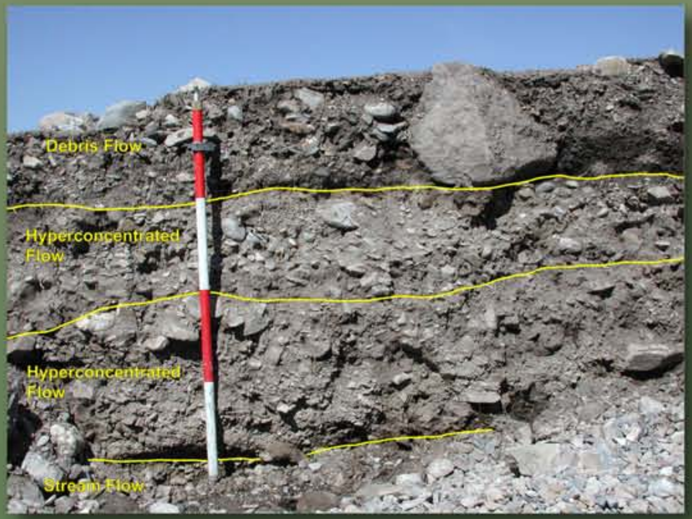
House moved by 1930 debris flow from Davis Creek near Farmington, Utah.

Channel erosion associated with a 2002 debris flow on Dry Mountain near Santaquin, Utah.



Different flow types exposed in alluvial-fan deposits near Lake Point, Utah.

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Giraud

GUIDELINES FOR THE GEOLOGIC EVALUATION OF DEBRIS-FLOW HAZARDS ON ALLUVIAL FANS IN UTAH

UGS MP 05-6

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2002 debris-flow deposit in Santaquin, Utah (photo by Dale Deiter, USFS).

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GUIDELINES FOR THE GEOLOGIC EVALUATION OF DEBRIS-FLOW HAZARDS ON ALLUVIAL FANS IN UTAH

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Richard E. Giraud

ABSTRACT

The Utah Geological Survey (UGS) developed these guidelines to help geologists evaluate debris-flow hazards on alluvial fans to ensure safe development. Debris-flow-hazard evaluations are particularly important because alluvial fans are the primary sites of debris-flow deposition and are also favored sites for development. The purpose of a debris-flow-hazard evaluation is to characterize the hazard and provide design parameters for risk reduction. The UGS recommends critical facilities and structures for human occupancy not be placed in active debris-flow travel and deposition areas unless the risk is reduced to an acceptable level.

These guidelines use the characteristics of alluvial-fan deposits as well as drainage-basin and feeder-channel sediment-supply conditions to evaluate debris-flow hazards. The hazard evaluation relies on the geomorphology, sedimentology, and stratigraphy of existing alluvial-fan deposits. Analysis of alluvial-fan deposits provides the geologic basis for estimating frequency and potential volume of debris flows and describing debris-flow behavior. Drainage-basin and feeder-channel characteristics determine potential debris-flow susceptibility and the volume of stored channel sediment available for sediment bulking in future flows.

The debris-flow hazard depends on site location on an alluvial fan. Generally, sediment burial and impact hazards are much greater in proximal fan areas than in medial and distal areas downfan. Hazard zones may also be outlined on the alluvial fan to understand potential effects of debris flows and determine appropriate risk-reduction measures. Geologic estimates of debris-flow-design parameters are necessary for the engineering design of risk-reduction structures.

INTRODUCTION

Overview

Debris flows and related sediment flows are fast-moving flow-type landslides composed of a slurry of rock, mud, organic matter, and water that move down drainage-basin channels onto alluvial fans (figure 1). Debris flows generally initiate on steep slopes or in channels by the addition of water from intense rainfall or rapid snowmelt. Flows typically incorporate additional sediment and vegetation as they travel downchannel. When flows reach an alluvial fan and lose channel confinement, they spread laterally and deposit the entrained sediment. In addition to being debris-flow-deposition sites, alluvial fans are also favored sites for urban development; therefore, a debris-flow-hazard evaluation is necessary when developing on alluvial fans. A debris-flow-hazard evaluation requires an understanding of the debris-flow processes that govern sediment supply, sediment bulking, flow volume, flow frequency, and deposition.

Evaluation of the debris-flow hazard follows the premise that areas where debris flows have deposited sed-

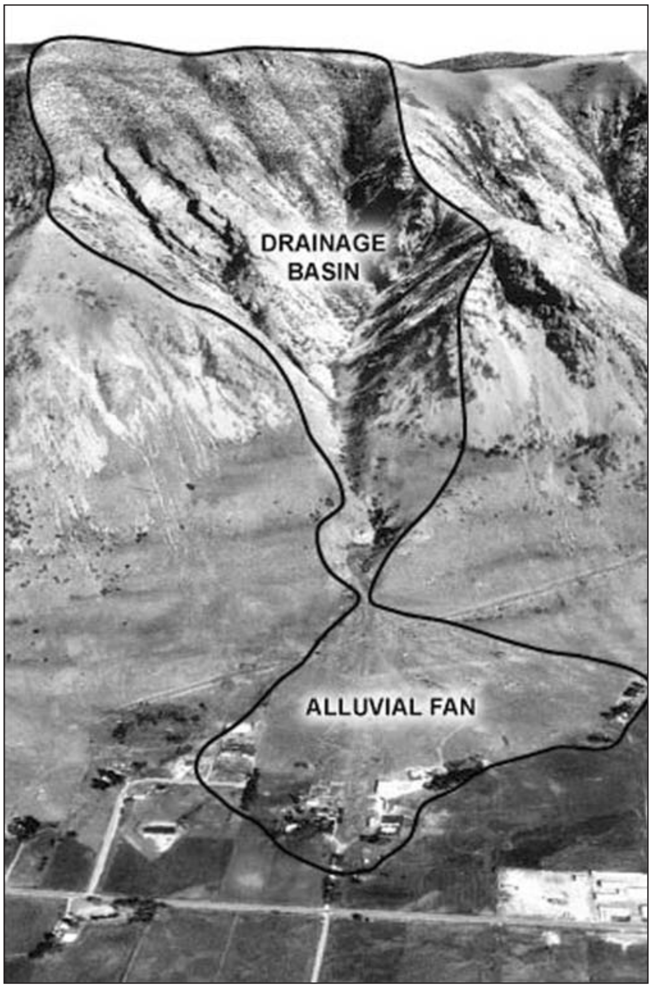

Figure 1. *Example of a drainage basin and alluvial fan at Kotter Canyon, north of Brigham City, Utah.*

iment in the recent geologic past are likely sites for future debris-flow activity. Evaluation of the debris-flow hazard uses geomorphic, sedimentologic, and stratigraphic information from existing debris-flow deposits and sediment-volume estimates from the feeder channel and drainage basin to estimate the hazard within the active depositional area of an alluvial fan. A complete debris-flow-hazard assessment typically involves geologic, hydrologic, hydraulic, and engineering evaluations. The nature of the proposed development and the anticipated risk-reduction measures required typically determine the scope of the hazard evaluation.

Large-volume debris flows are low-frequency events, and the time between large flows is typically a period of deceptive tranquility. Debris flows pose a hazard very different from other types of landslides and floods due to their rapid movement and destructive power. Debris flows can occur with little warning. Fifteen people have been killed by debris flows in Utah. Thirteen of these victims were killed in two different events at night as fast-moving debris flows allowed little chance of escape. In addition to threatening lives, debris flows can damage buildings and infrastructure by sediment burial, erosion, direct impact, and associated water flooding. The 1983 Rudd Canyon debris flow in Farmington deposited approximately 90,000 cubic yards of sediment on the alluvial fan, damaged 35 houses, and caused an estimated $3 million in property damage (Deng and others, 1992).

