DEBRIS-FLOW HAZARD ANALYSIS AND MITIGATION
An Example From Glenwood Springs, Colorado

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DEPARTMENT OF NATURAL RESOURCES,
STATE OF COLORADO
DENVER, COLORADO

1977

PRICE $4.00

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An Example From Glenwood Springs, Colorado

Prepared under contract to the
Colorado Geological Survey

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DOI: https://doi.org/10.58783/cgs.is08.fgtc1793

COLORADO GEOLOGICAL SURVEY
Department of Natural Resources
State of Colorado
Denver, Colorado

STATE OF COLORADO

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GOVERNOR

JOHN W. ROLD
Director

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The Honorable Richard D. Lamm
Governor of Colorado

Dear Governor Lamm:

During the past several years, the Colorado Geological Survey has become increasingly aware of the potential hazards to Colorado residents from debris flows. These potential hazards became grim reality in the Big Thompson Canyon and Sweetwater Creek areas during 1976 and in the City of Glenwood Springs in July 1977. As part of our continuing efforts to increase the understanding of the interrelationships between geologic processes and land-use problems, we retained Mr. Arthur I. Mears to analyze the Glenwood Springs debris-flow events. In the resulting report he has proposed appropriate mitigation measures for decreasing the future hazard in the affected area. This publication reports Mr. Mears' specific findings for three debris fans that were active July 24, 1977. The debris flows and debris flooding resulted in up to an estimated two million dollars in damages.

The analysis and structural solutions presented herein are specifically addressed to the present conditions of the debris fans. The three debris fans have been greatly altered from their natural state by construction of roads, houses, and an irrigation ditch. The selection, placement, height, and strength of the structural debris catching fences proposed for mitigation of the hazard are related to the present man-modified physical conditions of the debris fans and use of the hazard area. Although this study is site specific, the methods of analysis could be applied to similar hazards in other parts of the State.

Governmental entities having jurisdiction over debris-flow hazard areas must judge on an individual basis what land-use decision would be in the best interest of the health, safety, and welfare of the public. In developed areas with existing high property values, relatively costly structural protection may be the best alternative to acceptance of periodic damage to homes. In this case, restrictions on further development and reconstruction of badly damaged structures may be appropriate as a complementary policy. In undeveloped areas, a wider variety of options is possible. In many cases, avoidance and non-development of such hazardous areas probably will be the least costly and most effective method of hazard reduction. Detailed analysis of the debris-flow hazard may indicate that specific locations on a debris fan are developable with acceptable risk. In such a case, a combination of avoidance, calculated placement of improvements, and structural control may be possible.

This publication recommends solution to an existing unfavorable condition related to housing developments in high-hazard areas of three debris fans. By understanding the geologic processes involved, it is possible to decrease this hazard by structural means. Also, by understanding the processes in this and other areas, similar hazardous situations can be avoided in the future through wise land-use decisions.

Sincerely,

John W. Rold

John W. Rold
Director and State Geologist

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SUMMARY OF REPORT

Debris flow is the most hazardous process affecting development in the three drainage basins discussed in this report. Large volumes of debris lie in relatively unstable positions in each of these basins. Therefore, the debris-flow process will continue to be a persistent hazard in the future.

The average return period of debris-flow events of approximately the magnitude of those that occurred in July 1977, is 50 years; thus a 2-percent chance exists that they will occur in any particular year. When they do occur, debris flows in these basins can be expected to be approximately 5 ft (1.5 m) deep, to transport large boulders on their upper surfaces, to flow at velocities of 10 to 15 ft/sec (3.0 to 4.5 m/sec) on the upper 600 ft (180 m) of the debris fan, and to produce impact pressures on exposed structures of 400 to 900 lbs/ft^2 (19 kPa to 43 kPa).

Because of the physical characteristics and high probability of debris flows in this area, it is strongly recommended that specially designed structures be used to protect property. Two types of structures are recommended--reinforced lower building walls, and structural catching fences on the upper debris fans, above building locations. A preliminary economic analysis suggests that the annual amortized cost of these structures would be substantially less than the present annual cost of the debris-flows to the City of Glenwood Springs.

CHAPTER I. INTRODUCTION

An intense rainstorm on July 24, 1977, produced debris flows and damage to property in the southern part of Glenwood Springs, Colorado. Overall property damage and cost of clean up was estimated to be approximately $2,000,000, primarily to private residences and public facilities. Remarkably, there were no injuries during the flows.

