conditions to lower the potential for liquefaction, 2) designing the structure to withstand the effects of liquefaction, 3) avoid the risk by moving the proposed development to a less hazardous site, 4) insure the development so that if liquefaction- induced damage occurs, funds will be available to repair the damage, or 5) accept the risk if the potential for and consequences of liquefaction are clearly understood.

Structural solutions to reduce the effects of liquefied soils can take several forms. For buildings, foundation-support problems in liquefiable soils may be avoided by using end-bearing piles, caissons, or fully compensated mat foundations designed for the predicted liquefaction phenomena at the site (National Research Council, 1985). Methods of improving liquefiable soil foundation conditions are: 1) densification of soils through vibration or compaction, 2) grouting, 3) dewatering with drains or wells, and 4) loading or buttressing to increase confining pressures (National Research Council, 1985). Costs of site improvement techniques range from less than $0.50 to more than $500.00 per cubic yard of soil foundation material treated (National Research Council, 1985).

LIQUEFACTION POTENTIAL INFORMATION FOR DAVIS COUNTY

The results of the liquefaction study are summarized in four maps. Each map consists of two parts (A & B) separating Davis County into a south half and a north half (Anderson and others, 1982). The base maps are 50 percent reductions of U. S. Geological Survey 7 1/2-minute (topographic) quadrangles and have a scale of one in. equals 4,000 ft (scale 1:48,000). The four maps are: 1) Selected Geologic Data Map, 2) Soils and Ground Water Data Map, 3) Ground Slope and Critical Acceleration Map, and 4) Liquefaction Potential Map.

A summary of the methods used in preparing the maps follows; for a detailed discussion of the technical aspects of map preparation, refer to Anderson and others (1982). Maps prepared by Anderson and others (1982) take into consideration soil and ground-water conditions and earthquake probability in determining liquefaction potential in Davis County. Soil and ground-water conditions were evaluated on the basis of subsurface data, chiefly boreholes and cone penetrometer tests, obtained from private engineering consultants, state and local government agencies, and tests run as part of the liquefaction potential investigation. A calculation of the level of ground shaking needed to induce liquefaction was then made at each data point. Peak horizontal ground acceleration was used as the measure of ground shaking, and that needed to induce liquefaction under a particular set of soil and ground-water conditions was termed the critical acceleration. The liquefaction potential in Davis County has been rated based on the probability that the critical acceleration needed to induce soil liquefaction will be exceeded during a 100-year return period (table D-3). Local geological conditions were also considered in refining liquefaction potential boundaries (Anderson and others, 1982). As shown on the Selected Geologic Data Map, five slope failures covering more than ten square miles in three areas of Davis County have been mapped and interpreted as prehistoric lateral spread failures probably induced by past earthquake ground shaking (Van Horn, 1975, 1982; Miller, 1980; Anderson and others, 1982).

The liquefaction potential rating for a given location can be determined by locating the site on the Liquefaction Potential Map. The approximate probability of ground shaking

Table D-3. Criteria used to evaluate liquefaction potential (Anderson and others, 1982).

Liquefaction Potential	Critical Acceleration Needed To Induce Liquefaction (g = force of gravity)	Approximate Probability That The Critical Acceleration Needed To Induce Liquefaction Will Be Exceeded During The Next 100 Years
High	less than 0.12 g	greater than 50%
Moderate	between 0.12 & 0.20 g	between 10% & 50%
Low	between 0.20 & 0.30 g	between 5% & 10%
Very Low	more than 0.30 g	less than 5%

sufficient to induce liquefaction at that site in the next 100 years may then be determined by referring to the proper category in table D-3. The expected mode of ground failure if liquefaction occurs at a given location may be evaluated by determining the approximate ground surface slope at the site on the Ground Slope and Critical Acceleration Map and referring to table D-1. Contours depicting areas of less than 0.5 percent, 0.5 to 5.0 percent, and greater than 5.0 percent slope are included in this map. To differentiate between bearing capacity and soil oscillation failure modes in areas of less than 0.5 percent slope, the depth of the liquefiable layer must be known. This can be determined for specific sites by using the Soils and Ground Water Data Map to determine the depth to liquefiable soils and the nature of overlying and underlying units. However the map does not interpret depths to liquefiable layers between data points, so the two failure modes can only be differentiated at specific sites where data were collected.

RECOMMENDED USE OF MAPS IN LAND-USE PLANNING

These maps are at a regional scale and, although they can be used to gain an understanding of probable potential of a given area for liquefaction during earthquake ground shaking, they are not designed to replace site-specific evaluations. Mapped areas rated as having a low liquefaction potential may contain isolated areas with a high liquefaction potential and areas rated as having a high liquefaction potential may contain isolated areas which are not prone to liquefaction. Site-specific liquefaction potential studies should be conducted where this information is needed.

Large areas of Davis County have moderate to high potential for liquefaction during earthquake ground shaking, including most of the area west of State Highway 89. The liquefaction potential maps provide a general indication of where the hazard may exist, and serve as a means of evaluating the need for site-specific studies. Because of the distribution of data points and the relatively small scale of the maps, it does not preclude the necessity for site-specific evaluations. Where a use is planned at a site where data used in preparing the maps were collected, the point data may be useful in a site evaluation, depending on its quality. It is recommended that liquefaction potential be evaluated and, if necessary, mitigative measures recommended in site investigation reports submitted by the developer prior to planning commission approval as outlined in table A-1. Areas of moderate to high liquefaction potential need not be avoided, because structural measures and site modification techniques are available to reduce hazards. Reports addressing liquefaction potential in such areas are recommended for large structures, but not for single-family dwellings, as has been recommended by the engineers and geologists who conducted the liquefaction potential study (Anderson and others, 1987). This is because the cost of reducing liquefaction hazards commonly exceeds the value of single-family dwellings (L. R. Anderson, personal commun., August 31, 1987), and because liquefaction is generally not a life-threatening hazard.

SCOPE OF SITE INVESTIGATIONS

A liquefaction potential evaluation should be part of a standard soil foundation investigation for the proposed development. Initial evaluations for liquefaction potential should be based on depth to ground water and soil types. If soil and ground-water conditions indicate that liquefiable soils may be present, standard penetration tests and/or cone penetration tests should be conducted to determine critical accelerations needed to induce liquefaction. A site-specific liquefaction potential report should include accurate maps of the area showing any proposed development, the location of bore holes and/or test pits, and the site geology. Logs of bore holes and test pits should be included in the report and any ground water encountered should be noted on the logs. The location of and depths to liquefiable soils should be noted and the probability of critical accelerations needed to induce liquefaction in these soils being exceeded for appropriate time periods should be determined. Recommendations for hazard reduction techniques should be included. A meeting with the County Planning Department and County Engineer should occur prior to conducting site-specific liquefaction studies to discuss the scope of work and types of information that should be obtained from such a study.

A useful guide for use in preparing reports is found in Utah Geological and Mineral Survey Publication M, Guidelines For Preparing Engineering Geological Reports In Utah, by the Utah Section of the Association of Engineering Geologists (1986). When site-specific reports are received addressing liquefaction hazards, they should be reviewed by the county and, once approved, submitted to the planning commission along with review comments so that the planning commission has sufficient information available to make decisions regarding the proposed development.

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OTHER EARTHQUAKE HAZARDS

INTRODUCTION

A variety of phenomena that can cause damage to property and/or threaten lives may accompany earthquakes. The principal hazards are addressed in other chapters in this report covering surface fault rupture, ground shaking, liquefaction, tectonic subsidence, landslide, and rock-fall hazards. It is the purpose of this chapter to discuss other potentially damaging but less well-understood phenomena associated with earthquakes, including: 1) ground failure due to loss of strength in sensitive clays; 2) subsidence caused by vibratory settlement in granular materials; 3) flooding caused by seiches in Great Salt Lake; 4) flooding due to surface drainage disruptions; and 5) increased ground-water discharge.

GROUND FAILURE DUE TO LOSS OF STRENGTH IN SENSITIVE CLAYS

Nature And Causes

Fine-grained lake deposits underlie much of western Davis County. Near Farmington these deposits are about 810 feet thick (Feth and others, 1966), and some areas of Davis County may be underlain by as much as 1,000 feet of sediments (Parry, 1974) deposited by lakes occupying the Great Salt Lake Basin during the last 15 million years (Currey and others, 1984). Much of these lake sediments are silicate clays, some of which are classified as sensitive (Parry, 1974).

Most clays lose strength when disturbed; sensitive clays are those which experience a particularly large loss of strength. The sensitivity of clays is defined as the ratio of shear strength in an undisturbed condition to shear strength after being remolded (severely disturbed)(Costa and Baker, 1981). One proposed origin for these clays holds that the platy clay particles were deposited in an edge-to-edge "house of cards" (flocculated) structure in saline (generally marine) environments in which the sodium and other cations in the water provided bonding strength (Rosenqvist, 1953, 1968). Later, when this saline water is leached out by fresh ground water, the clays are left in an unstable arrangement subject to collapse and liquefication when disturbed or shaken. After disturbance, the clays may revert from a flocculated soil structure in which ground water fills the interstitial pore spaces, to a dispersed soil structure in which the interstitial water is expelled, often liquefying the clay (Costa and Baker, 1981).

Effects

The principal effect of disturbance of sensitive clays is ground failure. The kinds of ground failures associated with sensitive clays are similar to those accompanying liquefaction, including flow failures, slump-type landslides, and lateral spreads or translational landslides (Earthquake Engineering Research Institute, 1986; Costa and Baker, 1981). Liquefied sensitive clays may flow downhill on slopes of one degree or less (Costa and Baker, 1981). One triggering mechanism for ground failure in sensitive clays is intense ground vibration generated by earthquakes. The most devastating damage resulting from the 1964 Anchorage, Alaska, magnitude 8.6 earthquake was the result of translational landslides accompanying failure in sensitive clays. The largest of these landslides, located in the Turnagain Heights residential area, damaged 75 homes (Hansen, 1966).

The potential for ground failure in sensitive clays is related to the intensity and duration of ground shaking, and the sensitivity of the clays. Clays with sensitivities of 10 or more may be prone to failure during seismic ground shaking (Earthquake Engineering Research Institute, 1986). Clays exceeding sensitivities of 10 have been identified in Davis County along the Weber River and at the Interstate 15 Parrish Lane overpass (Parry, 1974), indicating that sensitive clays are present and may be widely distributed in Davis County. The intensity and duration of ground shaking needed to induce failure in these sensitive clays have not been investigated and, therefore, the probability of this type of ground failure occurring in Davis County cannot be currently determined.

Hazard Reduction

Earthquake-induced ground failure due to sensitive clays has the potential to cause damage to most types of structures. Possible actions which may be taken if sensitive clays are present include: 1) improving site conditions by converting the clays from a flocculated soil structure to a dispersed soil structure (preconstruction vibration techniques, etc.) and/or dewatering the site; and 2) designing the structure to withstand the effects of the potential ground failure using structural solutions such as end-bearing piles (placed below the sensitive clay), caissons, or fully compensated mat foundations designed for the anticipated failure type.

Land-Use Planning

Maps have not been produced which show the extent of sensitive clay deposits in Davis County, but assessment of this hazard can be undertaken at site-specific level as part of standard foundation investigations. This involves laboratory tests (unconfined compression tests) in which axial loads are applied to unconfined cylindrical samples, first in an undisturbed state and then in a remolded state (Spangler and Handy, 1973). The ratio of the strength of the soil under undisturbed versus disturbed conditions is then determined. Additional study is needed to determine the levels of ground shaking necessary to cause ground failure in sensitive clays before this hazard can be considered in regional land-use planning. Sensitive clays are a factor that should be considered in site-specific studies for all major construction, however, including critical facilities.

SUBSIDENCE CAUSED BY VIBRATORY SETTLEMENT IN GRANULAR MATERIALS

Nature And Causes

Loose granular materials such as some sands and gravels can be effectively compacted by vibration. The material assumes a more dense arrangement by particles moving closer together and decreasing the volume. Earthquake-induced ground shaking is one source of vibrations that may cause this type of subsidence. During the 1964 Alaska earthquake, vibratory settlement caused the ground to subside at some locations as much as 5.9 ft (Costa and Baker, 1981). Large areas of western Davis County are underlain by clean sand and gravel deposited in Pleistocene Lake Bonneville where the potential for settlement may exist. Also, many areas of fill exist in the county which may be susceptible to vibration-induced settlement. No studies to determine levels of ground shaking necessary to induce vibratory settlement in susceptible soils have been conducted in Davis County and, therefore, probabilities of this hazard occurring are unknown.

Effects

Differential settlement can occur if foundations are built across deposits with varying physical properties such as sorting and texture, possibly resulting in severe building damage as one part of the foundation settles more than another (Costa and Baker, 1981). Structural failure of building members (Dunn and others, 1980), and foundation cracking may also be caused by excessive settlement. Earthen fill is commonly used for construction of railway embankments, highway foundations, bridge abutments, and dikes and levees. Even minor differential settlement can cause extensive damage to these structures. If not adequately compacted during placement, these fills may be susceptible to this hazard because of the granular material commonly used (Schmidt, 1986). Utility lines and connections may be severed due to vibratory settlement. Rate of settlement is an important factor that must be considered in evaluating the potential for damage (Dunn and others, 1980). Settlements due to earthquake ground shaking would be nearly instantaneous.

Hazard Reduction

Structural methods to reduce damage due to settlement include supporting structures on piles, piers, caissons, or walls which are founded below the susceptible material (U. S. Department of the Interior, 1985). Where structural measures to reduce vibratory settlement in granular soils are not possible, actions which may be taken to mitigate the hazard include: 1) improve site conditions by removing or precompacting the in place granular materials prior to construction; and 2) properly engineer and compact fills.

Land-Use Planning

Maps delineating areas susceptible to vibratory settlement have not been completed for Davis County. Also, the levels of ground shaking necessary to induce settlement varies with conditions, and assessment of this hazard must be undertaken at a site-specific basis as part of a standard foundation evaluation. Standard penetration and cone penetrometer tests are commonly used to evaluate the potential for vibratory settlement (Dunn and others, 1980). The potential for vibratory settlement should be evaluated for all major construction, especially for critical facilities.

FLOODING CAUSED BY SEICHES IN GREAT SALT LAKE

Nature And Causes

A seiche is the oscillation of the surface of a lake or other landlocked body of water; seiches vary in period from a few minutes to several hours. Seiches are similar to the oscillations produced by sloshing water in a bowl or a bucket when it is shaken or jarred (Nichols and Buchanan-Banks, 1974). The magnitude of oscillation of the water surface is determined by the degree of resonance between the water body and the periodic driving force such as earthquake ground shaking and wind. When the periodic driving force is oscillating at the same frequency at which the water body tends to oscillate naturally, the magnitude of the oscillation is greatest and may cause unusually large waves (seiches) that "break at considerable height and with great suddenness along the coastline" (Costa and Baker, 1981).

The effects of seiches are in part determined by water depth, lake size and shape, and the configuration of the local shoreline. These parameters determine the lake's natural period of oscillation and inherent system of long waves, much as the natural frequency of a pendulum is determined by its physical characteristics (Lin and Wang, 1978). "The system of long waves includes an infinite number of species of waves, usually called the normal modes; the fundamental mode refers to the wave with the longest wavelength" (Lin and Wang, 1978). It is the fundamental mode that is generally observed during surging and seiching" (Lin and Wang, 1978). The period of the fundamental mode of Great Salt Lake's South Basin is 6 hours (Lin and Wang, 1978). Studies from other areas have shown that seiches may raise and lower a water surface from inches to many yards, causing damage from wave action as well as severe flooding (Blair and Spangle, 1979).