Variations in sediment-water concentrations produce a continuum of sediment-water flow types that build alluvial fans. Beverage and Culbertson (1964), Pierson and Costa (1987), and Costa (1988) describe the following flow types based on generalized sediment-water concentrations and resulting flow behavior: stream flow (less than 20% sediment by volume), hyperconcentrated flow (20 to 60% sediment by volume), and debris flow (greater than 60% sediment by volume). These categories are approximate because the exact sediment-water concentration and flow type depend on the grain-size distribution and physical-chemical composition of the flows. Also, field observations and video recordings of poorly sorted water-saturated sediment provide evidence that no unique flow type adequately describes the range of mechanical behaviors exhibited by these sediment flows (Iverson, 2003). All three flow types can occur during a single event. The National Research Council (1996) report on *Alluvial-Fan Flooding* considers stream, hyperconcentrated, and debris-flow types of alluvial-fan flooding. The term debris flood has been used in Utah to describe hyperconcentrated flows (Wieczorek and others, 1983).

These guidelines address only hazards associated with hyperconcentrated- and debris-flow sediment-water concentrations and not stream-flow flooding on alluvial fans. The term debris flow is used here in a general way to include all flows within the hyperconcentrated- and debris-flow sediment-water concentration range. These are the most destructive flows, and it can be difficult to distinguish between hyperconcentrated and debris flows based on their deposits. Stream flow involves sediment transport by entrained bed load and suspended sediment load associated with water transport. Sheetfloods are unconfined stream flows that spread over the alluvial fan (Blair and McPherson, 1994). Debris-flow and stream-flow-flooding hazards may be managed differently in terms of land-use planning and protective measures, but because debris-flows and stream-flow hazards are often closely associated, concurrent evaluation of both debris-flow and stream-flow components of alluvial-fan flooding is often beneficial.

The purpose of a geologic evaluation is to determine whether or not a debris-flow hazard exists, describe the hazard, and if needed, provide geologic parameters necessary for hydrologists and engineers to design risk-reduction measures. The objective is to determine active depositional areas, frequency and magnitude (volume) of previous flows, and likely impacts of future sedimentation events. Dynamic analysis of debris flows using hydrologic, hydraulic, and other engineering methods to design site-specific risk-reduction measures is not addressed by these guidelines.

These guidelines will assist engineering geologists in evaluating debris-flow hazards in Utah, engineers in designing risk-reduction measures, and land-use planners and technical reviewers in reviewing debris-flow-hazard reports. They are modeled after the Utah Geological Survey (UGS) *Guidelines for Evaluating Landslide Hazards in Utah* (Hylland, 1996) and *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Christenson and others, 2003). The geologist has the responsibility to (1) conduct a study that is thorough and cost effective, (2) be familiar with and apply appropriate investigation methods, (3) record accurate observations and measurements, (4) use proper judgment, and (5) present valid conclusions and recommendations supported by adequate data and sound interpretations. The geologist must also understand and clearly state the uncertainties and limitations of the investigative methods used and the uncertainties associated with design-parameter estimates.

Limitations

These guidelines identify important issues and general methods for evaluating debris-flow hazards; they do not discuss all methods and are not a step-by-step primer for hazard evaluation. The level of detail appropriate for a particular evaluation depends on several factors, including the type, nature, and location of proposed development; the geology and physical characteristics of the drainage basin, feeder channel, and alluvial fan; the record of previous debris flows; and the level of risk acceptable to property owners and land-use regulators. A uniform level of acceptable risk for debris flows based on recurrence or frequency/volume relationships, such as the 100-year flood or the 2% in 50-year exceedance probability for earthquake ground shaking, has not been established in Utah.

Historical records of sedimentation events in Utah indicate that debris flows are highly variable in terms of size, material properties, and travel and depositional behavior; therefore, a high level of precision for debris-flow design parameters cannot yet be attained. Consequently, prudent design parameters and engineering designs must be used where risk reduction is necessary. Appropriate disclosure of the debris-flow-hazard evaluation to future property owners is also advisable.

The "state-of-the-art" of debris-flow-hazard evaluation continues to evolve as our knowledge of sediment-flow processes advances. As new techniques become available and generally accepted they should be used in future hazard evaluations. Ranges for debris-flow bulking rates, flow volumes, runout distances, deposit areas, and deposit thicknesses have not been established and further research is necessary to quantify the physical characteristics of debris flows in Utah. The methods outlined in these guidelines are considered to be practical and reasonable methods for obtaining planning, design, and risk-reduction information, but these methods may not apply in all cases. The user is responsible for understanding the appropriateness of the various methods and where they apply.

DEBRIS-FLOW-HAZARD EVALUATION

A debris-flow-hazard evaluation is necessary when developing on active alluvial fans where relatively recent deposition has occurred. The evaluation requires application of quantitative and objective procedures to estimate the location and recurrence of flows, assess their impacts, and provide recommendations for risk-reduction measures if necessary. The hazard evaluation must state the intended land use because site usage has direct bearing on the degree of risk to people and structures. The UGS recommends critical facilities and structures for human occupancy not be placed in active debris-flow travel and deposition areas unless methods are used to either eliminate or reduce the risk to an acceptable level. In some cases, risk-reduction measures may be needed to protect existing development.

To evaluate the hazard on active alluvial fans, the frequency, volume (deposit area and thickness), and runout distance of past debris flows must be determined. The geologic methods presented here rely on using the geologic characteristics of existing alluvial-fan deposits as well as drainage-basin and feeder-channel sediment-supply conditions to estimate the characteristics of past debris flows. Historical records can provide direct evidence of debris-flow volume, frequency, and depositional area. The observation period in Utah is short, and debris flows either have not occurred or have not been documented. Therefore, geologic methods provide the principal means of determining the history of debris-flow activity on alluvial fans. Multiple geologic methods should be used whenever possible to compare results of different methods to understand the appropriateness, validity, and limitations of each method and increase confidence in the hazard evaluation.

Where stream flow dominates on an alluvial fan a stream-flow-flooding evaluation is necessary, but a debris-flow-hazard evaluation is not required. The National Research Council (1996) report on *Alluvial-Fan Flooding* and the Federal Emergency Management Agency (1999) *Guidelines for Determining Flood Hazards on Alluvial Fans* provide guidance for evaluating the stream-flow component of alluvial-fan flooding.

Information Sources

Sources of information for debris-flow-hazard evaluations include U.S. Geological Survey and UGS maps that show debris-flow source areas at a nationwide scale (1:2,500,000; Brabb and others, 2000), statewide scale (1:500,000; Brabb and others, 1989; Harty, 1991), and 30 x 60-minute quadrangle scale (1:100,000; UGS Open-File Reports) for the entire state. The 30 x 60-minute quadrangle maps show both the source and depositional areas of some historical debris flows. Alluvial-fan deposits are commonly shown on modern geologic maps, and the UGS and others map surficial (Quaternary) geology on 7½-minute scale quadrangle maps (1:24,000). Wasatch Front counties have maps available in county planning offices showing special-study areas where debris-flow-hazard evaluations are required. Surficial geologic maps generally show alluvial-fan deposits of different ages and differentiate stream alluvium from alluvial-fan deposits.

Numerous investigators have studied debris-flow processes and performed debris-flow-hazard evaluations in Utah. Many studies address the 1983 and 1984 debris flows that initiated during a widespread rapid-snowmelt period. Christenson (1986) discusses mapping, hazard evaluation, and mitigation measures following the debris flows of 1983. Wieczorek and others (1983, 1989) described the potential for debris flows and debris floods and mitigation measures along the Wasatch Front between Salt Lake City and Willard. Lips (1985, 1993) mapped 1983 and 1984 landslides and debris flows in central Utah. Cannon (1989) evaluated the travel-distance potential of debris flows that occurred in 1983 and 1984. Paul and Baker (1923), Woolley (1946), Croft (1967), Butler and Marsell (1972), Marsell (1972), and Keate (1991) provide documentation and photographs of historical debris flows and flooding in Utah prior to the 1983 events.