Processes such as those recently observed in Glenwood Springs are variously termed "floods," "mudslides," "mudflows," or "debris flows." The latter term, debris flow, is used in this study because the process involves a viscous, flowing mixture of mud, water, boulders, other granular solids, and organic debris. Although a debris flow contains a far greater volume of solid material than typical flood waters, it does not slide as a rigid body. Thus the term "slide" is incorrect and will not be used. The debris-flow process is not well understood and has rarely been studied in detail. However, it is known that flow dynamics and ability to transport large boulders differ greatly from water floods of similar discharges. Geologists have long been aware that any mitigation methods which treat the process as if it were a flood would probably be ineffective. Some insight into the dynamics of the debris-flow process can be gained from this eyewitness account, as reported in the July 27, 1977, issue of The Free Weekly Newspaper, Glenwood Springs:

> As the rain lessened, several residents who live high on the skirts of Lookout Mountain in southeast Glenwood began hearing rumbling noises.
> Sheriff Ed Hogue, looking up the mountain from his residence near the river, saw a huge wall of mud, flowing down the red dirt mountainside like lava from a volcano. It carried impressive boulders and lifted massive trees out of the ground.

Clearly, protection from future events requires recognition of the differences between debris flows and commonly observed water floods.

Active expansion of Glenwood Springs is taking place on debris fans that have been built by debris flows originating in the many small drainage basins located in the surrounding hills. As more development takes place on these fans the hazard from debris flows will continue to increase roughly in proportion to the number of people living in such areas. Similar problems exist at many other Colorado locations.

The objective of the present study is to research in detail the debris flows from three small drainage basins in the southern part of Glenwood Springs (Figure 1). Specifically, the study is designed to:

1. Relate the volumes of material removed from the basins in the most recent events to the volumes of material remaining in an unstable state in the basins.
2. Evaluate the present hazard potential.
3. Quantify the dynamics of the recent flows in terms of peak velocities and debris discharges.