Seiches may be generated by wind, landslides, and/or earthquakes (ground shaking, surface-fault rupture, and earthquake-induced landslides). The principal area at risk from seiches in Davis County is the shore of Great Salt Lake. Wind seiches in Great Salt Lake have been studied and the maximum wave amplitude generated by this type of seiche is expected to be about 2 ft (Lin and Wang, 1978). No systematic or theoretical studies of landslide or earthquake-induced seiching in Great Salt Lake have been completed. Seiches were reported along the southern shoreline of Great Salt Lake at Saltair and at the trestle at Lucin during the magnitude 6 Hansel Valley earthquake of October 5, 1909 (Williams and Tapper, 1953). The elevation of Great Salt Lake was 4202.0 ft on October 1, 1909 (U.S. Geological Survey lake elevation records). The seiche generated by the 1909 Hansel Valley earthquake overtopped the Lucin cutoff railroad trestle which had an elevation of 4214.85 ft (Southern Pacific Transportation Company records). Assuming that reports of the seiche overtopping the trestle are true, and that lake and trestle elevation records were accurately reported, the seiche wave was more than 12 ft high.

Effects

Damage from seiches is primarily related to flooding, erosion, and forces exerted by waves. Seiches are a potential hazard to shoreline development and in-lake structures, and are a concern to the proposed inter-island diking project in Great Salt Lake.

Hazard Reduction

Dikes which are protected against erosion on the lakeward side and engineered breakwaters can be used to protect development or dissipate wave energy. Shoreline buildings can also be floodproofed, elevated, and constructed or reinforced to withstand the lateral forces of seiches (Costa and Baker, 1981).

Land-Use Planning

Maps have not been produced that show areas that may be affected by seiches in Davis County. No comprehensive studies of landslide or earthquake-generated seiches have been completed for Great Salt Lake, but eyewitness accounts of the seiche generated by the 1909 Hansel Valley earthquake suggest that maximum wave amplitudes generated by earthquakes may far exceed maximum wave amplitudes associated with wind seiches. Landslide and earthquake-generated seiches are a hazard to shoreline development and in-lake construction and should be taken into consideration during planning phases of development in Great Salt Lake and within the proposed Great Salt Lake Beneficial Development Area (Utah Division of Comprehensive Emergency Management, 1985).

FLOODING DUE TO SURFACE DRAINAGE DISRUPTIONS DURING EARTHQUAKES

Flooding may be caused by earthquake ground shaking, surface-fault rupture, ground tilting, and landsliding during earthquakes if water tanks, reservoirs, pipelines, or aqueducts are ruptured, or if stream courses are blocked or diverted. The areas where such flooding may occur can be predicted to some extent by defining where such structures and streams cross known active faults, active landslides, and potentially unstable slopes. Damming of streams by landslides can cause upstream inundation and, if the landslide dam subsequently fails, cause catastrophic downstream flooding (Schuster, 1987). Maps delineating active faults and landslides are available at the Davis County Planning Department. Site-specific studies addressing earthquake and slope-failure hazards should be completed prior to construction for all major water-retention structures or conveyance systems so that mitigative measures can be recommended. For existing facilities, studies can be done to evaluate the possible extent of flooding and to recommend drainage modifications to prevent damaging floods. Potential flooding from diversion of stream courses is more difficult to evaluate, but should be considered during hazard evaluations for critical facilities.

INCREASED GROUND-WATER DISCHARGE DUE TO EARTHQUAKES

The effects of earthquakes on ground-water systems have not been extensively studied and, consequently, are not well understood. During the 1983 Borah Peak, Idaho, earthquake, local surface flooding and erosion were caused by increases in spring flow and expulsion of water from shallow bedrock aquifers. Resulting increases in stream flow of more than 100 percent occurred following the earthquake, and flow remained high for about 2 weeks before declining to near original levels (Whitehead, 1985). Although this earthquake appeared to be one in which the ground water was more profoundly affected than others, similar effects may occur during large-magnitude earthquakes in the vicinity of Davis County. Increased flow from springs in mountain drainages will be confined to stream channels, and adherence to Federal Emergency Management Agency flood-plain regulations should effectively reduce the risk. Increased flow from springs on the valley floor may result in ponded water and basement flooding.

CONCLUSIONS AND RECOMMENDATIONS

This chapter identifies a variety of phenomena associated with earthquakes which can damage property and threaten lives. Although many of the consequences of these hazards have been identified, the probability of occurrence has not been evaluated for Davis

County, and maps delineating areas in Davis County where hazards associated with these phenomena may occur are not available. Much study is required before these phenomena can be considered in regional planning for Davis County. However, some of these hazards can be evaluated on a site-specific basis; such studies should be considered for major construction projects, particularly critical facilities.

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LANDSLIDES

INTRODUCTION

Landsliding historically has been one of the most damaging geologic processes occurring in Davis County, both in the unincorporated county and in many cities. All active landslides and most older slides have been mapped at a scale of 1:24,000 to produce landslide-inventory maps. These maps serve as an indication of unstable ground. The landslide inventories, along with slope maps and other geologic data, have been used to evaluate slope stability on a broad scale and to prepare landslide-hazard maps. These hazard maps show areas of landslides and slopes which are potentially unstable under static (non-earthquake) conditions. Separate earthquake-induced (dynamic) landslide-hazard maps have been prepared for Davis County by Keaton and others (1987). This chapter describes landslide hazards and recommends guidelines for use of landslide-hazard and earthquake-induced landslide-potential maps in land-use planning.

LANDSLIDE CHARACTERISTICS

Landslides are generally defined as "mass movements of rock or soil downslope under the direct influence of gravitational forces without an aiding transporting medium such as water, air, or ice" (Costa and Baker, 1981, p. 243). Landslides considered in the landslide-hazard maps include rotational and translational slides and associated earth flows (Varnes, 1978). Rotational slides generally have a curved failure plane. The head of the rotational slide is back-tilted compared to the slope of the original surface. Most rotational slides are termed slumps, and may include an earth flow at the toe where material moves onto the land surface below the slump (figure F-1). Translational slides generally have a more planar failure surface, and may be broken into several discrete blocks. If rock is involved, the term rock slide may be used. The speed of landslides may vary. Both slide types may occur slowly and progressively over periods of years, or may be extremely rapid and occur in a matter of a few seconds. The landslide-hazard maps do not address rock falls or debris flows, which are other types of failures commonly grouped under the term landslides.

Landslides may be caused by any of several conditions. Oversteepening of slopes, loss of lateral support, weighting of the head, increased pore pressure, and earthquake ground shaking are among the major causes of landslides. Older landslides are particularly susceptible to reactivation due to conditions which exist in a displaced soil mass such as increased permeability and established failure planes.

Landslides are likely to occur in Davis County if a moderate to strong earthquake occurs in northern Utah. Ground failures, including landslides, commonly accompany earthquakes with Richter magnitudes greater than 4.5 (Keefer, 1984). Some form of landslide or ground failure (predominantly rockfall or rockslide) has been noted in the descriptions of 12 earthquakes that occurred in or immediately adjacent to Utah from 1850 to 1986 (magnitudes 4.3 to 6.6) (Keaton and others, 1987). Geologic evidence from trench excavations across Wasatch fault zone scarps indicate that past earthquakes on the Wasatch fault had magnitudes ranging from 7.0 to 7.5 (Schwartz and Coppersmith, 1984). It is expected that future Wasatch fault earthquakes will have similar magnitudes. Earthquakes of magnitude 7.5 could cause slope failures as far as 185 miles from the epicenter (Keaton and others, 1987).

Landslides are also likely to occur in years of abnormally high precipitation. Many landslides occurred in Davis County during the recent wet cycle (1982-1985), causing significant damage to homes and property. Most of this damage was caused by the Memorial Day 1983 Rudd Canyon debris flow which damaged 35 houses, 15 severely. The 1983 Rudd Canyon debris flow, which resulted in deposition of more than 100,000 yd^3 of earth material at the canyon mouth, was initiated by landsliding (less than 20,000 yd^3) in the Wasatch Mountains (Wieczorek and others, 1983).

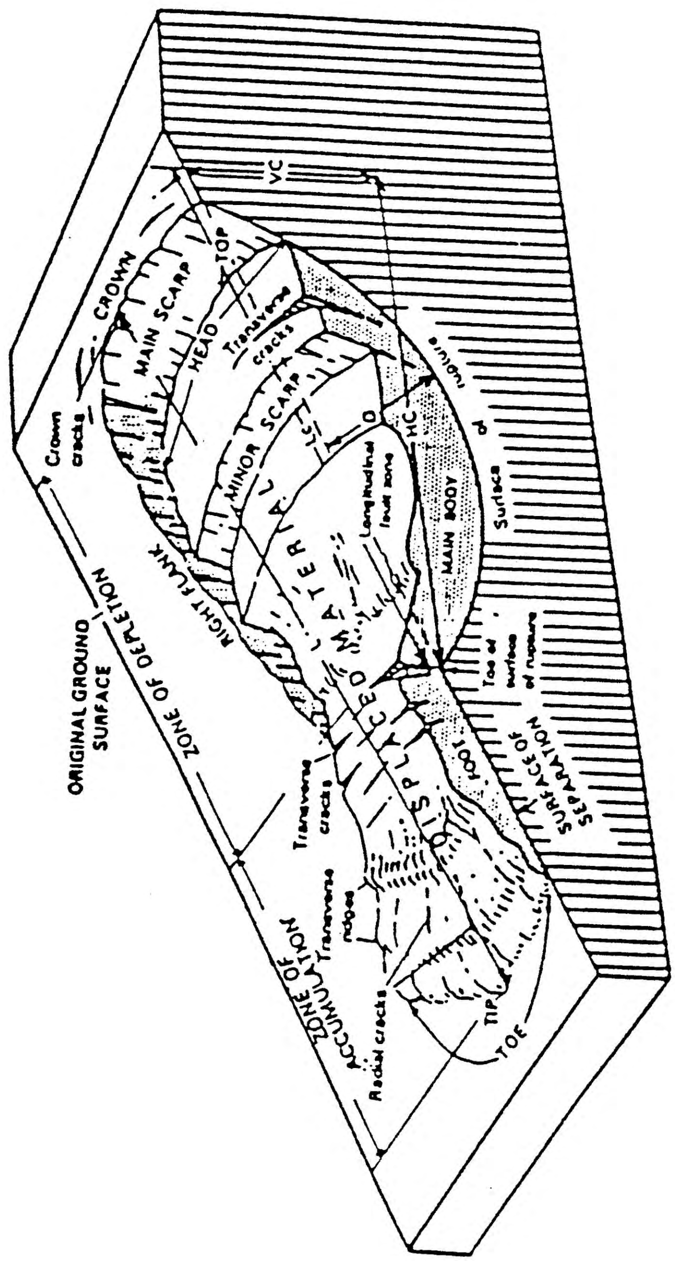

Figure F-1. Block diagram of a rotational landslide. Note the back- tilt below the main scarp and material at the zone of accumulation at the toe. If this landslide was translational, then the surface of rupture (failure plane) would be planar like the surface of separation beneath the foot. Adapted from Varnes (1978).

CONSEQUENCES

Damage from a landslide can occur at any point on the slide mass and above or below the landslide. The tops of most landslides are characterized by an arcuate downhill-facing scarp (main scarp) created by the downward displacement of the ground surface (figure F-1). The effect on a building straddling the main scarp is partial loss of foundation support and potential building collapse. Structures upslope from the head of a landslide are endangered because the newly formed main scarp is commonly unstable and may fail causing new scarps to form upslope. Buildings constructed within the central mass of the landslide may be subjected to differential displacement on minor scarps and movement in both vertical and horizontal directions. Table F-1 shows the relationship between ground displacement and expected levels of damage to structures. The toe of a landslide will normally move horizontally and upward and may proceed downslope causing extensive damage to structures. Cracks at the head and a bulge at the toe may precede the principal landslide movement. Landslides can damage roads, railroads, and power lines. Furthermore, landslides may rupture canals, aqueducts, sewers, and water mains, and thereby add water to the slide plane and promote further movement. In addition to ground movement, flooding may be caused by landslides. Flooding may occur due to discharge from springs along the basal slide plane (example, 1500 East landslide, Provo, Utah), usually in the toe area, or damming of streams causing upstream flooding as water is ponded and possible flooding downstream if the impounded water overtops or breaches the landslide dam. Spring discharge from landslides is a minor problem and can generally be mitigated by diverting drainage. Damming of streams is a major problem (Schuster, 1987), and was a principal hazard associated with the Thistle landslide in 1983 in Utah County. Lake Thistle, which had a maximum depth of about 225 feet, formed behind the landslide mass and flooded the town of Thistle. A much larger and more populated area downstream was at risk from flooding had the landslide failed or been overtopped and washed-out prior to draining of the lake. Another landslide that caused similar problems is the Gros Ventre landslide in Wyoming where 6 or 7 people were killed in the ensuing flood two years after the landslide event (Costa and Baker, 1981).

Table F-1. Relationship between ground displacement and damage to structures from Youd (1980).

Ground Displacement	Level Of Expected Damage
Less than 4 in.	Little damage, repairable
4 in. to 1 ft	Severe damage, repairable
1 ft to 2 ft	Severe damage, non-repairable
More than 2 ft	Collapse, non-repairable

LANDSLIDE SUSCEPTIBILITY

Several geologic units in Davis County are susceptible to landslides. Landslide-prone geologic units were identified by overlaying landslide-inventory and geologic maps and tabulating the number of landslides occurring in each geologic unit. The Precambrian Farmington Canyon Complex in the mountains in eastern Davis County weathers in a manner which provides much unstable hillside debris (colluvium), and debris slides are common. Debris slides in colluvium derived from the Farmington Canyon Complex were responsible for initiating many of the debris flows which occurred in 1983 and 1984. Landslides are also common in areas underlain by the sediments of Pleistocene Lake Bonneville. Rotational landslides (slumps) are particularly common in northern Davis County where stream incision into the Weber River Delta has created high bluffs and exposed silts and clays deposited during the high stand of Lake Bonneville. Many springs occur along these bluffs increasing landslide susceptibility.

Existing landslides pose a particular problem for development because of their tendency to reactivate. Many landslides in the mountains and along the bluff above the City of South Weber are re-activated old landslides or have developed on portions of larger older landslides.

Slope steepness is another important factor in determining slope stability. Almost any material will fail if the slope is steep enough.

Landslides may be triggered by earthquake activity. Although the same slopes which are considered unstable under static conditions will be even less stable during an earthquake, some slopes that are stable under static conditions may fail as a result of earthquake ground shaking, particularly if the earthquake occurs when slopes are wet. Most landslides caused by earthquakes are new slope failures, not reactivated older landslides (Keefer, 1984).

REDUCING LANDSLIDE HAZARDS

Many methods have been developed for reducing landslide hazards. Proper planning and avoidance is the least expensive measure, if landslide-prone areas are identified early in the planning and development process. Care in site grading with proper compaction of fills and engineering of cut slopes is a necessary follow-up to good land-use planning. Where avoidance is not feasible, various engineering techniques are available to stabilize slopes. De-watering (draining) can have a major impact on stabilizing slopes and existing landslides. Retaining structures built at the toe of a landslide may help stabilize the slide and reduce the possibility of smaller landslides. In some cases, piles may be driven through the landslide mass into stable material beneath the slide. If the dimensions of the landslide are known, and the landslide is not excessively large, removing the landslide may be effective. Some other techniques which may be used to reduce landslide hazards include bridging, weighting or buttressing slopes with compacted earth fills, and drainage diversion. A more complete list of landslide-hazard reduction techniques may be found in Costa and Baker (1981), Kockelman (1986), and other engineering geology publications. Every landslide and potentially unstable slope will probably have differing characteristics and will need to be evaluated for an appropriate hazard reduction technique.