Several researchers investigated different aspects of the 1983 and 1984 Davis County debris flows. Pack (1985), for the purpose of landslide susceptibility mapping, used a multivariate analysis to evaluate factors related to initiation of debris slides in 1983 that then transformed into debris flows. Pierson (1985) described flow composition and dynamics of the 1983 Rudd Canyon debris flow in Farmington. Santi (1988) studied the kinematics of debris-flow transport and the bulking of colluvium and channel sediment during a 1984 debris flow in Layton. Mathewson and others (1990) studied bedrock aquifers and the location of springs and seeps that initiated colluvial slope failures in 1983 and 1984 that then transformed into debris flows. Keaton (1988) and Keaton and others (1991) developed a probabilistic model to assess debris-flow hazards on alluvial fans. Williams and Lowe (1990) estimated channel sediment bulking rates by comparing cross-channel profiles of channels that discharged historical debris flows with channels that had not discharged flows in historical time. Deng and others (1992) studied debris-flow impact forces, types of house damage, and economic losses from the 1983 Rudd Canyon debris flow. Coleman (1995) studied the possible role of watershed terraces in contributing material to the 1983-84 debris flows. Ala (1995) studied the interaction of bedrock structure, lithology, and ground water and their combined influence on colluvial slope failures that generated debris flows. Skelton (1995) studied the geologic control of seeps and springs in the Farmington Canyon Complex and their role in generating colluvial slope failures. Eblen (1995) modeled colluvial slope stability to understand the initiation of the 1983 slope failures that mobilized into debris flows.

Outside of Utah others have outlined approaches for evaluating debris-flow hazards and methods for estimating design parameters for debris-flow-risk reduction. Hungr and others (1984) described approaches to estimate debris-flow frequency, volume, peak discharge, velocity, and runout distance in western Canada. VanDine (1985) described conditions conducive to debris flows, triggering events, effects, and mitigation in the southern Canadian Cordillera. Hungr and others (1987) described debris-flow-engineering concepts and risk reduction in source, transport, and deposition zones in British Columbia. Jackson (1987) outlined methods for evaluating debris-flow hazards on alluvial fans in the Canadian Rocky Mountains based on the presence of debris-flow deposits, alluvial-fan geomorphic features, deposit ages, debris-flow frequency, and basin conditions. Jackson (1987) also provided a flow chart summarizing debris-flow-hazard evaluation. Jackson and others (1987) used geomorphic and sedimentologic criteria to distinguish alluvial fans prone to debris flows and those dominated by stream-flow processes. Ellen and others (1993) used digital simulations to map debris-flow hazards in the Honolulu District of Oahu, Hawaii. VanDine (1996) summarized the use of debris-flow control structures for forest engineering applications in British Columbia. Boyer (2002) discussed acceptable debris-flow-risk levels for subdivisions in British Columbia and provided a suggested outline for debris-flow studies on alluvial fans.

U.S. Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service) soil surveys show soils on alluvial fans and in drainage basins. These soil surveys provide information on soil type, depth, permeability, erodibility, slope steepness, vegetation, and parent material. Some soil surveys document historical debris-flow activity.

Newspaper articles and event reports often provide descriptions of historical debris flows and photographs showing impacts on developed areas. Written observations and photographs of historical debris flows provide useful information on flow volume, flow velocity, flow depth, deposit thickness, deposit areas, and building damage. Comparison of historical debris-flow deposits with prehistoric deposits allows the geologist to check if the historical debris flow is a typical event relative to other flows preserved in the sedimentary record.

Stereoscopic aerial photographs are a fundamental tool for evaluating drainage basins and alluvial fans. Interpretation of aerial photographs can provide information on surficial geology, soils, bedrock exposures, channel characteristics, landslides, previous debris flows, relative deposit ages, erosional areas, land use, and vegetation types. Reviewing the oldest and most recent photos available is useful to evaluate drainage-basin and alluvial-fan changes through time. Obtaining aerial photographs taken after historical debris flows allows direct mapping of sediment sources and deposits.

Alluvial-Fan Evaluation

Alluvial fans are landforms composed of a complex assemblage of debris-, hyperconcentrated-, and stream-flow deposits. Alluvial-fan geomorphology, sedimentology, and stratigraphy provide a long-term depositional history of the frequency, volume, and depositional behavior of past flows, and provide a geologic basis for estimating debris-flow hazards.

Defining the Active-Fan Area

The first step in an alluvial-fan evaluation is determining the active-fan area using mapping and alluvial-fan dating techniques. The active-fan area is where relatively recent deposition, erosion, and alluvial-fan flooding have occurred (figure 2). In general, sites of sediment deposition during Holocene time (past 10,000 years; post-Lake Bonneville in northwest Utah) are considered active unless proven otherwise. Aerial photographs, detailed topographic maps, and field verification of the extent, type, character, and age of alluvial-fan deposits are used to map active-fan areas. The youngest debris-flow deposits are generally indicative of debris flows produced during the modern climate regime and are important for estimating the likely volume and runout for future flows. The active fan is often used as a zoning tool to identify special-study areas where detailed debris-flow-hazard evaluations are required prior to development.

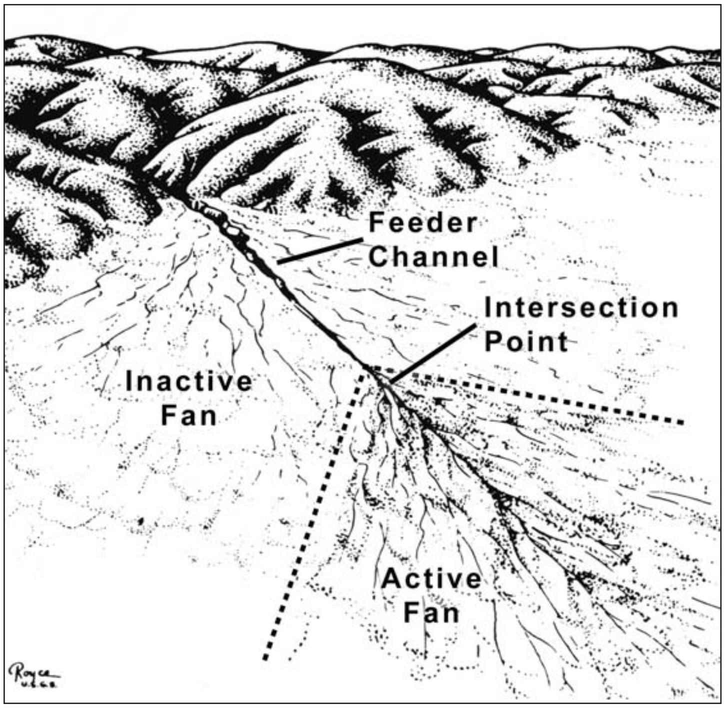

Figure 2. Active and inactive fans, feeder channel, and intersection point. Modified from Bull (1977). Reproduced with permission by Edward Arnold (Publishers) Ltd., London.

The National Research Council (1996) report on *Alluvial-Fan Flooding* provides criteria for differentiating active and inactive alluvial fans.

Mapping Alluvial-Fan and Debris-Flow Deposits

Geologic mapping is critical for identifying and describing the active areas of alluvial fans. Mapping of debris-flow and other deposits generally focuses on landforms; the extent, type, character, and age of geologic deposits, specifically individual debris flows; and stratigraphic relations between deposits. Peterson (1981), Christenson and Purcell (1985), Wells and Harvey (1987), Bull (1991), Whipple and Dunne (1992), Doelling and Willis (1995), Hereford and others (1996), and Webb and others (1999) provide examples and suggestions for mapping alluvial-fan deposits.