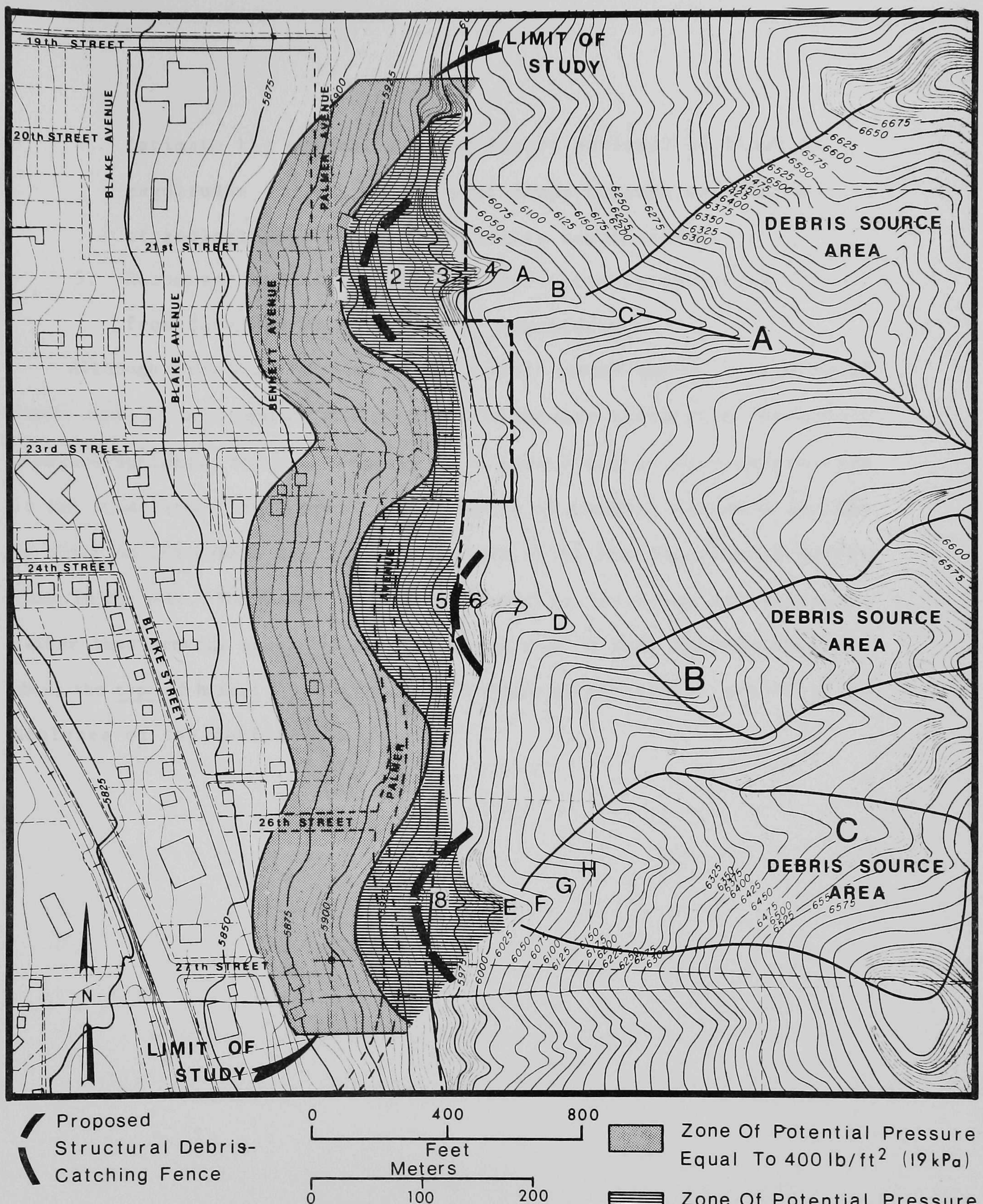

Figure 1. This map of debris-flow drainage basins shows debris source areas (large letters). Boulder-sized-sample localities (numbered), locations used in calculating velocities and discharges (small letters), debris-flow impact-pressure zones, and location of suggested debris-catching structure fences.

4. Estimate the probability (or return periods) of flows of magnitudes similar to the past flows through evaluation of geologic-hydrologic probability combinations.
5. Recommend methods by which property can be protected from future events of similar magnitudes.

Although this study focuses on three small basins and their associated debris fans, it is recognized that the hazard is far more widespread throughout Glenwood Springs. In some locations the hazard may be more severe than in the study area. For example, the majority of downtown Glenwood Springs is built on the debris fan of Cemetery Gulch which has experienced debris flows in the past. The present study provides specific analyses and solutions rather than general ones. It is anticipated that it will increase knowledge about the type of hazard that exists and will encourage additional quantitative analyses of the debris-flow process.

CHAPTER II. DEBRIS-FLOW DRAINAGE BASINS

A. Location of Basins

The three debris-flow drainage basins studied are indicated on Figure 1 and are named Gulch A, Gulch B, and Gulch C. These three basins differ from one another in size, area, and volume of available debris on steep slopes; however, their general characteristics in terms of potential for producing the flows are similar and are discussed below.

B. General Characteristics of Debris-Flow Drainage Basins

Solid material is transported downstream in all drainage basins by running water and other mass-wasting processes. However, progressively smaller and steeper basins often tend to transport solid material by a particular combination of flooding and mass-wasting processes. This combination, as described earlier, is called a debris flow and is often the most important erosion process in small drainage basins. Debris flows are the dominant process in the small basins studied here. In order for debris flows to occur, certain conditions must be met that include (1) sufficient available unconsolidated debris, including soil, rock, and organic material, (2) steep slopes, (3) a sufficiently high clay content in the debris, and (4) a large volume of debris compared with the available water. All of these necessary conditions exist in the basins studied here and are discussed subsequently in greater detail.

Unconsolidated debris is available on slopes within the drainage basins on steep slopes ranging from approximately 25° to 40° thus satisfying conditions (1) and (2). This material is derived primarily from weathering of the Maroon Formation which that is described by Robinson (1975) as a grayish-red to reddish-orange siltstone and silty sandstone and grayish-red, pale red and pale red-purple arkosic sandstone. The weathering of this formation produces a heterogeneous mixture of large blocks of sandstone and clay- and silt-rich soils that lie in metastable** positions on steep slopes and in gullies. During intense precipitation events such as that of July 24, 1977, the metastable equilibrium is upset and the soil, rock, and organic material slides, flows, and avalanches downslope into larger gullies within the basin. These gullies have lesser gradients, usually 15° to 25°, and as a result the debris movement stops momentarily, the central channels become blocked, and flood water from higher in the basins becomes temporarily impounded behind the debris dams. As described in the following chapter, this may result in the formation of debris flows. Additional debris in the basins is derived from weathering of the Eagle Valley Evaporite, a white to medium-gray gypsum and associated greenish-gray claystone, siltstone,