SUMMARY OF METHODS USED IN MAP PREPARATION

Landslide-inventory maps showing existing landslides in Davis County have been compiled at 1:24,000 scale using U. S. Geological Survey topographic quadrangles as base maps. The following parameters were evaluated while preparing the landslide-inventory maps: 1) landslide type, compiled from existing data and air photo interpretation using a classification scheme developed by Varnes (1978); 2) age class of landslides, using a classification scheme developed by McCalpin (1984); 3) elevation of the toe and crown of the landslide; 4) average pre-landslide slope; 5) failed geologic unit, as determined from existing geologic mapping; 6) other geologic units involved; 7) slope aspect; 8) landslide complexity (multiple landslides); and 9) the role of man in causing the failure. If the same landslide was mapped by more than one investigator, and discrepancies were found in the mapping of the perimeter of the landslide, the two maps were overlain and the outermost margin of the landslide on the combined maps was used.

The landslide-inventory maps and slope maps were then used to assess the susceptibility for slope failure on natural slopes under static (non-earthquake) conditions and to help construct 1:24,000 scale landslide-hazard maps. Slopes steeper than 30 percent have a relatively high potential for failure and are generally already subject to land-use restrictions for reasons other than slope stability, so these are included in the recommended study area on the landslide-hazard maps. In certain failure-prone materials such as fine-grained Lake Bonneville deposits, failures have occurred at slopes less than 30 percent. These flatter areas with existing landslides have also been included in the recommended study area on the landslide-hazards maps.

In those areas where unstable slopes occur surrounded by flatter, more stable slopes, it is necessary to extend landslide-hazard study boundaries beyond the base and top of the unstable slope. This situation occurs along the bluff above South Weber, and along incised drainages in Layton and Kaysville, where the potential instability in the steeper slope (bluff face) may affect areas both above and below. The width of the landslide-hazard study area in this situation depends on the height, steepness, ground-water conditions, and strength of the material making up the slope. In these areas of flat land above and below landslide-prone slopes, a conservative stable slope angle through the center of the steep slope was taken to determine where slope-stability studies are needed for the flatter land. Rollins, Brown, and Gunnel (1977) determined that this conservative slope angle should be 2 horizontal to 1 vertical (2:1) (50 percent) for dry granular soils, and 2.5:1 (40 percent) for moist fine-grained material. In general these zones extend less than 100-150 feet from the base or top of slopes and are too narrow to be shown at the map scale.

Earthquake-induced landslide-potential maps (1:48,000 scale) for Davis County have been prepared by Keaton and others (1987) using 50-percent reductions of U. S. Geological Survey topographic quadrangles as base maps. In evaluating seismic slope stability Keaton and others (1987) considered: 1) the strength of slope materials, 2) slope geometry, 3) ground-water conditions, and 4) the strength or intensity of earthquake ground shaking. These parameters were evaluated to determine the level (magnitude) of ground shaking necessary to cause slope instability in each type of earth material found in Davis County, for various slopes and slope geometries, and for dry and saturated ground-water conditions (Keaton and others, 1987). The probability of this level of ground shaking occurring during a 100-year time period was then determined and used to define geographic areas of high, moderate, low, and very low potential for seismic slope failure (Keaton and others, 1987). Table F-2 summarizes each category of earthquake-induced landslide potential with respect to the probabilities of the critical accelerations needed to induce failure in each category being exceeded in a 100-year time period and the possible levels of displacement associated with that failure.

RECOMMENDED USE OF MAPS FOR LAND-USE PLANNING AND DEVELOPMENT

The landslide-hazard maps that accompany this chapter show areas of existing landslides and potential landslide hazard at 1:24,000 scale using U.S. Geological Survey 7 1/2 minute (topographic) quadrangles as base maps. These maps are chiefly intended for use by planners to identify areas where site-specific investigations addressing slope stability should be performed prior to development. It is recommended that slope-failure potential be evaluated and, if necessary, mitigative measures recommended in site-specific engineering geologic reports submitted by the developer prior to planning commission approval as outlined in table A-1.

The results of the earthquake-induced landslide-potential study are presented on a 1:48,000 scale map consisting of two parts (A & B) separating Davis County into a south half and a north half. The earthquake-induced landslide-potential rating for a given location can be determined by locating the site on the Earthquake-Induced Landslide-Potential Map. The approximate probability of ground shaking sufficient to induce slope failure, for both dry and wet soil conditions, occurring during a 100-year period for the landslide-potential rating given on the map may then be determined by referring to the proper category in table F-2.

Both the landslide-hazard and the earthquake-induced landslide-potential maps provide a general indication of where slope-failure hazards may exist, and serve as a means for evaluating the need for site-specific studies. These maps are at a regional scale and, although they can be used to gain an understanding of the potential for landslides occurring in a given area, they are not designed to replace site-specific evaluations. Mapped areas rated as having landslide hazards or having a high potential for earthquake-induced landsliding may contain isolated areas which are not prone to landsliding, even during earthquake ground shaking. Also, areas outside the landslide-hazard study boundary, or rated as having a low earthquake-induced landslide potential, may contain isolated areas which are highly susceptible to landsliding.

Table F-2. Earthquake-induced landslide potential categories, soil moisture levels considered, probability of exceedence of critical acceleration needed to cause failure during 100-year period, and possible magnitudes of displacement from Keaton and others (1987).

Seismic Slope-Failure Potential	Soil Moisture Conditions	Probability Of Critical Acceleration Necessary To Cause Slope Failure Being Exceeded In A 100-Year Time Period	Possible Levels of Displacement
High	Dry and wet	50 percent or greater	4 in. or more
Moderate	Dry	10 to 50 percent	1 to 4 in.
	Wet	50 percent or greater	4 in. or more
Low	Dry	Less than 10 percent	Less than 1 in.
	Wet	10 to 50 percent	Up to 4 in.
Very Low	Dry and wet	10 percent or less	Less than 1 in.

SCOPE OF SITE INVESTIGATIONS

Site evaluations for landslides and potentially unstable slopes, including earthquake-induced landslides, should be performed prior to construction of any structures for human occupancy in landslide hazard areas shown on the maps. The investigation should include accurate maps of the area showing the proposed development, existing landslides and steep slopes, and the site geology. An assessment of present slope stability and the effects of development on slope stability should be included. Where necessary, a factor of safety should be computed by a competent geotechnical engineer or engineering geologist to determine the stability of natural or proposed cut slopes. Slope-stability analyses should include potential for movement under static, development-induced, and earthquake-induced conditions as well as all likely ground-water conditions. Site grading, including design of cuts and fills, should comply with Chapter 70 of the 1988 Uniform Building Code. A useful guide for preparing site-investigation reports is found in Utah Geological and Mineral Survey Miscellaneous Publication M, Guidelines for Preparing Engineering Geological Reports in Utah, by the Utah Section of the Association of Engineering Geologists (1986). Site investigation reports should be reviewed by the county. This review will determine if the submitted report is adequate and complete. As new and more accurate information becomes available, the landslide-hazard maps will be amended.

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DEBRIS FLOWS

INTRODUCTION

Debris flows are mixtures of water, rock, soil, and organic material (70-90 percent solids by weight; Costa, 1984) that form a muddy slurry much like wet concrete, and flow downslope, commonly in surges or pulses, due to gravity. They generally remain confined to stream channels in mountainous areas, but may reach and deposit debris over large areas on alluvial fans at and beyond canyon mouths. The eastern portion of Davis County is particularly susceptible to debris-flow hazards because of the steep mountains and the weathering characteristics of the bedrock (the Precambrian Farmington Canyon Complex) which provides much unstable hillside debris (Wieczorek and others, 1983; Pack, 1985). Debris flows have occurred often in Davis County during historical time and have caused damage to property and loss of life (table G-1).

It is the purpose of this chapter to discuss: 1) the nature of debris-flow hazards in Davis County; 2) the potential consequences; 3) Davis County Debris-Flow Hazard Special Study Zone Maps; and 4) recommendations regarding use of the maps for land-use planning. The Debris-Flow Hazard Special Study Zone Maps, which were constructed from the boundaries of active alluvial fans and areas with slopes steeper than 30 percent, identify areas where debris-flow hazards should be evaluated prior to approval of proposed development.

NATURE AND CAUSES OF DEBRIS FLOWS

Although this chapter chiefly addresses debris flows, other forms of flow are also considered because debris flow, debris flood (hyperconcentrated streamflow), and normal streamflow form a continuum of sediment/water mixtures that grade into each other as the relative proportion of sediment to water changes and as stream gradient changes (Pierson and Costa, 1987). Deposition of sediment transported by these types of flows ultimately takes place on alluvial fans at and beyond canyon mouths. Deposition on alluvial fans is caused by the decrease in channel gradient and increase in channel area, resulting in a decrease in depth and velocity of flow and an increase in internal friction of the flowing debris as the stream leaves its constricted channel and enters the main valley floor (Jochim, 1986).

Debris flows can form in at least two different ways. In mountainous eastern Davis County, where cloudburst rainstorms are common, overland flow and flood waters can scour materials from the ground surface and stream channels, thereby increasing the proportion of soil materials to water until the mixture becomes a debris flow (Wieczorek and others, 1983). The size and frequency of debris-flow events generated by rainfall are dependent upon several factors including the amount of loose material available for transport, the magnitude and frequency of the storms, the density and type of vegetative cover, and the moisture content of the soil (Campbell, R. H., 1975; Pack, 1985; Wieczorek, 1987). Debris flows during the 1920s and 1930s in Davis County were generated by overland erosion during summer cloudburst storms which fell on watersheds depleted of vegetative cover by overgrazing and burning (Copeland, 1960).

Debris flows can also mobilize directly from debris slides. A debris slide is a type of landslide in which the material involved is predominantly coarse-grained debris, chiefly colluvium, and the form of movement is mainly translational (Varnes, 1978). A debris flow may be generated when the debris slide reaches a stream, or when the water content is increased in the debris slide by some other means until sufficient to permit flow. Debris flows during the springs of 1983 and 1984 in Davis County were mobilized from debris slides caused by rapid melting of an unusually thick snowpack (Wieczorek and others, 1983).

As the relative proportion of water to sediment increases with either the addition of more water or removal of sediment by deposition, debris flows become hyperconcentrated streamflows. Hyperconcentrated streamflows are often referred to as debris floods or mud floods. In hyperconcentrated streamflow, soil materials are transported by fast-moving flood waters

Table G-1. Historical Davis County debris flows (from Marsell, 1972; Wieczorek and others, 1983; and U.S. Army Corps of Engineers, 1984).

DRAINAGE	YEARS	REPORTED DAMAGE OR LOSS OF LIFE
Dry Fork, Kays Creek	1984	house damaged.
Middle Fork, Kays Creek	1947, 1953	
South Fork, Kays Creek	1912, 1923, 1927, 1945, 1947	
North Fork, Holmes Creek	1983	
South Fork, Holmes Creek	1917	
Baer Creek	1983	
Shepard Creek	1923, 1930, 1983	
Farmington Creek	1878, 1923, 1926, 1930, 1947, 1983	1923 - 7 deaths, several houses damaged.
Rudd Creek	1983, 1984	1983 - 35 houses damaged, 15 severely.
Steed Creek	1923	
Davis Creek	1878, 1901, 1923	
Ricks Creek	1923, 1929, 1930	1923 - 1 house damaged, 1930 - 1 house damaged.
Parrish Creek	1930 (several events)	several houses destroyed, school damaged.
Stone Creek	1983	houses damaged.
Mill Creek	1983	

(Wieczorek and others, 1983). Solids account for 40% to 70% of the material by weight (Costa, 1984). These flows can originate either through progressive incorporation of materials into flood waters or through dilution of debris flows (Waitt and others, 1983; Wieczorek and others, 1983). Because of difficulties in distinguishing hyper-concentrated streamflow from flood stages of normal streamflow, there is no adequate record of historical hyperconcentrated-streamflow events in Davis County.

In normal streamflow, solids account for less than 40% of the water/sediment mixture by weight (Costa, 1984). Snowmelt flooding in Davis County is a nearly annual event and abnormally high snowmelt floods occurred in Davis County in 1922, 1952 (Marsell, 1972), 1983, and 1984. Snowmelt-induced flood magnitudes are somewhat predictable and depend on the volume of snow in the mountains and the rate of temperature increase in the spring. Summer cloudburst floods account for more localized but often very destructive flooding and can occur with little warning. Davis County experienced 39 cloudburst floods between 1850 and 1969 (Butler and Marsell, 1972). The clear-water flooding hazard has been significantly reduced in recent years by the construction of flood detention structures and improvements in storm-sewer systems and stream channels.

EFFECTS OF DEBRIS FLOWS

Loss of life during debris-flow, hyperconcentrated-streamflow, and normal-streamflow events may result from drowning, high-velocity impact, or burial. The following discussion of damages associated with debris flows is taken chiefly from Campbell (1975). The effects on residential structures range from simple inundation to complete destruction by high-velocity impact. The velocity of a debris flow is an important consideration in determining the level of damage to structures. Many debris flows move with speeds on the order of 27 mi/h (40 ft/sec), but others move as slowly as 0.7 mi/h (1 ft/sec) as they flow down relatively gentle slopes. Debris flows of sufficient volume and momentum have destroyed residential structures and moved the remains off their foundations. Debris flows of relatively small volume but high momentum have broken through outside walls and even completely through structures. Low-velocity debris flows may enter dwellings through open doors or push laterally through windows and doorways and flood interiors. All three types of flows may fill basements with mud, water, and debris, or pile debris around structures. Debris may also bury yards, streets, parks, driveways, parking lots, and any ground-level structure. In the distal portions of the alluvial fans, damage is usually comparatively minor, consisting primarily of mud and water damage to outer walls of buildings, basements, and yards. Keaton and others (1988) have devised an intensity scale, generally related to thickness of deposition, for damages associated with debris-flow events (table G-2). This table gives a good indication of the types and severity of potential damage.

DEBRIS-FLOW HAZARD REDUCTION

Methods for reducing debris-flow hazards include: 1) avoidance; 2) source-area stabilization; 3) transportation-zone (debris-flow track between the source area and the depositional zone) modification; and 4) defense measures in the depositional zone (Hungr and others, 1987). Different methods or combinations of methods may be appropriate for different drainages or types of development.

Debris-flow hazards may be reduced by avoiding, either permanently or at the time of imminent danger, areas at risk from debris flows (source areas, transportation zone, and depositional zones). Permanent avoidance is not possible in some areas because many Davis County cities have large numbers of existing structures on active alluvial fans (potential depositional zones) where damage due to debris flows may occur. Permanent avoidance of debris-flow hazards could be required for proposed new development in most Davis County cities through enforcement of existing foothill-development (zoning) ordinances, but this is generally not politically acceptable unless other mitigation techniques are not feasible.

Warning systems may be used to avoid life-threats from debris flows at the time of imminent danger, generally through evacuation of threatened areas. Hungr and others (1987)

Table G-2. Alluvial-fan sedimentation intensity scale proposed by Keaton and others (1988).