The geomorphic, sedimentologic, and stratigraphic relations recognized during mapping of alluvial-fan deposits provide insight into debris-flow recurrence, volumes, depositional behavior, and therefore debris-flow hazard in the proximal, medial, and distal fan areas (figure 3). The intersection point or apex of the active fan is where the feeder channel ends and sediment flows lose confinement and can spread laterally, thin, and deposit sediment (figure 2; Blair and McPherson, 1994). Most feeder channels lose confinement on the upper fan, but others may incise the inactive upper fan and convey sediment and flood flows farther downfan via a fanhead trench or channel (figure 2).

In proximal fan areas, debris flows generally have the highest velocity and greatest flow depth and deposit thickness, and are therefore the most destructive. In distal fan areas, debris flows generally have lower velocities and shallower flow depths and deposits, and therefore are less destructive. Often, distal fan areas are dominated by stream-flow processes only. However, some debris flows may create their own channels by producing levees on the fan and conveying sediment farther downfan, or blocking the active channel and avulse (make an abrupt change in course) to create new channels. Unpredictable flow behavior is typical of debris flows and must be considered when addressing debris-flow depositional areas, runout distances, and depositional behavior on alluvial fans.

The proximal part of an alluvial fan is generally made up of vertically stacked debris-flow lobes and levees that result in thick and coarse deposits that exhibit the roughest surface on the fan (figure 3). Hyperconcentrated flows may be interbedded with debris flows in the proximal fan area, but are generally thinner and have smoother surfaces due to their higher initial water content. Proximal fan deposits generally transition to thinner and finer grained deposits downfan, resulting in smoother fan surfaces in medial and distal fan areas (figure 3). Coarser grained sedimentary facies grade downfan into finer grained facies deposited by more dilute sediment flows. The downfan decrease in grain size generally corresponds with a decrease in fan-slope angle. Coarser grained debris-flow deposits generally create steeper proximal-fan slopes (6-8°) while finer grained stream-flow deposits form gentle distal-fan slopes (2-3°) (National Research Council, 1996).

Differences in bedding, sediment sorting, grain size, and texture are useful to distinguish debris-, hyperconcentrated-, and stream-flow deposits. Costa and Jarrett

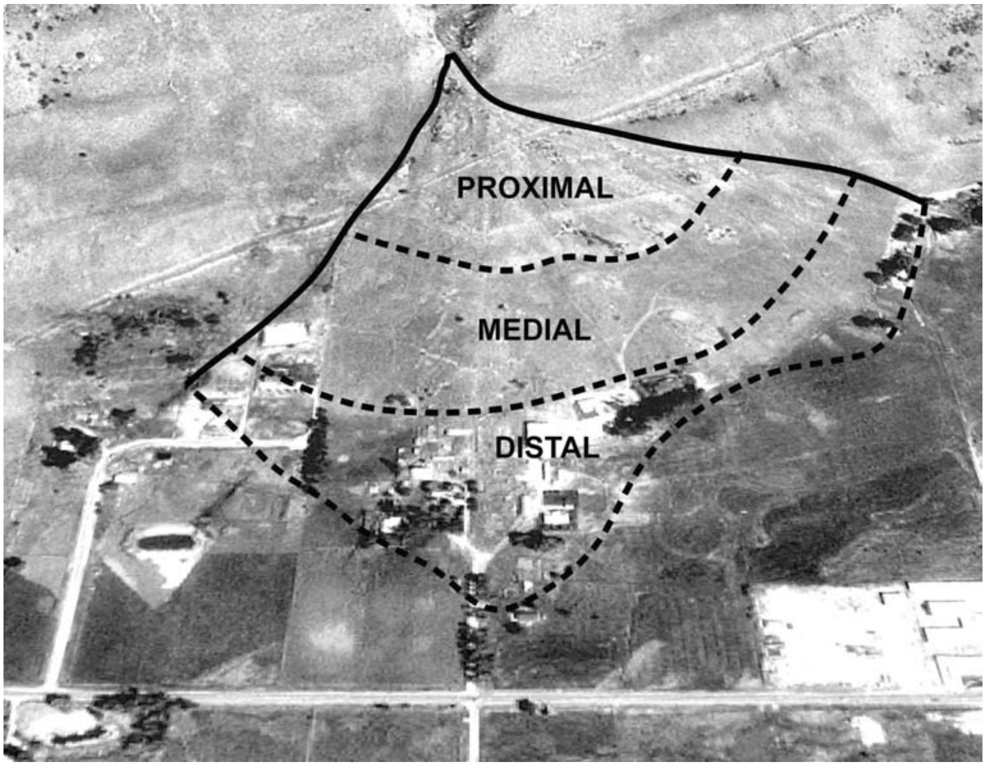

Figure 3. *Approximate proximal, medial, and distal fan areas on the Kotter Canyon alluvial fan, north of Brigham City, Utah.*

(1981, p. 312-317), Wells and Harvey (1987, p. 188), Costa (1988, p. 118-119), Harvey (1989, p. 144), the National Research Council (1996, p. 74), and Meyer and Wells (1997, p. 778) provide morphologic and sedimentologic criteria (surface morphology, internal structures, texture, grain size, and sorting) for differentiating the three flow types. In general, debris-flow deposits are matrix supported and poorly sorted, hyperconcentrated-flow deposits are clast supported and poorly to moderately sorted, and stream-flow deposits are clast supported and moderately to well sorted. Table 1 is modified from Costa (1988) and shows geomorphic and sedimentologic characteristics of debris-, hyperconcentrated-, and stream-flow deposits. Grain-size analysis is useful in classifying deposits into the different flow types (Pierson, 1985).

More than one flow type may occur during a sedimentation event. Keaton (1988) described an ideal vertical alluvial-fan stratigraphic sequence based on deposits in Davis County and published eyewitness accounts. The ideal sequence resulting from a single debris flow consists of a basal plastic debris-flow deposit, sequentially overlain by a viscous debris-flow, hyperconcentrated-flow, and finally a stream-flow deposit owing to time-varying availability of sediment and water. Janda and others (1981) identified a similar vertical sequence in debris-flow deposits at Mount St. Helens, Washington and attributed the vertical sequence to rapid transitions between flow types.

Determining the Age of Debris-Flow Deposits

Both relative and numerical techniques (Noller and others, 2000) are useful for dating debris-flow deposits and determining the frequency of past debris flows on a fan. Relative dating methods include boulder weathering, rock varnish, soil-profile development (including pedogenic carbonate accumulation), lichen growth, and vegetation age and pattern. The amount of soil development on a buried debris-flow surface is an indicator of the relative amount of time between debris flows at that particular location. Numerical dating techniques include sequential photographs, historical records, dating the age of vegetation, and isotopic dating, principally radiocarbon. Radiocarbon ages of paleosols buried by debris flows can provide closely limiting maximum ages of the overlying flow (Forman and Miller, 1989). Radiocarbon ages of detrital charcoal within a debris-flow deposit provide a general limiting maximum age. The applicability and effectiveness of radiocarbon dating of debris-flow events is governed by the presence and type of datable material and available financial resources (Lettis and Kelson, 2000).

Subsurface Exploration

Subsurface exploration using test pits, trenches, and natural exposures is useful in obtaining sedimentologic and stratigraphic information regarding previous debris flows. Test-pit and trench excavations can provide information on flow type, thickness, the across- and downfan extent of individual flows, and volume based on thickness and area. The type, number, and spacing of excavations depend on the purpose and scale of the hazard investigation, geologic complexity, rate of downfan and across-fan transitions in flow type and thickness, and anticipated risk-reduction measures. T-shaped test pits or trenches allow determination of three-dimensional deposit relationships. Excavations in the proximal fan areas generally need to be deeper due to thicker deposits. To evaluate the entire fan, tens of excavations may be required.