Intensity	Damage	Description
0	None	No damage.
1	Negligible	Damage to landscape and access; no damage to structures; minor scour and/or sediment deposition.
2	Slight	Sediment generally less than 3.3 ft thick deposited against buildings without structural damage; sediment flooded around parked vehicles.
3	Moderate	Sediment generally greater than 3.3 ft thick deposited against buildings with easily repairable structural damage; basements partially filled with sediment; parked vehicles shoved by sediment with repairable damage.
4	Severe	Sediment greater than 3.3 ft thick deposited against buildings with repairable structural damage; basements completely filled with sediment; wood structures detached from foundations; parked vehicles shoved by sediment with nonrepairable damage (e.g., distorted frames).
5	Extreme	Sediment greater than 3.3 ft thick deposited against buildings with nonrepairable damage; structures collapsed by force (drag or impact) of flow; wood structures shoved from foundations; parked vehicles so badly damaged that they have small salvage value.

identify three categories of debris-flow warning systems: pre-event, event, and post-event. Pre-event warning systems are designed to identify periods of time when climatic conditions have increased the potential for debris-flow occurrence. Davis County has established a computer-linked remote weather station ALERT system which allows real-time evaluation of rainfall, wind, soil-moisture, streamflow, and landslide-movement data. Although this ALERT system has not yet been used to predict debris-flow events, this may be possible in the future as the relationship between climatic conditions and the initiation of debris flows in Davis County becomes better understood. Event warning systems are designed to provide an alarm when a debris-flow event is occurring (Hungr and others, 1987). Two types of event warning systems are being implemented in Davis County. Computer-linked remote extensometers have been used to monitor real-time movement of detached landslides in Rudd and Baer Canyons. Computer-linked remote streamflow gages, which have been placed on most Davis County streams, can sound alarms if streamflow drops below or rises above preset levels. In both cases, the event warnings are designed to alert Davis County Flood Control and Davis County Sheriff Department personnel of potential debris-flow events. Post-event warning systems, such as slide-warning fences, are usually designed to warn of disruption of transportation routes (Hungr and others, 1987). This type of warning system has not been used in Davis County where most transportation routes are in urban areas, and where mass-media warnings, barricades, and detours have been sufficient in the past.

Source-area stabilization consists of reducing the amount of hillside material available for incorporation into debris-flow or hyperconcentrated-streamflow events. Improving drainage-basin vegetation is one method of source-area stabilization. The prevention of wildfires and forest fires combined with protection against overlogging and overgrazing will protect existing vegetation. Terracing of mountain slopes, such as was done in the 1930s in Davis County by the Civilian Conservation Corps under the supervision of the U. S. Forest Service (Bailey and Croft, 1937), is useful in preventing debris flows caused by erosion during cloudburst storms. Landslide events on oversteepened slopes comprising the source-area scars of former debris flows may be the source of additional hillside material during future landslide-initiated debris-flow events (Baldwin and others, 1987). Landslide-mitigation techniques have been used in California to reduce debris-flow hazards. These techniques include: 1) control of subsurface drainage; 2) diversion of surface drainage, 3) grading of source-area scars to a uniform slope, 4) riprap repair of the source-area scar, and 5) retaining walls (Baldwin and others, 1987). Stabilization of source areas for landslide-initiated debris flows has not been attempted in Davis County.

Transportation-zone modifications are generally designed to reduce the incorporation of channel material into debris flows and improve the ability of the channel to pass debris surges downstream. Scour of unconsolidated material in stream beds and undercutting of unstable stream banks are two of the most important processes contributing to debris-flow-surge growth (Hungr and others, 1987). Check dams (small debris-retention structures placed in unstable channel areas to prevent incorporation of material from that part of the channel into debris flows) are used extensively in Europe and Japan to arrest or reduce debris-flow surges (Hungr and others, 1987). Stream bed stabilization may also be achieved by lining the channel. The ability of stream channels to pass debris surges downstream may be improved through: 1) removal of channel irregularities; 2) enlargement of culverts combined with installation of upstream removable grates to prevent blockage; and 3) construction of flumes, baffles, deflection walls, and dikes (Jochim, 1986; Baldwin and others, 1987). Structures crossing potential debris-flow channels may be protected by: 1) bridging the channels with sufficient clearance to allow debris surges to pass under structures; 2) construction of debris sheds designed to allow debris flows to pass over structures; and 3) designing structures to withstand debris-flow impact, burial, and reexcavation (Hungr and others, 1987). Transportation-zone modifications in Davis County have been restricted to some stream channels below canyon mouths and consist mainly of dikes and deflection walls constructed in the 1920s and 1930s, and removal of channel irregularities and lining of channels in the 1980s. Stream channels above canyon mouths have generally not been modified.

Defense measures in the deposition zone are designed to control both the areal extent of deposition and damage to any structures located there (Hungr and others, 1987). Defense measures include deflection devices, impact walls, and debris basins. Deflection devices are used to control the direction and reduce the velocity of debris flows (Baldwin and others, 1987). Types of deflection devices include: 1) pier-supported deflection walls; 2) debris fences (a series of steel bars or cables placed horizontally at increasing elevations above the stream channel); 3) berms; 4) splitting-wedge walls (reinforced concrete wall in the shape of a "V" with the point facing uphill); and 5) gravity structures like gabions (hollow wicker-works or iron cylinders filled with earth) (Baldwin and others, 1987; Jochim, 1986). Impact walls are designed to sustain the instantaneous force of impact from debris flows while containing the soil and vegetation debris until it can be removed (Baldwin and others, 1987). This impact force may be as high as 125 lb/ft^3 (Hollingsworth and Kovacs, 1981). Types of impact walls employed in the United States include concrete walls, soldier pile walls, and soil and/or rock gravity walls (including gabions) (Baldwin and others, 1987). Two types of debris basins, open and closed, are commonly employed to reduce debris-flow hazards. Both types are designed to constrain the area of debris deposition to predetermined limits laterally, upstream, or downstream (Hungr and others, 1987). Open debris basins commonly have a basin-overflow spillway designed to direct excess material to an insensitive area or back into the stream channel, but straining outlets to remove water from entrapped debris are not generally provided. Closed debris barriers and basins can be located in the lower part of the transportation zone as well as in the deposition zone or on the alluvial fan (Hungr and others, 1987). Any suitable location along the lower part of the debris-flow path can be chosen to erect a barrier across the path and create a basin upstream. Closed debris barriers are provided with both straining outlets to pass water discharges and spillways to handle emergency debris overflows (Hungr and others, 1987). Both types of debris basins require access for removal of entrapped debris and maintenance. Debris basins, both open (constructed in the 1930s) and closed (constructed in the 1980s), are the primary debris-flow hazard-reduction technique employed in Davis County. Figure G-1 shows the location of these debris basins. The Davis County debris basins vary greatly in storage capacity and their adequacy to contain various magnitude debris-flow events has

SUMMARY OF METHODS USED IN MAP PREPARATION

Preliminary surficial geologic mapping by A. R. Nelson and S. F. Personius (unpublished mapping, 1987) was used to define debris-flow hazard areas at the mountain front. These maps differentiate active alluvial fans, where deposition during debris-flow and hyperconcentrated-streamflow events may occur, from areas not subject to debris flows, including older fans which are no longer active. Upper Holocene alluvial fans and undivided young alluvial fans, as mapped by A. R. Nelson and S. F. Personius (unpublished mapping, 1987), were combined and redesignated younger Holocene (active) alluvial fans on the Debris-Flow Hazard Special Study Zone maps, and represent areas considered susceptible to debris-flow hazards. In addition, all mountainous areas with slopes greater than 30 percent are considered to be susceptible to debris-flow initiation. The adequacy of existing debris basins or structures built to divert debris flows were not considered during preparation of the Debris-Flow Hazard Special Study Zone Maps. The existence and adequacy of these structures should be considered for site-specific studies, however.

The frequency of occurrence (recurrence) of debris-flow events in a drainage basin depends upon climatic factors as well as the availability of debris. Recurrence intervals vary among drainage basins and depend on the magnitude of the event (volume of sediment transported). For example, the recurrence interval for sedimentation events exceeding 40,000 yd^3 of material deposited at the Ricks Creek debris basin has been calculated to range between 55 and 1,590 years, but the recurrence interval for sedimentation events exceeding 65,000 yd^3 of material deposited at the Rudd Creek debris

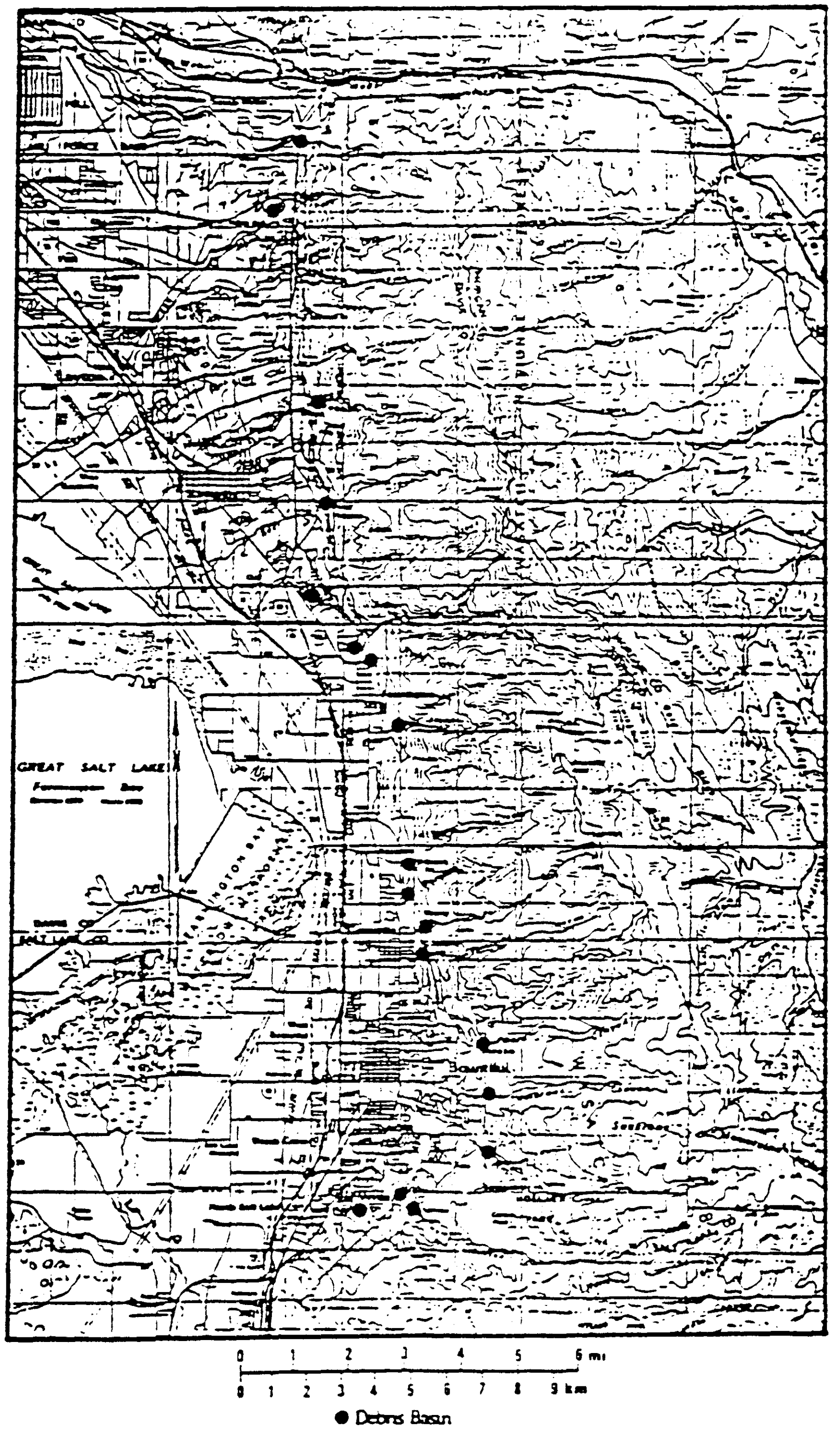

Figure G-1. Location map for Davis County debris basins. Adequacy of basins has generally not been evaluated.

basin has been calculated to range between 155 and 5,845 years (Keaton and others, 1988). These numbers are significant because the volumes given represent the capacity of debris basins constructed at the mouths of Ford (Ricks Creek) and Rudd Canyons, respectively (Keaton and others, 1988). Recurrence intervals for different magnitude debris-flow events are not currently available for the other Davis County drainages.

RECOMMENDED USE OF MAPS IN LAND-USE PLANNING

The Debris-Flow Hazard Special Study Zone maps show areas where site-specific studies addressing debris-flow hazards are recommended prior to development. These maps are at a scale of 1:24,000 and are designed to show potential hazard areas for planning purposes only. It is recommended that debris-flow hazards be evaluated and, if necessary, hazard reduction measures recommended in site-specific engineering geologic reports submitted by the developer prior to planning commission approval for all construction in the debris-flow hazard special study zone. Because of the relatively small scale of the maps, the possibility exists that some small hazard areas are not shown; studies are therefore recommended for critical facilities even outside the debris-flow special study zones. The importance in terms of life-safety of such structures merits this precaution, and studies need only consider the hazard and either confirm that it does not exist or perform the necessary study if a potential hazard is found.

SCOPE OF SITE INVESTIGATIONS

The scope of investigation for site-specific reports evaluating debris-flow hazards for proposed development should include: 1) an analysis of the drainage basin's potential to produce debris flows based on the presence of debris slides and colluvium-filled slope concavities, and an estimate of the largest probable volumes likely to be produced during a single event; 2) an analysis of the stream channel to determine if the channel will supply additional debris, impede flow, or contain debris flows in the area of the proposed development; 3) an analysis of man-made structures upstream that may divert or deflect debris flows; and 4) recommendations concerning any channel improvements, flow modification and catchment structures, direct protection structures, or floodproofing measures, if necessary, to help protect the proposed development.

For critical facilities within the debris-flow hazard special study zone, the storage capacity of any debris basins upstream from the site to reduce the debris-flow hazard must be evaluated. The quality of debris-basin maintenance should also be addressed. The U. S. Army Corps of Engineers (1988) has evaluated the adequacy of many of the central Davis County basins to contain the 100-year debris-flow event volumes, but Davis County is challenging the methodology used in determining what those 100-year event volumes should be (Williams and others, 1988). Wieczorek and others (1983), Pack (1985), and Keaton and others (1988) identified factors to be considered when evaluating debris-flow hazards, and these references should be consulted when conducting site investigations. When site-specific reports are submitted, they should be reviewed by the county and, once approved, forwarded to the planning commission along with review comments so that the planning commission has sufficient information to make decisions regarding the proposed development.

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ROCK FALL

INTRODUCTION

Rock falls are a naturally occurring erosional process in mountain areas along the Wasatch Front. As urban development advances higher onto the bench areas and into the canyons, the risk from falling rocks becomes greater. The purpose of this chapter is to explain how the Rock-Fall Hazards Special Study Area maps were made and how they should be used. This information can benefit land-use planners, developers, real estate agents, and the general public by informing them of potential hazards and ultimately helping avoid casualties and damage.

CHARACTERISTICS OF ROCK FALLS

Rock falls originate when erosional processes and the pull from gravity dislodge rocks from slopes. The most susceptible slopes are those with outcrops broken by bedding surfaces, joints, or other discontinuities into abundant loose individual fragments called clasts. Boulders on shoreline benches eroded by lakes and in alluvium or glacial till also contain clasts which may dislodge and fall when occurring on or above steep slopes. When the clast falls or rolls from the slope, it may travel great distances by rolling, bouncing, and sliding.

A primary mechanism responsible for triggering rock falls is water in outcrop discontinuities. In Norway, for example, 60 percent of all rock falls occur in April and May during maximum snowmelt and October and November during periods of heavy rainfall (Costa and Baker, 1981). In addition, rock falls are also the most common type of slope instability initiated by earthquakes. Case (1987a) estimates that a major Wasatch Front earthquake (magnitude 7-7.5) could produce thousands of rock falls along the Wasatch Front. Keefer (1984) indicates that rock falls may occur in earthquakes as small as magnitude 4.0. In the August, 1988, San Raphael Swell earthquake (magnitude 5.3) in central Utah, hundreds of rock falls occurred, temporarily obscuring the surrounding cliffs in clouds of dust (Case, 1988a).

EFFECTS OF ROCK FALL

Rock falls present a hazard because of the potential damage a large rock mass, traveling at a relatively high velocity, could cause to structures and personal safety. Rock falls that occur in remote or uninhabited regions go largely unnoticed. It is only when falling rocks pose a threat to man that rock falls must be considered in land-use planning and development regulations.

A 1987 rock-fall event near Dead Horse Point, Utah, was large enough to register on seismographs as far away as Blanding (Case, 1987b). Locally, rock falls have historically caused problems along canyon roads by blocking traffic or occasionally striking vehicles. The structures most often affected by rock falls in canyons are exposed aqueducts. Water service in both Big Cottonwood and Provo Canyons has been suspended due to damage to aqueducts by impact and puncture from falling rocks. Homes built along the mountain front are also subject to rock falls when exposed boulders gradually become unstable through weathering of the supporting sediments and eventually roll downslope.

SUSCEPTIBILITY TO ROCKFALLS

The primary factor in determining if an area is susceptible to rock falls is the presence of a source for rock-fall clasts. If there are no rocks on a slope, the rock-fall hazard below becomes negligible. Case (1987c, 1988b) of the Utah Geological and Mineral Survey identified all the range-front slopes, called spurs, along the Wasatch Front on which a rock-fall source was found. The other major factor in identifying rock-fall hazards is the distance a dislodged rock will travel down-slope. These two factors, source and distance, can be combined to provide reasonable estimates of areas susceptible to rock falls which are then classified as special study areas (Nelson, 1988).

The runout limit for each susceptible spur was determined using the Colorado Rock-fall Simulation Program (Pfeiffer and Higgins, 1988). The program uses representative slope profile information for each spur and estimates of the rigidity and roughness of the slope surface. Rock-fall events were simulated originating the highest and steepest potential rock-fall source areas mapped by Case (1987c, 1988b) on each spur. Rocks were started with an initial velocity (throw) of 1 ft/sec. The size of rock-fall clasts used in the simulation was based on the largest clast observed in the slopes below the rock-fall source area. The combination of factors yielding the longest runout distance was used as the lower limit of the special study area. It is believed that this represents a worst-case rock-fall event and provides some margin of safety.

Slopes steeper than 30 percent were placed in the special study area where potential rock-fall source areas have not been mapped and where computer models of the potential runout distances did not extent to slopes less than 30 percent. The rock-fall analyses suggest that, in general, most rocks would stop above the 30 percent slope break, making this slope the lower boundary of the study area in most areas. The special study area boundary between the spurs follows the 30 percent slope break and includes all canyon areas. No studies have been performed in canyons, and there all slopes are considered susceptible.

REDUCING ROCK-FALL HAZARDS

When faced with any geologic hazard the best alternative, where feasible, is avoidance. Therefore it is suggested that developers first try to locate buildings so that structures are not positioned in an area susceptible to rock falls. Often, however, new developments cannot be designed around a rock-fall path, and hazard reduction measures must be considered. When faced with land-use decisions, developers should carefully compare the costs of hazard reduction with the costs of avoidance.

Techniques for reducing rock-fall hazards may include mitigation of the actual hazard or modifying the exposed structure or facility. Rock-stabilization techniques such as bolting, cable lashing, burying, and grouting discontinuities; and removal or break-up of potential rock clasts are all physical methods of mitigating the hazard. Deflection berms, slope benches, and rock-catch fences may all stop or at least slow down falling rocks. Strengthening a structure to withstand impact is an example of modifying what is at risk. Twenty-seven techniques for reducing landslide hazards including rock falls are described by Kockelman (1986). Mitigation problems can arise when rock source areas are located on land not owned by the developer.

In areas where the rock-fall hazard is present but very low, disclosure of potential hazards to land owners and residents with an acknowledgment of risk and willingness to accept liability may be an acceptable alternative to avoidance or mitigation, at least for single family residences.

USE OF THE ROCK-FALL HAZARD SPECIAL STUDY AREA MAPS

The Rock-Fall Hazards Special Study Area maps provide an evaluation of areas susceptible to falling rocks at a county-wide scale (1:24,000). During the planning commission approval and building permit application process the proposed site plan will be reviewed, and if any proposed structure falls within the special study area, a site investigation may be required to assess the hazard. The site-specific data may indicate that a hazard does not exist at the site. If, after review, this is found to be the case, development would proceed. Should the site-specific data indicate that a rock-fall hazard exists, the consultant should give recommendations for avoiding or reducing the hazard, and these considerations included in the site plan. Regardless of the conclusions, results of the site-specific study should be submitted to the county for review. The Davis County Planning Commission considers the recommendations of planning staff and consultants and makes the final decision for approval of developments.

It is important that geological input be used early in the development process. In the past, developers have faced considerable expense in redesigning subdivisions around geologic problems. The astute real-estate purchaser often seeks geological counsel prior to making an offer, or makes a favorable geologic report a contingency of purchase. The hazard maps may also prove useful to private citizens and real-estate agents by providing information needed to make an informed decision in the purchase of property.

SCOPE OF SITE INVESTIGATIONS

When development is proposed within the Rock-Fall Hazard Special Study Area, the developer must employ a qualified engineering geologist or geotechnical engineer to assess the site-specific rock-fall hazard. Site investigations must define rock-fall sources and estimate runout paths and runout distances from each source. Rock-fall sources may be outcrops or individual clasts on a slope. Size, shape, depth of burial, and slope geometry are all factors to be considered in defining sources as well as runout path and distance. Computer models are available to simulate runout, but physical evidence such as extent of clast accumulations below sources, topographic configuration, damaged vegetation, and natural barriers are also important to consider.

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STREAM, LAKE, AND DAM-FAILURE FLOODING

INTRODUCTION

A flood is defined as the stage or height of water above some given datum such as the banks of the normal stream channel (Costa and Baker, 1981) or commonly occupied shoreline of a lake. Floods are recurrent natural events which become a hazard to residents of a flood plain or shoreline whenever water rises to the extent that life and property are threatened. In Davis County, stream flooding due to melting snow is a nearly annual event, particularly along the Weber River. Stream flooding in Davis County also occurs as the result of summer cloudburst rainstorms. Davis County experienced 39 cloudburst floods between 1850 and 1969 (Butler and Marsell, 1972). Shoreline flooding along Great Salt Lake also occurs in Davis County. Recent fluctuations in the level of the lake caused over one hundred million dollars in losses in Utah in a single year (Federal Emergency Management Agency, 1985). Flooding due to the failure of dams could also potentially occur in Weber County. The severity of flooding accompanying dam failure depends on the size of the reservoir impounded behind the dam and the extent of the failure.

The Federal Emergency Management Agency (FEMA) has produced maps depicting areas where stream flooding may be expected in Davis County. The Utah Division of Comprehensive Emergency Management has recommended establishing a "Beneficial Development Area" around Great Salt Lake to help reduce lake-flooding hazards. The U. S. Bureau of Reclamation, the U. S. Forest Service, and the Utah Geological and Mineral Survey have produced maps of areas which could potentially be flooded due to dam failure. Davis County Flood Control has the primary responsibility for regulating flood plains and reducing flood hazards in Davis County. It is the purpose of this chapter to: 1) discuss the nature of stream, lake, and dam-failure flooding hazards, 2) discuss the potential consequences of flooding, and 3) give recommendations regarding how river- and stream-flooding maps and "Beneficial Development Area" recommendations should be used by Davis County and the cities therein in land-use planning. This chapter does not consider hazards associated with flooding related to debris flows on alluvial fans. These hazards are addressed in a separate chapter entitled "Debris Flows."

NATURE AND CAUSES OF FLOODING

Stream Flooding

Stream flooding may be caused by direct precipitation, melting snow, or a combination of both. For rivers with large drainage basins and many tributaries, like the Weber and Jordan Rivers, the primary cause of flooding is rapidly melting snow, usually occurring from late April to early July (Corps of Engineers, 1969; Federal Emergency Management Agency, 1982). Snowmelt floods are characterized by large volume runoff, moderately high peak flows, and marked diurnal fluctuation in flow (Federal Emergency Management Agency, 1982). They are somewhat predictable because flood levels depend primarily on the volume of snow in the mountains and the rate of temperature increase in the spring. Prior to 1983, the largest snowmelt floods of record on the Weber River occurred in 1893, 1896, 1907, 1909, 1920, 1922, and 1952 (Federal Emergency Management Agency, 1980) and the largest snowmelt floods on the Jordan River occurred in 1909, 1922, and 1952 (Corps of Engineers, 1969; Marsell, 1972). More recently, snowmelt floods occurred along both rivers in 1983, 1984, and 1985.

Localized, high-intensity, convective- type thunderstorms centered over tributary areas are most effective in generating flooding in small drainage basins (Costa and Baker, 1981) such as are found in the Wasatch Mountains in Davis County. Such storms, which last from a few minutes to several hours, generally occur between mid-April and September (Federal Emergency Management Agency, 1978; 1982). Cloudburst thunderstorms are generally characterized by high peaks, high velocity, short duration, and small volume of runoff (Federal Emergency Management Agency, 1982). The flooding potential of cloudburst rainstorms is dependent upon many factors including: 1) the intensity or amount of rainfall per unit time; 2) the duration or length of time of rainfall; 3) the distribution of rainfall and direction of storm movement over a drainage basin; 4) soil characteristics; 5) antecedent soil-moisture conditions; 6) vegetation conditions; 7) topography; and 8) drainage pattern. Because many of these conditions are generally not known until rain is actually falling on critical areas, the magnitude of flooding from a given cloudburst storm is difficult to predict. Davis County communities have experienced many cloudburst floods in historical times (table I-1).

Table I-1. **Historic cloudburst floods, Davis County, Utah (Utah Division of Comprehensive Emergency Management, 1981).**

City	Year
Bountiful	1908, 1922, 1938, 1948, 1951, 1954, 1955, 1957, 1961, 1968, 1969, 1972, 1977 (2), 1980
Centerville	1901, 1904, 1923, 1930 (3), 1932
Farmington	1878, 1901, 1912, 1923, 1926 (2), 1929, 1930 (4), 1931, 1932, 1936, 1957, 1963, 1969
Kaysville	1892, 1917, 1947
Layton	1967
Clearfield	1953, 1967
Sunset	1963
Syracuse	1956

Lake Flooding

Fluctuating water levels are a problem with all types of lakes, but flooding can be especially acute on lakes which, like Great Salt Lake, have no outlet. Water-level fluctuations on lakes can be caused by both nature and man. Natural factors include principally precipitation, evaporation, runoff, ground water, ice, aquatic growth, and wind (Federal Emergency Management Agency, 1985). Man-induced factors include dredging, diversions, consumptive use of water, and regulation by engineering works (Federal Emergency Management Agency, 1985).

Lake-level fluctuations may be grouped into three categories: 1) long term, 2) seasonal, and 3) short term. Long-term fluctuations are the result of persistent low or high water-supply conditions for more than one year. Figure I-1 shows the effects of long-term excess precipitation with respect to Great Salt Lake elevation. Long-term climatic trends play a major role in determining lake levels, as do diversions of water sources by man. The intervals between periods of high and low lake levels and the length of such periods during long-term fluctuations vary widely and erratically (Federal Emergency Management Agency, 1985). The extreme lake levels are likely to persist even after the factors which caused them have changed.

Seasonal fluctuations reflect the annual hydrologic cycle. Lakes are lowest in winter and generally rise in the spring due to melting snow, heavier rains, and cooler temperatures, until the lake peaks in the early summer (Federal Emergency Management Agency, 1985). During the summer, more persistent winds, drier air, and warmer temperatures intensify evaporation; also the runoff and ground-water flow to the lake generally decrease significantly. As the water supplied to the lake becomes less than the evaporation, the water level begins the downward trend to winter minima (Federal Emergency Management Agency, 1985). Great Salt Lake elevations generally fluctuate approximately two feet between winter low and summer high lake levels (figure I-2).

Short-term fluctuations are caused by strong winds and sharp differences in barometric pressure (Federal Emergency Management

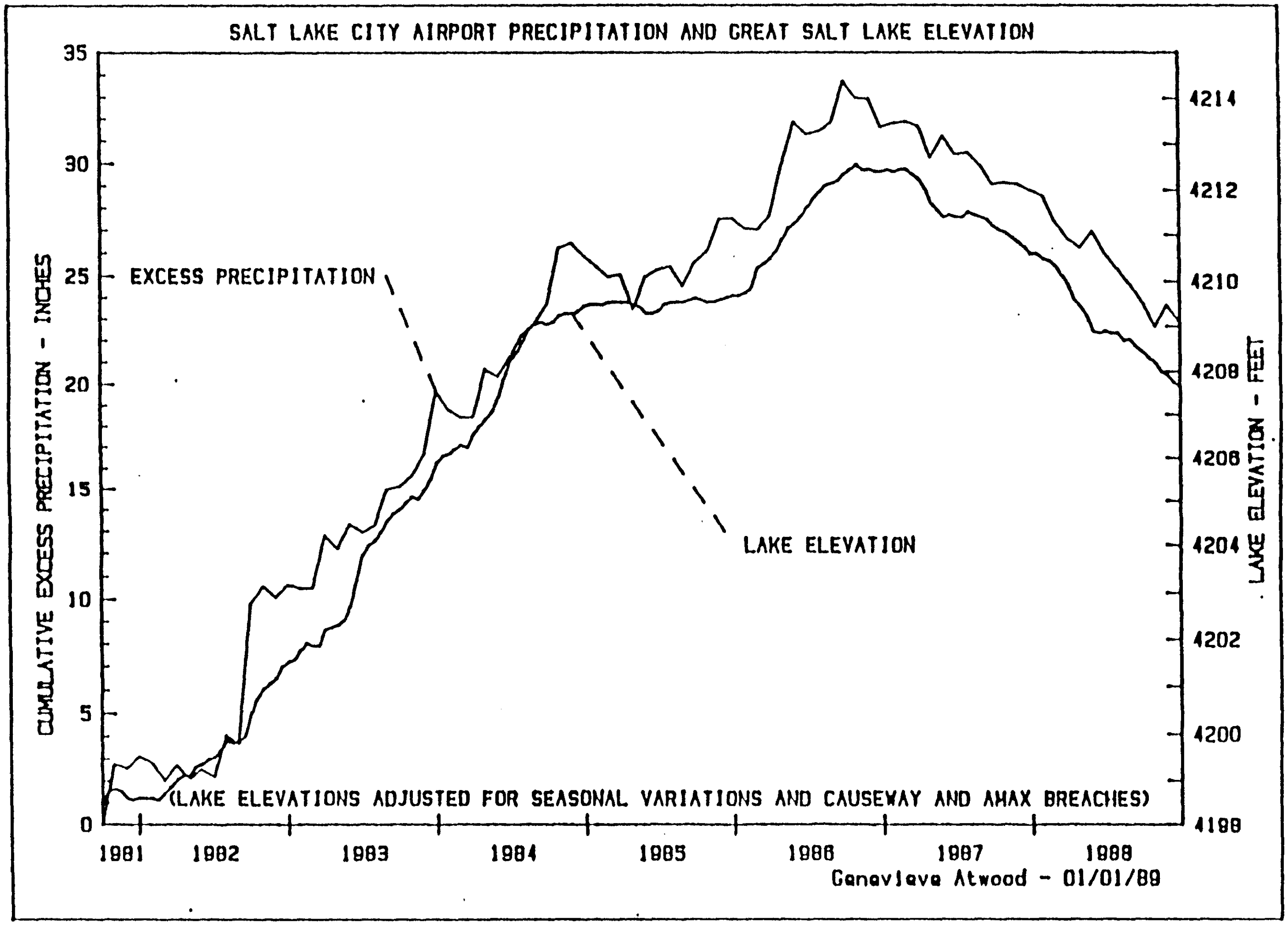


Figure I-1. Graph showing the effect of recent cumulative excess precipitation on Great Salt Lake elevation. Lake elevations have been adjusted to remove seasonal water-level variations and the effects of the Great Salt Lake causeway and Amax dike breaches (Atwood and Mabey, written commun., 1989).