Mulvey (1993) used subsurface stratigraphic data from seven test pits to estimate flow types, deposit thicknesses, the across- and downfan extent of deposits, deposit volumes, and age of deposits to interpret the depositional history of a 2-acre post-Bonneville fan in Centerville. Blair and McPherson (1994) used across- and downfan stratigraphic cross sections to display, analyze, and interpret the surface and subsurface interrelationships of fan slope, deposit levees and lobes, deposit and sediment facies, and grain size. However stratigraphic interpretation can be problematic. Debris-flow

Table 1. *Geomorphic and sedimentologic criteria for differentiating water and sediment flows (modified from Costa, 1988).*

Flow Type	**Landforms and Deposits**	**Sedimentary Structures**	**Sediment Characteristics**
Stream flow	Bars, fans, sheets, splays; channels have large width-to-depth ratio	Horizontal or inclined stratification to massive; weak to strong imbrication; cut-and-fill structures; ungraded to graded	Beds well to moderately sorted; clast supported
Hyperconcentrated flow	Similar to water flood, rectangular channel	Weak stratification to massive; weak imbrication; thin gravel lenses; normal and reverse grading	Poorly to moderately sorted; clast-supported
Debris flow	Marginal levees, terminal lobes, trapezoidal to U-shaped channel	No stratification; weak to no imbrication; inverse grading at base; normal grading near top	Very poor to extremely poor sorting; matrix supported; extreme range of particle sizes; may contain mega-clasts

deposits in a sedimentary sequence that have similar grain sizes and lack an intervening paleosol or other distinct layer can be difficult to distinguish. The lack of distinction between individual debris-flow deposits can lead to underestimating debris-flow recurrence and overestimating debris-flow magnitude (Major, 1997).

Drainage-Basin and Channel Evaluation

Drainage-basin and channel evaluations determine the conditions and processes that govern sediment supply and transport to the fan surface, and provide an independent check of alluvial-fan evaluations. Drainage-basin and channel evaluation involves estimating the erosion potential of the basin and feeder channel and the volume, grain size, and gradation of sediment that could be incorporated into a debris flow. The evaluation also considers different debris-flow initiation mechanisms. The results of the drainage-basin and channel evaluation are used to estimate the probability of occurrence and design volumes of future debris flows. In some cases, evaluation of the drainage basin and channel may be performed independently of the alluvial-fan evaluation. For example, a wildfire in a drainage basin may initiate a post-burn analysis of the drainage basin and channels to estimate or revise the erodible sediment volume and the probability of post-fire debris flows.

Debris-Flow Initiation

Debris flows initiate in the drainage basin and require a hydrologic trigger such as intense or prolonged rainfall, rapid snowmelt, and/or ground-water discharge. Intense thunderstorm rainfall, often referred to as cloudburst storms by early debris-flow investigators in Utah (Woolley, 1946; Butler and Marsell, 1972), has generated numerous debris flows. Conditions in the drainage basin important in initiating debris flows are the basin relief, channel gradient, bedrock and surficial geology, vegetation and wildfire, and land use. Exposed bedrock on hillsides promotes rapid surface-water runoff, which helps generate debris flows. Wildfires can destroy vegetation and may also create water-repellent soils that result in rapid runoff. All of these conditions work in combination to promote debris flows.

In Utah, above-normal precipitation from 1980 through 1986 produced numerous snowmelt-generated landslides (mostly debris slides) that transformed into debris flows and then traveled down channels (Brabb, 1989; Harty, 1991). Many of these debris flows occurred during periods of rapid snowmelt and high stream flows, when Santi (1988) indicates that saturated channel sediment is more easily entrained into debris flows.

In contrast to wet climate conditions, dry conditions often lead to wildfires that partially or completely burn drainage-basin vegetation, creating conditions for increased runoff and erosion. Intense thunderstorm rainfall on steep burned slopes may produces debris flows. Relatively small amounts of intense thunderstorm rainfall (a few tenths of an inch per hour) are capable of triggering fire-related debris flows (McDonald and Giraud, 2002; Cannon and others, 2003).

During the drought years of 1999-2004 in northern Utah, 26 debris flows occurred in 7 wildfire areas, including repeated flows from single drainages in different storms and multiple flows from different drainages during the same storm. Debris-flow-hazard evaluations following a wildfire address burn severity and hillslope and channel conditions. Cannon and Reneau (2000) provide methods for evaluating debris-flow susceptibility following wildfires. Evanstad and Rasely (1995) and the U.S. Natural Resources Conservation Service (2000) estimated fire-related hillslope sediment yield for Wasatch Front drainages in Davis and Weber Counties and the lower Provo River drainage basin in Utah County. However, their sediment volume estimates are for annual post-burn hillslope sediment yields only and do not include channel sediment bulking that must be considered when estimating total debris-flow volumes. Wells (1987), Florsheim and others (1991), Cannon and others (1995), Meyer and others (1995), Cannon and Reneau (2000), Kirkham and others (2000), Robichaud and others (2000), and Cannon (2001) discuss post-burn conditions and debris-flow susceptibility following wildfires.

Debris-Flow Susceptibility of the Basin

Debris-flow susceptibility is related to the erosion and landslide potential of drainage-basin slopes and the volume of erodible sediment stored in drainage-basin channels. Characterizing drainage-basin morphologic parameters, mapping bedrock and surficial geology, and estimating the volume of erodible channel sediment provides information on the likelihood and volume of future debris flows.

Important basin parameters include area, relief, and length and gradient of channels. A description of the types and density of vegetation and land use provides information on the possible effects of wildfire and land use on surface-water runoff and erosion. Small, steep drainage basins are well suited for generating debris flows because of their efficiency in concentrating and accelerating overland surface-water flow.

Both surficial and bedrock geology play a role in the susceptibility of drainage basins to produce flows. Some bedrock weathers rapidly and provides an abundant sediment supply, whereas resistant bedrock supplies sediment at a slower rate. Exposed cliff-forming bedrock greatly increases runoff.

Some bedrock, such as shale, weathers and provides fine-grained clay-rich sediment, whereas other bedrock types provide mostly coarse sediment. The clay content of debris flows directly influences flow properties. Costa (1984) states that small changes (1 to 2%) in clay content in a debris flow can greatly increase mobility due to reduced permeability and increased pore pressure. The presence of silt and clay in a slurry aids in maintaining high pore pressure to enhance the potential flow mobility and runout (Iverson, 2003).

Surficial geologic deposits that influence the sediment supply include (1) colluvium on steep slopes susceptible to forming debris slides, (2) partially detached shallow landslides, (3) foot-slope colluvium filling the drainage basin channel that may contribute sediment by bank erosion and sloughing, and (4) stream-channel alluvium.

Mapping debris slides in a drainage basin and determining their potential to transform into debris flows is important in evaluating debris-flow susceptibility. Most of the 1983-84 debris flows along the Wasatch Front initiated as shallow debris slides in steep colluvial slopes below the retreating snowline (Anderson and others, 1984; Pack, 1985). Aerial-photo analysis can show colluvium on steep slopes and previous debris slides or partially detached debris slides. A literature search of historical debris slides in the area and in areas of similar geology will help to identify debris-slide susceptibility. For example, documented relations exist between debris slides and debris flows in drainage basins in the Precambrian Farmington Canyon Complex of Davis County (Pack, 1985) and in the Tertiary-Cretaceous rocks of the Wasatch Plateau (Lips, 1985).

Drainage basins that experience rapid snowmelt events have an increased debris-flow hazard. Pack (1985), Mathewson and others (1990), and Eblen (1995) determined that in the 1983-84 Davis County debris flows, water infiltration into fractured bedrock aquifers from rapid snowmelt contributed to increased pore-water pressure in steep colluvial slopes that triggered localized colluvial landslides (debris slides) that transformed into debris flows. Santi (1988) suggested that sediment bulking is more likely when passage of a debris flow occurs during periods of stream flow and associated saturated channel sediment, and will result in larger debris-flow volumes.