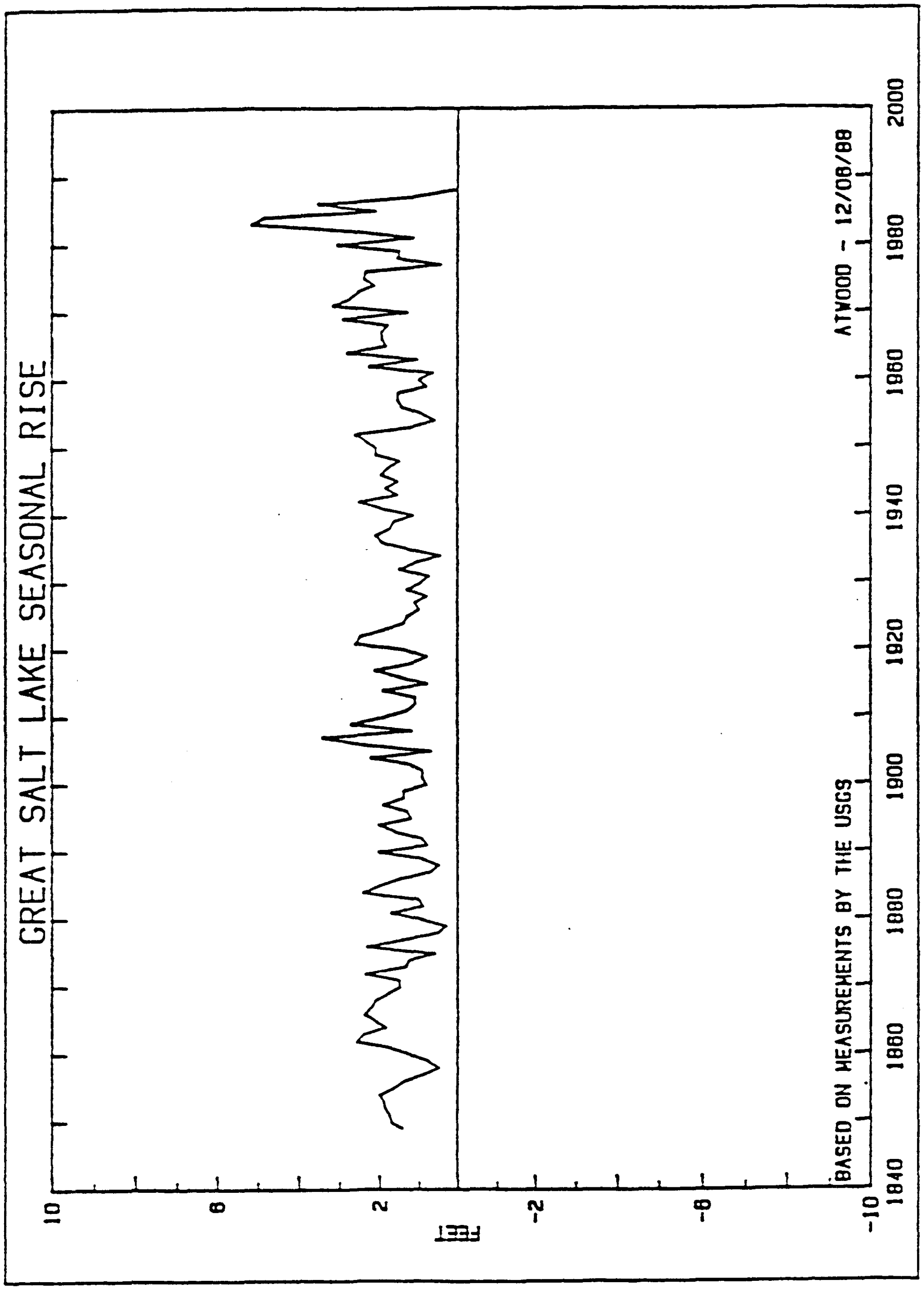


Figure I-2. Graph showing the seasonal rise of Great Salt Lake (Atwood and Mabey, written commun., 1989).

Agency, 1985). These fluctuations usually last less than one day and do not represent any changes in the amount of water in the lake.

Lake flooding in Davis County is confined to the area around Great Salt Lake. In prehistoric time, water levels in lakes occupying the Great Salt Lake basin, such as Lake Bonneville, are known to have fluctuated with great elevation differences between high and low stands (figure I-3). Geologic evidence indicates that Great Salt Lake reached a post-Lake Bonneville high of approximately 4,221 feet about 2,000 years before present (Murchison, 1989). Archaeological evidence indicates that the most recent high stand of Great Salt Lake was at 4,217 feet sometime during the 1600s (Utah Division of Comprehensive Emergency Management, 1985; Murchison, 1989). Until the spring of 1986, the historic high of Great Salt Lake was about 4,211.5 feet (Arnow, 1984). This level was reached in the early 1870s and is based on a relative elevation estimate of water depth over the Stansbury bar (Gilbert, 1890). Direct measurements of the lake's elevation began in 1875 (Currey and others, 1984). The lake dropped slowly from its high in the 1870s, reaching an historic low of 4,191.35 feet in 1963. Above-average precipitation in recent years caused Great Salt Lake to attain a new historical high of 4,211.85 feet in June of 1986 and April of 1987 (U. S. Geological Survey records). This rise in lake level caused significant damage to structures and property along the shoreline and within the lake (power lines, causeways, dikes, buildings, and refuse dumps). Figure I-4 summarizes historical levels of Great Salt Lake and illustrates that significant lake fluctuations can occur within a relatively short time.

Dam-Failure Inundation

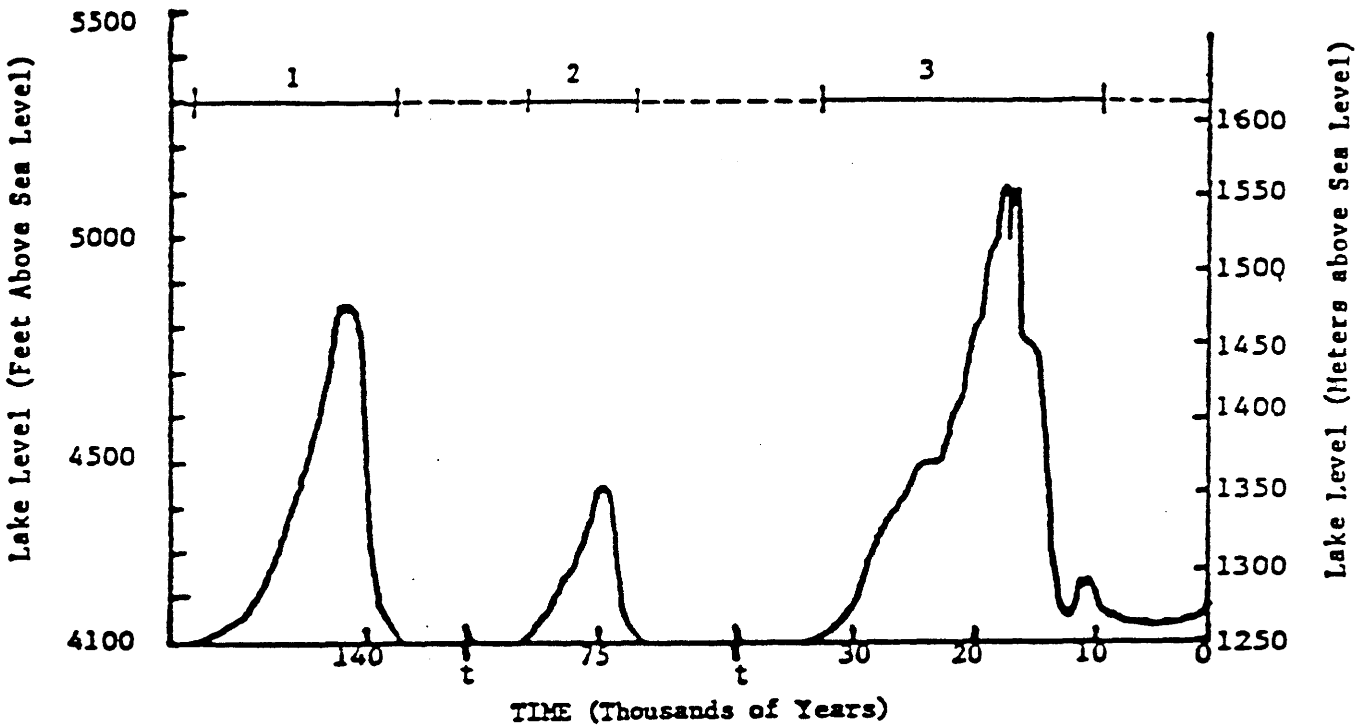
Flooding may also result from dam failure. Dam failures generally occur with little warning, and the severity of flooding depends on the size of the reservoir impounded behind the dam and the extent of failure.

The term dam failure includes all unintentional releases of water from the dam, including complete failure and release of all impounded water (Harty and Christenson, 1988). Only 8 of 33 dam failures documented in Utah prior to 1984 were complete failures; most of these failures were due to overtopping and/or erosion around spillways and outlets during flood events (Harty and Christenson, 1988). Dam failures have also occurred, however, due to structural and foundation failures caused by landsliding, seepage, and piping (Dewsnup, 1987). Most historical dam failures in Utah have been small dams in rural areas; larger dams are less prone to failure because of more rigorous design, construction, and inspection practices (Harty and Christenson, 1988). Earthquake-induced ground shaking, surface faulting, liquefaction, tectonic subsidence, landslides, and seiches, may occur in Davis County and could cause dam failures. Failures of dams upstream outside of the county could result in flooding and failure of other dams downstream in the county. This is particularly true along the Weber River, where four dams (Wilkinson, Echo, Wanship, and Smith-Morehouse) are found upstream outside of Davis County.

EFFECTS OF FLOODING

Loss of lives due to drowning may occur where floodwaters are deep or flowing with high velocity. Water damage accompanies all types of floods and the amount of damage largely depends upon depth of inundation. The damage potential of floodwaters increases dramatically with increases in floodwater velocity (Federal Emergency Management Agency, 1985). High-velocity floodwaters can cause structures to collapse due to pressures applied by fast-moving water. Moving water can also induce erosion and can undermine structures. The damage potential of floodwaters may be increased hundreds of times when they contain substantial amounts of rock, sediment, ice, or other materials (Federal Emergency Management Agency, 1985). Areas subject to rapid inundation by floodwaters or flash floods pose special threats to life and property because there is insufficient time for evacuation, emergency floodproofing, or other protective measures (Federal Emergency Management Agency, 1985).

In areas where flooding may be of long duration, such as along lake shorelines, water damage to structures is especially serious. This flooding generally is not life-threatening, but may produce permanent property loss or damage.



Explanation

1 - Little Valley lake cycle.
2 - Cutler Dam lake cycle.
3 - Bonneville lake cycle.
t - Splice point on graph. Periods of time during interlacustrine phases have been removed to condense graph.

Figure I-3. Schematic diagram showing a hydrograph of probable lake levels in the Lake Bonneville (Great Salt Lake) basin for the past 150,000 years. Numbered solid lines above lake-level curves represent time periods when lakes in the basin stood at high levels. Dashed lines represent time periods when lakes in the basin stood at low levels or were nonexistent. (Modified from Currey and Oviatt, 1985, by Machette and others, 1987, with additional modifications for this report).

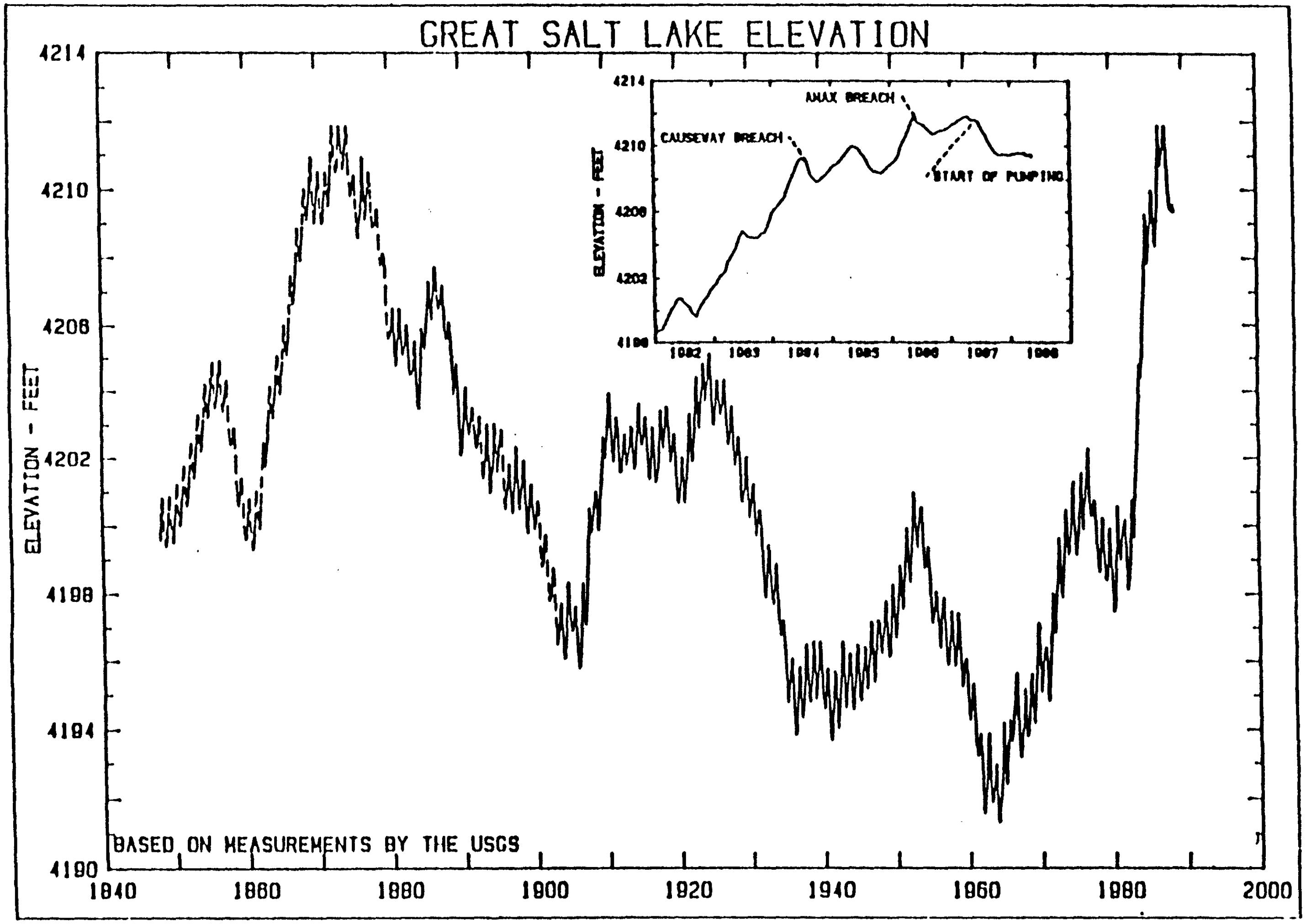


Figure I-4. Historical Great Salt Lake hydrograph (Atwood and Mabey, written commun., 1989).

Along the shore of Great Salt Lake the problems associated with water damage are compounded by the presence of salt in the water.

SUMMARY OF METHODS USED IN MAP PREPARATION

Stream-Flooding Maps

Maps depicting stream flood-hazard areas in Davis County have been prepared by the Federal Emergency Management Agency (1978, 1980, and 1981a,b,c,d,e). These maps show the areas expected to be inundated by floods with 100-year and 500-year recurrence intervals. These flooding events have a 1.0 and 0.2 percent chance, respectively, of being equaled or exceeded during any year. Although these recurrence intervals represent the "long-term average" period between floods of a specific magnitude, rare floods could occur at short intervals or even within the same year (Federal Emergency Management Agency, 1981e). It should be noted that these maps depict flood hazards only for major drainages and, therefore, some areas which may potentially flood have not been mapped as flood-hazard areas. Also many of the maps were made prior to construction of debris basins and other flood-control structures, which may reduce the hazard. As a result of recent flooding events in Davis County, it is now recognized that alluvial-fan flooding differs from the stream flooding depicted on FEMA maps. Davis County and the U. S. Army Corps of Engineers are currently evaluating alluvial-fan flooding and hope to produce maps depicting this type of flooding in Davis County in the near future.

Methods used to produce the flood-hazard maps are outlined in the Federal Emergency Management Agency's Flood Insurance Studies (1978, 1980, and 1981a,b,c,d,e). The 100-year flood, which has been adopted by the FEMA as the base flood for purposes of flood-plain management measures, has been divided into a floodway and a floodway fringe (figure I-5). The floodway is the channel of the stream plus any adjacent flood-plain areas that must be kept free of encroachment in order that the 100-year flood may be carried without substantial increases in flood heights (Federal Emergency Management Agency, 1982). The area between the floodway and the boundary of the 100-year flood is termed the floodway fringe. The floodway fringe encompasses that portion of the flood plain that could be completely developed without increasing the water-surface elevation of the 100-year flood more than 1.0 foot at any point.

Davis County has adopted a flood-control ordinance which supplements FEMA maps and regulations. This ordinance and the accompanying map designates drainages and channels where the County has the primary responsibility for flood mitigation. The ordinance regulates and requires development permits for areas within 100 feet of either side of a designated drainage. Designated drainages and channels include: 1) the drainages of North Canyon, Hooper Draw, Mill Creek, Barton Creek, Stone Creek, Deuel Creek, Parrish Creek, Barnard Creek, Ricks Creek, Davis Creek, Steed Creek, Farmington Creek, Shepard Creek, Rigby's Dry Hollow, Haights Creek/Bear Canyon, Holmes Creek, Kays Creek, and Howard Slough; 2) the Jordan and Weber Rivers; 3) the 2300 North ditch in Clinton; 4) channels west of Bluff Road (300 North, Westpoint, and 700 South, 3000 West, and 2000 West, Syracuse); 5) the A-1 Agricultural Drainage; and 6) the West Gentile Drainage.

Lake-Flooding Maps

Using the best available historical and scientific data on Great Salt Lake, government policymakers and lake experts have recommended that a beneficial development strategy should exist for lake-shore areas up to 4,217 feet in elevation (Utah Division of Comprehensive Emergency Management, 1985). This strategy establishes a "Beneficial Development Area" along the shore of Great Salt Lake between 4,191.4 feet (historic low stand, 1963) and 4,217 feet. Within this area, it is recommended that development take place in a manner that will encourage the maximum use of the land for the people of Utah, while avoiding unnecessary disaster losses (Utah Division of Comprehensive Emergency Management, 1985). No maps depicting the proposed "Beneficial Development Area" have been produced. Areas along the

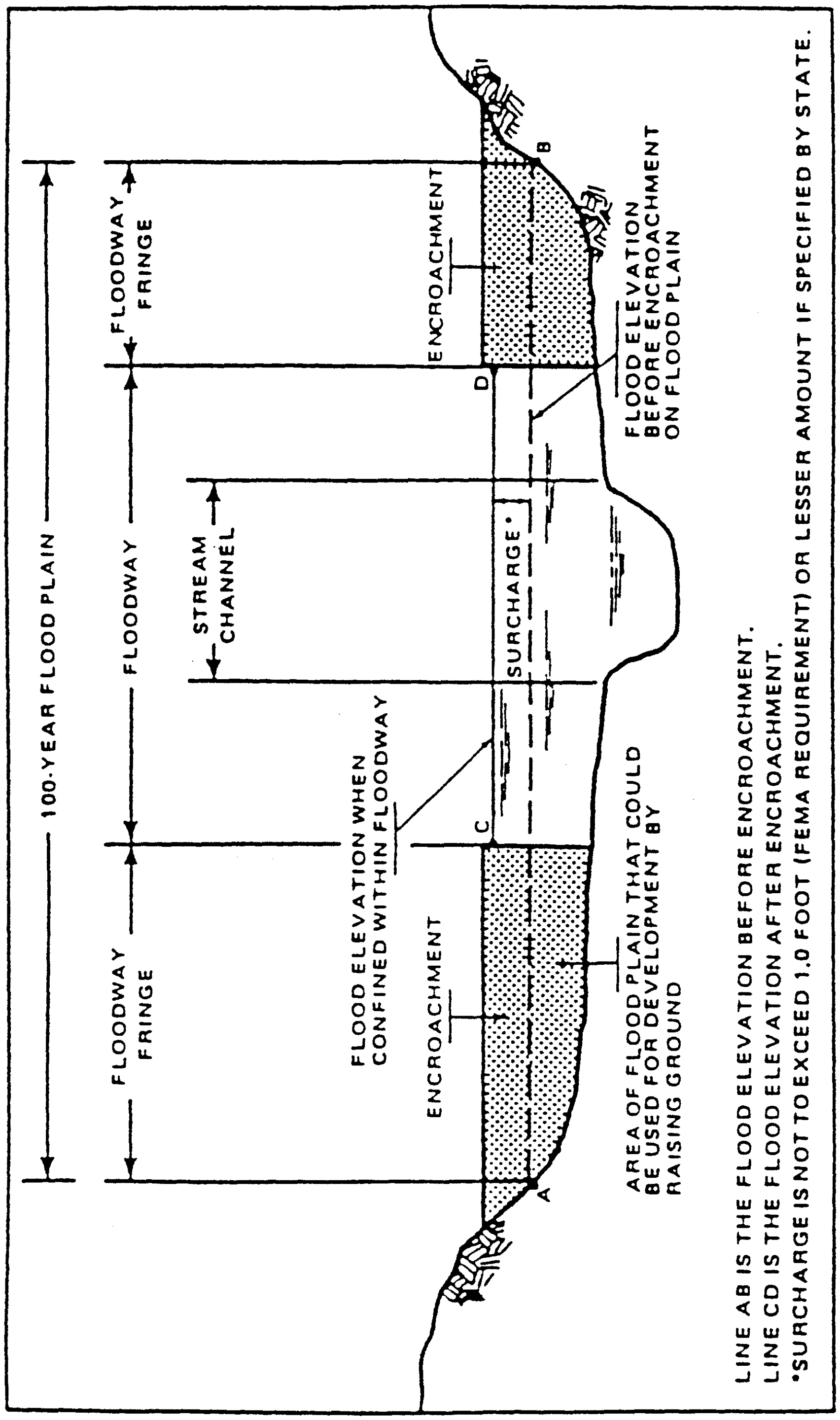


Figure I-5. Floodway schematic showing the relationship of the 100-year flood plain, the floodway, and the floodway fringe (Federal Emergency Management Agency, 1982).

eastern shoreline of Great Salt Lake in Davis County where the proposed beneficial development strategy is recommended include all areas below an elevation of 4,217 feet. An approximation of the area can be identified by interpolating the location of the 4,217-foot contour on 1:24,000 U. S. Geological Survey topographic quadrangle maps (5-foot contour interval), but in general it is necessary to perform an accurate field survey.

Dam-Failure Inundation Maps

Dam-failure inundation studies, which include maps of areas expected to be flooded as a result of dam failure, have been completed for Wilkinson (Case, 1986), Echo (U. S. Bureau of Reclamation, 1984), Wanship (U. S. Bureau of Reclamation, 1985), and Smith-Morehouse (U. S. Forest Service, various years) Dams on the Weber River; dams on tributaries to the Jordan River (Case, 1988); and for Barton Creek, Stone Creek, Rudd Canyon, and Shepard Creek debris basins, and Kaysville and Holmes Reservoirs (Utah Division of Water Rights, 1986-1987). Harty and Christenson (1988) have compiled these and other dam-failure inundation studies onto a statewide map. Methods used to construct the maps are identified in the reports accompanying the individual studies.

FLOOD-HAZARD REDUCTION

Methods for dealing with stream flooding include: 1) avoidance; 2) drainage-basin improvement; 3) flow modification and detention; 4) flood warning and evacuation; 5) floodproofing; and 6) requirement of flood insurance in areas of frequent flooding. Methods for dealing with lake flooding include avoidance, diking, diverting inflow to the lake, and increasing outflow and/or evaporation through pumping (Utah Division of Water Resources, 1977). Different methods or combinations of methods may be appropriate for different types of flooding or development. Careful design, construction, and inspection practices prior to, during, and after dam construction combined with well-prepared emergency response plans are the best methods to deal with dam-failure inundation studies.

Stream Flooding

Avoidance is not possible in some areas because large numbers of structures in Davis County are on active alluvial fans which are subject to periodic flooding. Avoidance of flood hazards in undeveloped areas may be accomplished by discouraging development on flood plains of streams and along the shore of Great Salt Lake, or by regulating uses vulnerable to flood losses through local governmental police powers. Methods for discouraging new development and for removal or conversion of existing development on flood plains are described in detail in Kockelman (1977).

Drainage-basin improvement consists primarily of measures to increase infiltration and decrease runoff. Improving drainage-basin vegetation is one method of decreasing runoff. The prevention of wildfires and forest fires combined with protection against overgrazing by wild and domestic animals will protect existing vegetation. Terracing of slopes, such as was done in the 1930s in Davis County mountains, is useful in decreasing runoff during rainstorms and spring snowmelt.

Flow modification and detention can be an effective way of lowering flood hazards. Loss from floods often leads to persistent demands for public-works programs to provide protection through structures and improvements such as dams, ditches, canals, sluices, holding basins, and detention reservoirs; channel deepening, straightening, widening, and paving; bypass or diversion channels, dikes, revetments, floodwalls, levees, and underground drainage facilities; or combinations of several of these (Kockelman, 1977). Construction of flood-control works can, however, be self-defeating. As the urban development of flood plains continues, the number of persons and the value of property in areas subject to flooding tend to increase at rates greater than that at which protection can be provided (Kockelman, 1977). Most flood-control works are expensive and require periodic maintenance. Also, during dry cycles the public becomes complacent and are unwilling to see tax dollars spent on maintaining structures they deem unneeded. Many of the flood-control structures constructed in the 1930s were in poor repair when the 1983 floods occurred. At Ricks

Creek, a new debris basin was constructed around an older debris basin because a home was allowed to be constructed in the older basin. The presence of flood-control structures may lead the public to believe that flood hazards have been eliminated rather than simply lowered. Flood-control structures may not prevent losses from great and infrequent floods that exceed design criteria, often with catastrophic results. Unfortunately, after such catastrophes the public commonly assumes that they were flooded because the flood-control structures were inadequately designed.

Flood warning and evacuation may be the best means of reducing life loss due to floods where flood-control structures are inadequate or non-existent. Reliable and timely flood warnings would permit temporary evacuation of people and some personal property from flood-hazard areas, particularly in areas like Davis County where the time interval between the onset of rainfall and downstream flooding is short. Davis County is presently establishing a network of remote real-time reporting computer-linked weather stations which will aid in interpreting when flood warning and evacuation is necessary.

Floodproofing may be the most effective way of lowering flood damage in areas where floods are of short duration and have low stages and velocities. Floodproofing measures include using special cements for flooring; providing adequate electric fuse protection; anchoring buoyant tanks; sealing the outside walls of basements; installing automatic sump pumps, sewer-check valves, seal-tight windows and doors, and door and window flood shields; and using wire-reinforced glass (Kockelman, 1977). Structural modifications may be necessary, including reinforcing basement walls and floor underpinnings to withstand the increased hydrostatic pressures, permanently sealing exterior openings to basements, erecting low floodwalls, and elevating the lowest floor and access roads to at least 2 feet above the 100-year flood elevation.

For stream flooding, FEMA has developed Flood Insurance Rate Maps for major Davis County drainages. These maps are designed to be used in conjunction with the Federal Insurance Administration's National Flood Insurance Program. Davis County and the cities therein have entered into this program. The National Flood Insurance Program permits construction of new structures in the floodway only if accompanying increases in flood heights are less than 1.0 foot and hazardous velocities are not produced. Development density in floodway-fringe areas is not restricted. In both floodway and floodway-fringe areas, the National Flood Insurance Program requires new development to be elevated above the level of the 100-year flood. The National Flood Insurance Program requires that flood insurance be purchased if the property is within the boundary of the 100-year flood and is financed with federally-guaranteed loans. Fred May, Utah Division of Comprehensive Emergency Management (584-8370), may be contacted for information regarding the National Flood Insurance Program. County and city planning offices can provide information regarding which zones properties fall within as depicted on the FEMA Flood Insurance Rate Maps.

Lake Flooding

The most effective way to reduce hazards from lake flooding would be to adopt a beneficial development strategy for lake-shore areas up to 4,217 feet in elevation, and ensure that development within this lake-shore area is either compatible with or protected from the flood hazard. Recent shoreline flooding around Great Salt Lake has been locally controlled by dikes, but this is not a permanent long-term solution to flooding. Stabilization of the water level is most desirable, and this may be accomplished in several ways, including pumping to adjacent basins to increase evaporation and diversion of inflow.

Great Salt Lake shoreline flooding can be controlled by increasing evaporation through pumping. It is this means of mitigation that is currently being used to control Great Salt Lake levels. Lake water is pumped out into the west desert to increase the surface area for additional evaporation to take place. While these pumps will be effective in controlling lake levels during years which are somewhat wetter than normal, it is possible for precipitation during a very wet period to exceed the capabilities of the pumping/evaporation program. Other mitigative measures would then need to be considered in addition to the West Desert Pumping Program.

Shoreline flooding around Great Salt Lake could also be controlled by diverting water from rivers which flow into the lake. This option has been most frequently discussed with respect to the Bear River. To be effective, the water must be diverted completely out of the Great Salt Lake basin. Bear River water could be discharged into the Snake River drainage.

Dam-Failure Inundation

Little can practically be done through land-use planning to reduce dam-failure flooding hazards. Methods used to reduce hazards from stream flooding, such as proper land use along flood plains, will help reduce damage do to dam-failure flooding to some extent. Emergency response based on evacuation maps is the principal means of reducing hazards due to dam-failure flooding, however. Davis County Flood Control, the Utah Division of Water Rights, Dam Safety Division, and the U. S. Bureau of Reclamation are the principal agencies responsible for the safety of dams in Davis County.

RECOMMENDED USE OF MAPS IN LAND-USE PLANNING

The Federal Emergency Management Agency has produced maps at varying scales depicting areas of potential stream flooding for major drainages in Davis County. FEMA recommends that no new development be permitted in the 100-year flood plain unless: 1) detailed engineering studies show that the proposed development will not increase the flood hazard to other property in the area, 2) the proposed development is elevated above the 100-year flood base elevation, and 3) for federally-insured loans, flood insurance is purchased from a company participating with the Federal Insurance Administration or a like private carrier.

To supplement FEMA maps and recommendations, Davis County has adopted a flood-control ordinance which designates drainages and critical flood areas where the County has primary responsibility for flood mitigation and defines that responsibility. This ordinance requires that permits be obtained from the Davis County Flood Control Department for any development proposed within 100 feet of either side of a designated drainage, protects flood channels against changes that might adversely affect flow capacity, sets standards and policies for open channels and piped storm drains, mandates maintenance access along designated channels (rights of way, easements, fee title), and provides for County ownership of flood-control structures within development boundaries.