Wieczorek and others (1983, 1989) used groundwater levels, the presence of partially detached landslide masses, and estimates of channel sediment bulking to evaluate debris-flow potential along the Wasatch Front between Salt Lake City and Willard. Superelevated levees, mud lines, and trim lines along channels are evidence of peak discharge. Measurements from these features are useful in estimating velocity and peak flow (Johnson and Rodine, 1984). Determining the age of vegetation growing on the levees provides a minimum age of past debris-flow activity.

Land use and land-use changes within a drainage basin may also influence debris-flow susceptibility. Land development often creates impervious surfaces that increase the rate and volume of runoff. Development may also remove vegetation and expose soils, promoting erosion, increasing sediment yield, and decreasing natural slope stability within the drainage basin. Debris-flow-hazard evaluation must address development-induced conditions where applicable.

Channel Sediment Bulking and Flow-Volume Estimation

Sediment supply, erosion conditions, and hydrologic conditions of the drainage basin and channel determine the sediment and water concentration (flow type) and flow volume that reaches an alluvial fan. Estimating channel sediment volume available for entrainment or bulking is critical because study of historical debris flows indicates 80 to 90% of the debris-flow volume comes from the channel (Croft, 1967; Santi, 1988; Keaton and Lowe, 1998). Most estimates of potential sediment bulking are based on a unit-volume analysis of erodible sediment stored in the channel, generally expressed in cubic yards per linear foot of channel (Hungr and others, 1984; VanDine, 1985; Williams and Lowe, 1990). The sediment volume stored in individual relatively homogeneous channel reaches is estimated, and then the channel-reach volumes are summed to obtain a total volume. The total channel volume is an upper bound volume and needs to be compared to historical (VanDine, 1996) and mapped alluvial-fan flow volumes to derive a design volume. If easily eroded soils and slopes prone to landsliding are present, then appropriate volumes for landslide and hillslope contributions determined from other drainage-basin landslide volumes should be added to the channel volume.

Estimating a potential sediment-bulking rate requires field inspection of the drainage basin and channels. Measuring cross-channel profiles and estimating the erodible depth of channel sediment is necessary to estimate the sediment volume available for bulking (figure 4). Even though a great deal of geologic judgment may be required to make the volume estimate, this is probably the most reliable and practical method for bedrock-floored channels. The design volume should not be based solely on empirical bulking of specific flood flows (for example, bulking a 100-year flood with sediment) because empirical bulking does not consider shallow landslide-generated debris flows (National Research Council, 1996), channel bedrock reaches with no stored sediment, and the typically longer recurrence period of debris flows. The channel inspection should also provide a description of the character and gradation of sediment and wood debris that could be incorporated into future debris flows.

Hungr and others (1984), VanDine (1985), and Williams and Lowe (1990) use historical flow volumes and channel sediment bulking rates to estimate potential debris-flow volumes. Williams and Lowe (1990), following the 1983 debris flows in Davis County, compared cross-channel profiles of drainages that had discharged historical debris flows with those that had not to estimate the amount of channel sediment bulked by historical flows. They estimated an average bulking rate of 12 cubic yards per linear foot (yd^3/ft) of channel for historical debris flows and used it to estimate flow volumes for drainage basins without historical debris flows, but recommended using this estimate only for perennial streams in Davis County. Bulking rates for intermittent and ephemeral streams are generally lower. For example, Mulvey and Lowe (1992) estimated a bulking rate of 5 yd^3/ft for the 1991 Cameron Cove debris flow in Davis County. Some of the fire-related debris flows at the 2002 Dry Mountain/Santaquin event (McDonald and Giraud, 2002) have estimated bulking rates of 1.5 yd^3/ft of ephemeral channel. Hungr and others (1984), VanDine (1985, 1996), and Williams and Lowe (1990) all concluded that channel length and channel sediment storage are the most important factors in estimating future debris-flow volumes.

Some drainage basins may have recently discharged a debris flow leaving little sediment available in the feed-

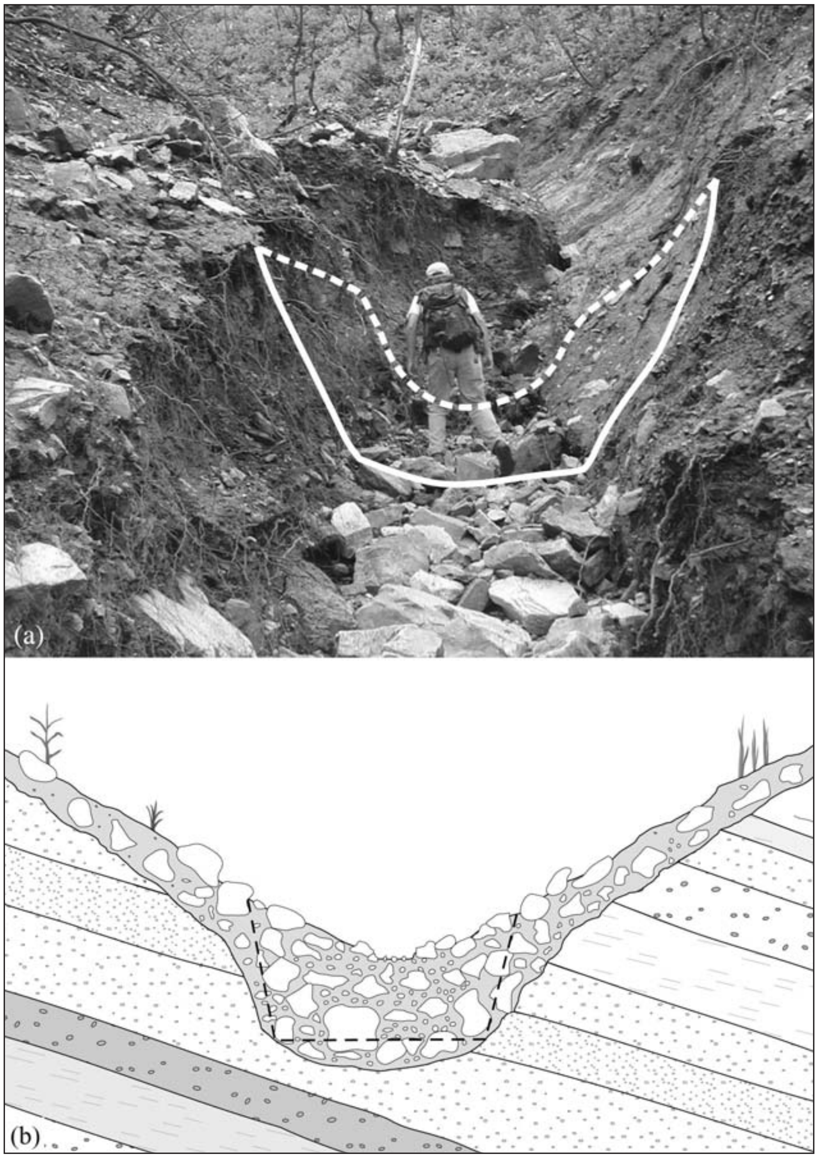

***Figure 4**. Channel sediment and cross section used to estimate sediment volume available for bulking. (a) Channel erosion from the September 10, 2002, fire-related debris flow on Dry Mountain east of Santaquin, Utah. The solid line shows the eroded channel after the debris flow, the dashed line shows the estimated channel prior to debris-flow passage. (b) Sketch of channel cross-section showing stored channel sediment above bedrock. The dashed line shows the estimated upper bound width and depth of channel sediment available for sediment bulking.*

er channel for sediment bulking for future debris flows. Keaton and others (1991) state that channels with recent debris flows will discharge future flows of less volume until the feeder channel has recharged with sediment. In these situations an evaluation must consider remaining channel sediment as well as the rate of sediment recharge to the channel (National Research Council, 1996). The percent of channel length lined by bedrock is a distinct indication of the volume of sediment remaining because sediment cannot be scoured from bedrock reaches. Williams and Lowe (1990) suggest that in Davis County the drainage basins capable of producing future large debris flows are basins that have not discharged historical debris flows. However, drainage basins having a limited debris-flow volume potential due to lack of channel sediment may still have a high stream-flow-flooding potential.