Maps have not been prepared depicting the proposed "Beneficial Development Area" along Great Salt Lake where lake flooding is considered possible. However any development below 4,417 feet in elevation is within the proposed "Beneficial Development Area". It is recommended that Davis County and the cities in the county along the shore of Great Salt Lake coordinate efforts to determine the most advantageous type of development in this area.

Maps showing dam-failure inundation areas in Davis County have been prepared by state and federal agencies. These maps are of little use from the standpoint of land-use planning, but are of great value in delineating areas for possible evacuation if dam failure occurs or is imminent. The 1990 Utah legislature passed a bill requiring that emergency action plans be developed for any dam which would pose a threat to life or cause significant damage to property if it failed.

SCOPE OF SITE INVESTIGATIONS

Davis County and the cities therein are members of the National Flood Insurance Program and, therefore, development is required by the Federal Emergency Management Agency to comply with National Flood Insurance Program standards along drainages for which Flood Insurance Rate Maps are available. FEMA has established guidelines for amending Flood Insurance Rate Maps for areas where the mapping is wrong or conditions have changed, such as areas where debris basins or detention ponds have been established after the maps were completed. Although flooding can occur along some of the minor drainages for which Flood Insurance Rate Maps are not available, developers will not be required by FEMA to mitigate the hazard. Davis County Flood Control may be contacted for information regarding these minor drainages. Flood-hazard studies to determine the elevation of the structure with respect to the 100-year flood plain, and to make recommendations regarding floodproofing or other mitigation techniques for development within flood-hazard areas, should be undertaken when locating structures along or near all drainages.

Site investigations for proposed development in lake-flooding areas near Great Salt Lake need only indicate site elevation. Development proposals in areas with elevations less than 4,217 feet will be reviewed with respect to lake-flooding potential and compatibility of proposed use by the city or county planning department and the Davis County Flood Control Department. No special site investigations are required for development in dam-failure inundation zones, except where they coincide with other stream-flooding hazard areas discussed above.

Elevations determined as part of stream and lake flood-hazard investigations should be conducted by qualified engineers and surveyors and tied to known bench marks. Recommendations concerning floodproofing or flood-control structures should be submitted to Davis County Flood Control by a registered Professional Engineer.

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SHALLOW GROUND WATER

INTRODUCTION

"Water in saturated zones beneath the land surface, referred to as ground water, occurs in various materials at various depths throughout Utah; ground water fills fractures and pore spaces in rocks and fills voids between grains in unconsolidated deposits (clay, silt, sand, and gravel)" (Hecker and others, 1988). Ground water is considered to be shallow where the water table is within 30 feet of the ground surface.

Hazards associated with shallow ground water include flooding of subsurface facilities such as basements, surface flooding, destabilization of foundations or excavations, and liquefaction of soils during earthquakes. Problems from shallow ground water generally arise only when the saturated zone is within about 10 feet or less of the ground surface because this is the depth to which most foundations of buildings are excavated. Shallow ground water is a significant factor which must be considered when siting waste-disposal facilities and septic-tank soil-absorption systems. Liquefaction can occur in saturated sandy soils up to a depth of 30 feet during earthquakes and result in ground failure (Youd and others, 1978).

It is the purpose of this chapter to discuss: 1) the nature of shallow ground-water hazards in Davis County, 2) the potential consequences, 3) shallow ground-water hazards maps prepared by Anderson and others (1982), and 4) recommendations regarding use of the maps in land-use planning. Liquefaction hazards are discussed in a separate chapter entitled "Liquefaction". Surface flooding from shallow ground water in areas experiencing subsidence as a result of earthquakes is discussed in a separate chapter entitled "Tectonic Subsidence". Shallow ground water in rock is not as common as shallow ground water in unconsolidated sediments and is not considered here because it poses a relatively insignificant geotechnical hazard (Hecker and others, 1988). "Foundations and conventional waste-water disposal systems in rock are uncommon, and foundation stability is not appreciably reduced by saturated conditions. Also, rock is not susceptible to liquefaction" (Hecker and others, 1988).

NATURE AND CAUSES OF SHALLOW GROUND WATER

Shallow ground water occurs in unconsolidated sediments in much of western Davis County. "Ground water in unconsolidated deposits, chiefly stream alluvium and alluvial-fan and lacustrine (lake) basin fill, occurs under unconfined and confined conditions and frequently occurs in geologic units, known as aquifers, which are permeable enough to yield water in usable quantities to wells and springs" (Heath, 1983, in Hecker and others, 1988). An unconfined aquifer is generally not saturated throughout its entire thickness; the top of the zone in which the pore spaces in the unconsolidated sediments are saturated is termed the water table (figure J-1). "Localized occurrences of unconfined ground water above the principle water table are called perched zones" (Hecker and others, 1988) (figure J-1). Perched ground water commonly occurs above localized deposits of low-permeability sediment. Where ground water saturates the entire thickness of an aquifer below an areally-extensive low-permeability zone, termed a confining bed, the aquifer is said to be under confined conditions. Ground water beneath a confining bed is usually under artesian pressure as a result of hydrostatic pressure exerted by higher water levels in recharge areas, and water in wells penetrating a confined aquifer usually rises above the top of the aquifer to the level of the potentiometric surface (figure J-1). The level of the potentiometric surface is determined by the amount of hydrostatic pressure at that point in the confined aquifer. "Confining beds in unconsolidated sediments are generally semi-permeable and thus allow underlying, artesian water to leak upward and help maintain a water table above the confined aquifer" (Hecker and others, 1988) (figure J-1). Shallow ground water in Davis County occurs in perched and unconfined aquifers.

"Water in shallow saturated zones is replenished by infiltration from streams, lakes,

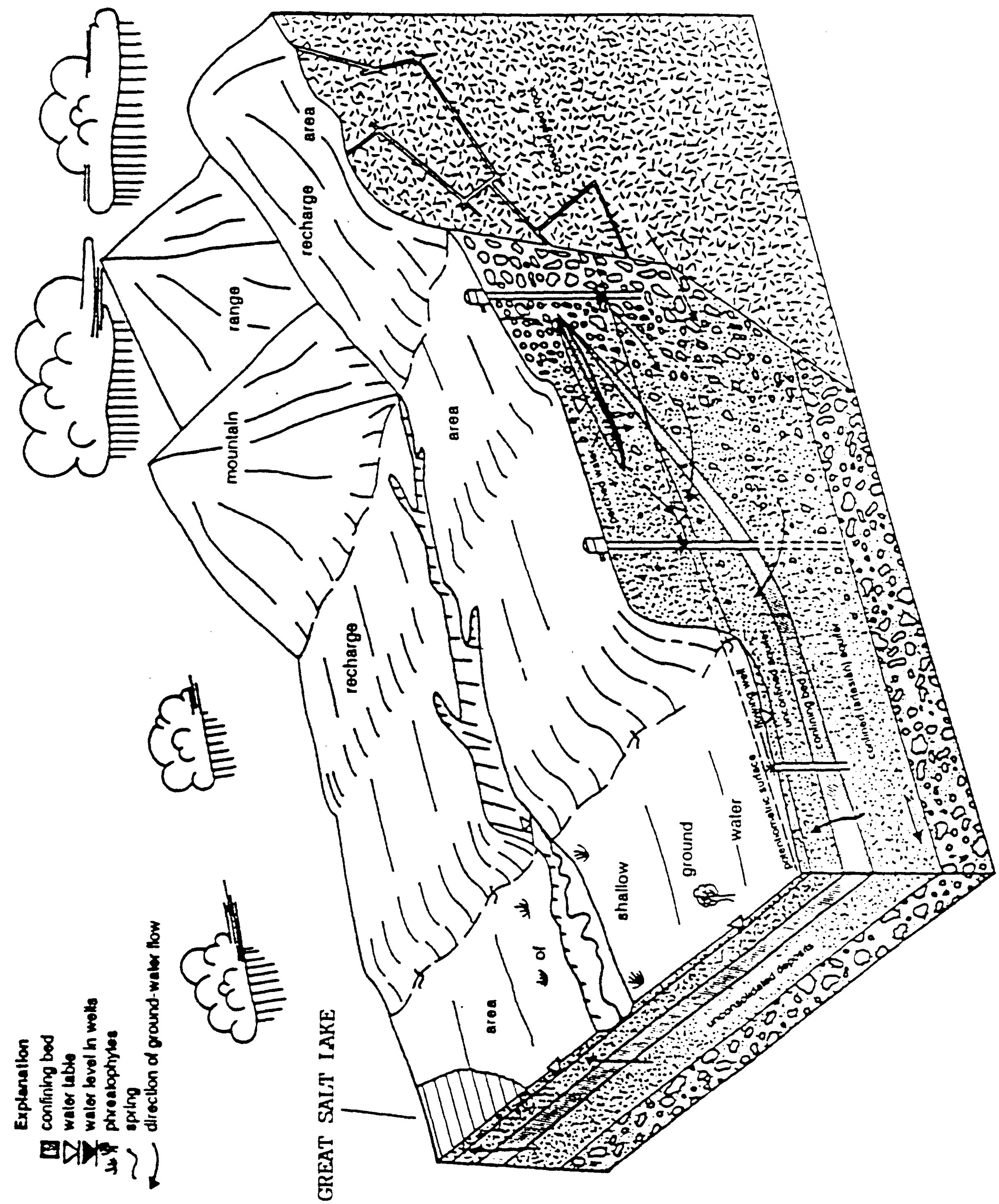

Figure J-1. Relation of unconfined, confined, and perched ground water in typical basin or wide stream valley. In the well at right, the water level corresponds to the water table; in the other two wells, which tap the confined aquifer, the water rises above the confining layer and the water talbe to the potentiometric surface (Modified from Hely and others, 1971).

and precipitation, lateral subsurface flow from adjacent higher ground-water areas, and upward leakage from underlying confined aquifers" (Hecker and others,1988). The shallowest water tables are generally found in stream valleys and in the center of basins where upward leakage from underlying artesian aquifers is greatest and their potentiometric surfaces are commonly above the ground surface (figure J-1). "Ground water discharges naturally from springs and by evapotranspiration (direct evaporation and plant transpiration). Man influences local water levels through irrigation, pumping from wells, and surface-drainage diversions and reservoirs" (Hecker and others, 1988).

According to Hecker and others (1988):

> The shallow water table is dynamic and fluctuates daily, seasonally, annually, and over longer periods in response to a variety of conditions. Ground-water levels may rise and fall with seasonal variations in precipitation, longer-term changes in climate, or changes in rates of irrigation or pumping. A series of years with greater-than-average precipitation beginning in the late-1960s, but particularly since 1982, has increased ground-water recharge to basins and generally elevated ground-water tables statewide

in the mid-1980s, including Davis County. Drought conditions in the late-1980s have caused a general decline.

HAZARDS ASSOCIATED WITH SHALLOW GROUND WATER

The most significant hazard associated with shallow ground water is the flooding of subsurface facilities (such as basements), utility lines, and septic-tank soil-absorption fields. Structures extending below the water table may experience water damage to foundations as well as contents. Landfills and waste dumps may become inundated and contaminate aquifers. Underground utilities may also experience water damage. Septic-tank soil-absorption fields can become flooded which may cause ground-water contamination as well as system failure. Roads and airport runways may buckle or settle as bearing strength in susceptible soils are reduced by saturation. Wetting of collapsible or expansive soils by ground water may cause settlement or expansion and damage to foundations and structures.

Dissolution of subsurface materials and soil piping causing sinkholes and collapse-induced depressions may also be caused by shallow ground water. Water flowing through bedrock fissures in limestone or gypsiferous rocks can dissolve the rock and create holes which may collapse. Sinkholes and piping can occur in unconsolidated sediments as water flowing through conduits beneath the ground surface erodes sediments to create cavities ("pipes") which may collapse.

Because shallow ground water is readily accessible from the surface, contaminants are easily introduced. Pollutants will flow with the ground water and may enter lower aquifers or seep into wells. About 85 percent of the Utah's wells are located within basin-fill aquifers; some are becoming increasingly contaminated (Waddell and Maxell, 1987).

SHALLOW GROUND-WATER HAZARD REDUCTION

Avoidance is the easiest method of reducing shallow ground-water problems. However, because many of Davis County's population centers are on the relatively flat land on the floor of Salt Lake Valley, coincident with areas of shallow ground water, avoidance may not be possible. Construction techniques may be employed which reduce or eliminate the adverse effects of ground-water flooding. Water-proofing of subsurface structures may be the most common technique used, and may include installation of drainage systems around basements. Requirements for water-proofing are given in the Uniform Building Code. Slab-on-grade buildings, which have no basement, are common in areas with a shallow water table. Pile foundations may also be used to increase foundation stability. Occasionally it is necessary to add fill to the construction site to raise the elevation of the building.

Pumping water to lower the water table

is also possible in areas subject to a shallow water table. This procedure is typically used only during the construction phase, and is an expensive and unreliable technique for permanently lowering a water table. However, basement sump pumps are effective for individual homes.

Septic-tank soil-absorption fields do not function properly if inundated by shallow ground water. Utah State Health Department regulations therefore require that the base of the drain lines be at least two feet above the highest seasonal ground-water table. Wisconsin mound septic-tank soil-abortion systems are currently experimental in Utah, but may be an alternative system that could be used in shallow ground-water areas. The drain lines in this type of system are buried in a mound above the natural ground surface to increase evaporation and increase the soil thickness above the water table.

SUMMARY OF METHODS USED IN MAP PREPARATION

Difficulties in mapping shallow ground-water tables occur because of diurnal, seasonal, annual, or longer period fluctuations. These variations may be in response to storms, seasonal changes in precipitation, long-term climatic changes, draw down from wells, or flooding from irrigation. To determine the potential for shallow ground-water problems, it is best to identify the highest level the water table can be expected to reach. This is very difficult to do because of these fluctuations, and the map shows long-term averages rather than highest levels.

Shallow ground-water maps have been constructed by Anderson and others (1982) as part of a liquefaction potential study, primarily from borings for their study and from soil-foundation reports.

RECOMMENDED USE OF SHALLOW GROUND-WATER HAZARD MAPS

Most problems associated with shallow ground water occur when the water table is within about 10 feet of the ground surface. Site-specific shallow ground-water studies are recommended for all types of construction with subsurface facilities in areas where the water table is shown to be within 10 feet of the ground surface on Anderson and others' (1982) Soils and Ground-Water Data Map. Areas where the water table is within 30 feet of the ground surface are shown on the maps because of the possibility of liquefaction at greater depths. The maps also show areas where the water table is generally between 30-50 feet of the ground surface.

The principal users targeted for these maps are planners, building officials, health department officials, and others who must know where further studies are required prior to development. Buildings scheduled for construction in western Davis County, depending on the type of structure, may need additional information about the potential for shallow ground-water problems before a building permit is issued. Also, shallow ground-water studies are required before approval is given by the Davis County Health Department for septic-tank soil-absorption systems.

Because of fluctuations of the water table, the accompanying maps are not intended to replace site-specific data. Ground-water information is quite extensive in some of the more urbanized areas, but is sparse in rural areas where subsurface investigations have not been performed or are not available.

SCOPE OF SITE INVESTIGATIONS

If a project is located in a shallow (< 10 feet) ground-water areas, site-specific studies should be conducted to identify the highest shallow ground-water level recorded or visible in sediments as well as the present and highest expected level of the water table. To do this, it may be necessary to use additional information about long-term water-level fluctuations from measurements in wells over time and define a range of seasonal and annual fluctuation. Water-table measurements during known wet periods, such as 1983-1985, can also be used to approximate highest levels. Shallow ground-water hazards can be addressed in the soil-foundation report for a site, which should contain recommendations for stabilizing or lowering the water table, if necessary, and design of floodproofing or other mitigation strategies. Such studies must also address soil conditions and the potential for collapse, piping, dissolution, or swelling if saturated. The site-specific studies will be reviewed by the county. The shallow ground-water maps will be amended as new information becomes available.

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