DEBRIS-FLOW-RISK REDUCTION

Eisbacher and Clague (1984), Hungr and others (1987), and VanDine (1996) group debris-flow-risk reduction into two categories: passive and active. Passive methods involve avoiding debris-flow-hazard areas either permanently or at times of imminent danger. Passive methods do not prevent, control, or modify debris flows. Active methods modify the hazard using debris-flow-control structures to prevent or reduce the risk. These debris-flow-control structures require engineering design using appropriate geologic inputs. In terms of development on alluvial fans, active risk-reduction measures with control structures generally attempt to maximize the buildable space and provide a reasonable level of protection.

Hungr and others (1987) and VanDine (1996) divide debris-flow-control structures along lower channel reaches and on alluvial fans into two basic types: open structures (which constrain flow) and closed structures (which contain debris). Examples of open debris-flow-control structures include unconfined deposition areas, impediments to flow (baffles), check dams, lined channels, lateral walls or berms, deflection walls or berms, and terminal walls, berms, or barriers. Examples of closed debris-flow-control structures include debris racks, or other forms of debris-straining structures located in the channel, and debris barriers and associated storage basins with a debris-straining structure (outlet) incorporated into the design.

In Utah, engineered sediment storage basins are the most common type of control structure used to reduce debris-flow risks. These structures generally benefit the community as well as the individual subdivider or landowner, but they are typically expensive, require periodic maintenance and sediment removal, and must often be located in areas not owned or controlled by an individual subdivider. For these reasons, debris-flow- and flood-risk-reduction structures are commonly government public-works or shared public-private responsibilities, rather than solely a subdivider or landowner responsibility. This is particularly true in urban settings where the delineated hazard area may include more than one subdivision and other pre-existing development. In some cases, local flood-control agencies such as Davis County Flood Control manage both debris-flow and stream-flooding hazards.

DESIGN CONSIDERATIONS FOR RISK REDUCTION

The debris-flow hazard at a particular site depends on the site's location on the alluvial fan. Both debris-flow impact and sediment burial are more likely and of greater magnitude in proximal fan areas than in medial and distal fan areas (figure 3). Decisions regarding acceptable risk and appropriate control-structure design involve weighing the probability of occurrence in relation to the consequences of a debris flow and the residual risk level after implementing risk-reduction measures. Therefore, hazard evaluations estimate the likely size, frequency, and depositional area of debris flows on an alluvial fan as accurately as possible.

Considering Frequency in Design

The frequency of past debris flows on an alluvial fan is a fundamental indicator of future debris-flow activity. To address the past frequency of debris flows, detailed geologic studies involving geochronology are generally required. Little or nothing is known about the past frequency of debris flows on most alluvial fans in Utah. Studies by Keaton (1988), Lips (1993), and Mulvey (1993) indicate that large, destructive debris flows on the alluvial fans they studied have return periods of a few hundred to thousands of years. However, return periods vary widely among alluvial fans and few data exist to quantify debris-flow frequency-volume relations. Other difficulties in developing and using probabilistic models in debris-flow-hazard assessment include:

- Frequencies are time-dependent. Many drainages must recharge channel sediment following a large-volume debris flow; the size and probability of future debris flows depend on the size of and time since the last event.

- Statistically based cloudburst storms typically used for stream-flooding evaluations (for example, the 100-year storm) are not applicable to debris-flow models because debris-flow discharges do not relate directly to flood discharges, and in Utah many debris flows are caused by rapid snowmelt rather than cloudburst storms.

- Wildfires and land-use changes in the drainage basin introduce significant uncertainty because they can temporarily greatly increase debris-flow probabilities.

Because of these complexities, generally accepted return periods for design of debris-flow risk-reduction measures based on probabilistic models do not exist, unlike for earthquake ground shaking and flooding, which have established design return periods of 2,500 years (International Building Code) and 100 years (FEMA's National Flood Insurance Program), respectively. Although Keaton (1988) and Keaton and others (1991) developed a probabilistic model for debris flows in Davis County where a relatively complete record of historical debris flows exists, the high degree of irregularity and uncertainty in return periods limited their results and the practical application of their model. In some cases rather than assigning an absolute probability of debris-flow occurrence, many debris-flow practitioners assign a relative probability of occurrence (VanDine, 1996) based on frequencies in similar basins and fans in the geographic areas that have experienced historical debris flows.

The UGS believes Holocene-age (past 10,000 years) debris-flow deposits on an alluvial fan are sufficient evidence to recommend site-specific, debris-flow-hazard studies and appropriate implementation of risk-reduction measures. Holocene deposits were deposited under climatic conditions similar to the present and therefore indicate a current hazard unless geologic and topographic conditions on the alluvial fan have changed. If site-specific data on debris-flow recurrence are sufficient to develop a probabilistic model, then the model may be used in consultation with local government regulators to help determine an appropriate level of risk reduction.

Debris-Flow-Hazard Zones

Debris-flow-hazard zones identify potential impacts and associated risks, help determine appropriate risk-reduction measures, and aid in land-use planning decisions. Hungr and others (1987) outline three debris-flow-hazard zones: (1) a direct impact zone where high-energy flows increase the risk of impact damage due to flow velocity, flow thickness, and the maximum clast size; (2) an indirect impact zone where impact risk is lower, but where damage from sediment burial and debris-flow and water transport is high; and (3) a flood zone potentially exposed to flooding due to channel blockage and water draining from debris deposits. These zones roughly equate to proximal, medial, and distal fan areas, respectively (figure 3). Historical debris-flow records, deposit characteristics, and detailed topography are required to outline these hazard zones. Site-specific studies are required to define which zone applies to a particular site and to determine the most appropriate land use and risk-reduction techniques to employ.

Estimating Geologic Parameters for Engineering Design

Geologic estimates of debris-flow design parameters are necessary for engineering design of risk-reduction structures. The most appropriate data often come from historical or late Holocene debris flows that can be mapped on the fan surface. Flow and deposit characteristics are also necessary to estimate peak discharge and calibrate computer-based hydraulic flow routing models (O'Brien and Julien, 1997).

Geologic parameters required for engineering design vary depending on the risk-reduction structure proposed. Engineering designs for debris-flow risk-reduction structures are site specific (VanDine and others, 1997), and generally involve quantifying specific fan, feeder channel, deposit, and flow parameters. Geomorphic fan parameters include areas of active deposition, surface gradients, surface roughness (channels, levees, lobes), and topography. Feeder channel parameters include channel gradient, channel capacity, and indications of previous flows. Deposit parameters include area, surface gradient, thickness, gradation, and largest clast size. Flow parameters are difficult to determine unless measured immediately after an event, and are often inferred from deposit characteristics or evidence from the feeder channel. The flow parameters include estimates of flow type(s), volume, frequency, depth, velocity, peak discharge, and runout distance.

Debris flows can have significantly higher peak discharge than stream-flow flooding. Estimation of peak discharge is critical because it controls maximum velocity and flow depth, impact forces, ability to overrun protective barriers, and runout distance (Hungr, 2000). VanDine (1996) states that debris-flow discharges can be up to 40 times greater than a 200-year flood, which shows the importance of carefully estimating peak discharge when designing protective structures. Pierson (1985) describes flow composition and dynamics of the 1983 Rudd Canyon debris flow in Davis County, and includes some flow properties typically considered in engineering design. Costa (1984) also lists specific physical properties of debris flows. Keaton (1990) describes field and laboratory methods to predict slurry characteristics based on sedimentology and stratigraphy of alluvial-fan deposits. Flow characteristics are also important to help estimate associated water volume.

Estimating debris-flow volume is necessary where debris storage basins are planned. Because debris-flow behavior is difficult to predict and flows difficult to route, debris storage basins and deflection walls or berms are common methods of debris-flow risk reduction. The routing of debris flows off an alluvial fan is a difficult and complex task. O'Brien and Julien (1997) state that channel conveyance of debris flows off an alluvial fan is not recommended unless the situation is appropriate because there are numerous factors that can cause the flow to plug the conveyance channel. Debris basins typically capture sediment at the drainage mouth before the debris flow travels unpredictably across the alluvial fan. For debris basin capacity, the thickness and area of individual flows on the alluvial fan and erodible channel sediment volumes are needed to estimate design debris volumes. Estimates of sediment stored in channels are usually maximum or "worst-case" volumes that represent an upper volume limit. Channel estimates may exceed the alluvial-fan estimates because typically not all channel sediment is eroded and deposited on the fan, and the channel estimate includes suspended sediment transported off the fan by stream flows. Conversely, the alluvial-fan estimate may exceed the channel estimate if a recent large flow has removed most channel sediment. VanDine (1996) considers the design volume to be the reasonable upper limit of material that will ultimately reach the fan.

Flow volume is also important in modeling runout and deposition. O'Brien and Julien (1997), in their hydraulic modeling of debris-flow runout, emphasize the importance of making conservative estimates of the available volume of sediment in the drainage basin, and comparing that volume to alluvial-fan deposit volumes to determine an appropriate modeling volume.

Geologic design parameters are also needed for the design of other types of engineered risk-reduction structures. For deflection walls and berms or for foundation reinforcement, fan gradient, flow type (debris versus hyperconcentrated versus stream), flow depth, peak flow, flow velocity, and debris size and gradation are important to ensure that the structure has the appropriate height, side slope, and curvature to account for run-up and impact forces. For design of debris barriers, flow volume, depth, deposition area, and gradient are needed to determine the appropriate storage volume. The size and gradation of debris, and the anticipated flow type are important in the design of debris-straining structures. Flow types are important to help estimate associated water volumes. Baldwin and others (1987), VanDine (1996), Deng (1997), and VanDine and others (1997) describe other design considerations for debris-flow-control structures.

Even though geologic evaluations use quantitative and objective procedures, estimating design parameters for risk-reduction structures has practical limits. As stated earlier, historical records of debris flows show flows to be highly variable in terms of size, material properties, and travel and depositional behavior. Many debris-flow design-parameter estimates have high levels of uncertainty and often represent a best approximation of a complex natural process; therefore, appropriate limitations and engineering factors of safety must be incorporated in risk-reduction-structure design. Investigators must clearly state the limitations of the evaluation methods employed and the uncertainties associated with design-parameter estimates.

REPORT GUIDELINES

These guidelines supplement the *Guidelines for Preparing Engineering Geologic Reports in Utah* (Association of Engineering Geologists, Utah Section, 1986) and *Guidelines for Evaluating Landslide Hazards in Utah* (Hylland, 1996) that provide recommendations for engineering geology and landslide reports. The scope of study and techniques used to evaluate debris-flow hazards vary depending on the development proposed and site characteristics. Pertinent data, analysis, conclusions, and recommendations must be documented in a written report. The report must present sufficient information to allow technical reviewers to evaluate the conclusions and recommendations. The following list summarizes essential report information.

1. The scope of the project and intended land use.

2. Reference materials used for evaluation (aerial photographs, maps, and published and unpublished reports), including scale and publication date, where appropriate.

3. A location map (such as part of a 1:24,000-scale U.S. Geological Survey topographic quadrangle map) showing the site relative to surrounding physical features and the drainage basin(s) for the alluvial fan(s) at the site.

4. One or more site maps at a scale suitable for site planning (map scale depends on site and/or development size; recommended site map scale 1 inch = 100 feet) showing proposed development (if known), and topography at an appropriate contour interval.

5. The alluvial-fan evaluation should include:

    (a) site-scale geologic map showing areas of active-fan deposition (generally Holocene-age alluvial fans) and other surficial deposits, including older debris-flow and alluvial-fan deposits and their relative age;

    (b) site-scale location map showing test pits, trenches, natural exposures, stratigraphic sections, and profile(s) of the alluvial fan showing fan gradients;

    (c) test-pit and trench logs (generally at 1 inch = 5 feet) showing descriptions of geologic units, layer thicknesses, maximum grain sizes, and interpretation of flow types;

    (d) basis for design flow-volume estimates (deposit thickness and area estimates); a range of estimates is suggested based on maximum, average, and minimum thickness and area estimates;

    (e) runout distance, spatial extent, thickness, flow type, and deposit characteristics of historical flows, if present;

    (f) deposit age estimates or other evidence used to estimate the frequency of past debris flows; and

    (g) an evaluation of the debris-flow hazard based on anticipated probability of occurrence and volume, flow type, flow depth, deposition area, runout, gradation of debris, flow impact forces, and streamflow inundation and sediment burial depths.

6. The drainage basin and channel evaluation should include:

    (a) vicinity (1:24,000 scale) geologic map on a topographic base of the drainage basin showing bedrock and surficial geology, including shallow landslides (debris slides) and a measurement of drainage-basin morphologic parameters;

    (b) an estimate of the susceptibility of the drainage basin to shallow landsliding, likely landslide volume(s), and volume of historical landslides, if present;

    (c) estimates of the susceptibility of the drainage basin slopes to erosion;

    (d) a longitudinal channel profile, showing gradients from headwaters to the alluvial fan;

    (e) cross-channel profiles and a map showing their locations; and

    (f) basis for channel volume estimates including initial debris slides, total feeder channel length,

length of channel lined by bedrock, cross-channel profiles, and estimated volume of channel sediment available for sediment bulking including estimated bulking rate(s) in cubic yards per linear foot of channel.

7. If risk-reduction designs are considered, the following elements should be included:

   (a) For debris storage basins, both alluvial-fan and channel volume estimates must be compared to select an appropriate design debris volume. For flows that may initiate as debris slides, an appropriate debris-slide volume must be included. Due to uncertainties inherent in both methods, the volume estimates may differ significantly. Rationale for the chosen volume estimate must be provided.

   (b) For debris-flow-deflection structures or debris-flow-resistant construction (reinforcement of foundations, flood-proofing), hydraulic modeling of debris-flow discharge, run-up, and runout and calculation of impact forces is recommended. Specific information on flow type(s), deposit distribution and thickness, flow velocity, peak flow, and runout is necessary to calibrate models.

8. Conclusions regarding the geologic evaluation of the debris-flow hazard should include:

   (a) the probability of debris-flow occurrence (if possible), estimates of debris-flow volume, delineation of hazard areas, and the likely effects of debris flows on the proposed development;

   (b) recommendations for hydrologic, hydraulic, and engineering studies to define buildable and non-buildable areas (if appropriate) and design risk-reduction measures;

   (c) geologic design parameters for debris-flow-control structures, as appropriate; implications of risk-reduction measures on adjacent properties, and need for long-term maintenance; and

   (d) the residual risk to development after risk-reduction measures are in place.

As noted in 8b above, the geologic evaluation is often only the first step in the debris-flow-hazard evaluation and risk-reduction process. Depending on the risk-reduction techniques considered, subsequent hydrologic, hydraulic, and/or engineering studies may be needed to estimate peak flows and water volumes, route sediment, and design control structures. Geologists, hydrologists, and engineers must work as a team to recommend reasonable, appropriate, cost-effective risk-reduction techniques.

Geologic evaluations of debris-flow hazards must be performed by a licensed Utah Professional Geologist. The report must include the geologist's professional stamp and signature. The geologist should be an engineering geologist with at least a B.S. in geology or related field, a minimum of 3 years experience in a responsible position in the field of engineering geology, have experience in debris-flow-hazard evaluation, and must meet minimum qualifications as defined in local government ordinances. A registered Professional Engineer must stamp all studies that include engineering analysis and design.

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