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** Metastable: Refers to a condition of stability which is maintained under only a limited set of conditions and may be easily upset to become an unstable condition.

and sandstone (Robinson, 1975). This formation interfingers with the Maroon Formation but produces a small percentage of the debris in the three basins studied. Small quantities of basalt are also present on the steep slopes. As discussed below, an abundance of debris exists in the basins. These steep, unstable slopes are located in the lower basins below elevations of approximately 6700 ft (2040 m) (Figure 1).

The third necessary condition for debris-flow formation is the presence of clay in the soils. The clay mixes with the debris, and when combined with the necessary amount of water, gives the flows the strength to transport the coarser debris and large rocks down the channels. In this area sufficient quantities of clay are produced from weathering of the Maroon Formation.

The fourth condition required for debris-flow occurrence is the development of the critical ratio of debris to water in the flows. For debris flows to occur, it is necessary that the flows contain approximately 20 to 70 percent water by volume. If a rainfall event produces large volumes of water relative to debris, water flooding will dominate the transport process and solid material will be transported as bedload and suspended load. If, however, the rainfall event causes the production of large volumes of debris compared to water, debris flows will result. The drainage basins studied satisfy this condition for debris flowage because adequate volumes of debris are moved into the channels and transported by runoff waters.

These four conditions are all necessary and are related to the geology of the area. However, they are not sufficient by themselves to produce the debris flow. A sufficient intensity and duration of precipitation is obviously also necessary although unrelated to basin characteristics and geology. The precipitation event helps determine the probability of debris flows and will be discussed in Chapter IV.

C. Relative Susceptibilities of Basins to Future Debris Flows

One of the objectives of this study is to evaluate qualitatively the susceptibilities of the basins to future flows of the types observed in July 1977. For instance, if all or most of the material was removed in the last event, then a basin would not be able to produce debris flows in the future. In contrast, if mass wasting in the basins associated with the last event undermined certain debris areas, they might be even more likely to contribute to future flow. Therefore, to assess drainage-basin susceptibility it is necessary to relate various hydrologic and geologic characteristics of the basins and to compare the amount and position of the remaining debris to the debris removed in this storm.

Each of the basins can be described in terms of its total area and the area of metastable debris. The area of metastable debris is always less than the total basin area (Table 1).

TABLE 1

Basin Name	Total Basin Area (A) [acres(ha)]	Debris Basin Area [acres(ha)]	Debris Basin Gradient [degrees]	Debris Volume (K) [ac-ft(m^3)]	A/K Ratio
A	78 (32)	27 (11)	25-40	270(3.33×10^5)	0.29
B	96 (39)	6 (2.5)	25-40	94(1.16×10^5)	1.02
C	124 (50)	9 (3.5)	25-40	87(1.07×10^5)	1.43

Note: The ratio A/K is an index related to the amount of water runoff available per unit volume of available metastable debris. All A/K ratios here are "small" and suggest (1) a continuing potential for destructive flows, and (2) a tendency for the basins to produce viscous debris flows rather than water floods.

The debris source areas are located in the lower part of each basin. When comparing basins of similar surface infiltration potentials, it is intuitive that the larger basins will tend to produce the greater volumes and discharges (volume/time) of floodwaters. However, unstable debris volume must also be considered when evaluating debris-flow potential or susceptibility. This is considered in column 5 of Table 1 where estimates of the remaining volume of debris are tabulated. Thus, during a given storm Gulch A has less water available to move the available debris than either of the other two basins. As a result of this, Gulch A may remain as a persistent debris-flow source for a longer period of time than either Gulch B or C. All three basins easily contain sufficient debris to produce destructive flows for a very long period of time (Figure 2). In contrast, much larger drainage basins (several mi^2 and larger) will usually have much larger A/K ratios,

Figure 2. Large quantities of unconsolidated debris remain on steep slopes in each of the drainage basins.

suggesting that debris flows are not as common near the downstream ends of the basins.

Debris flows and other mass-transport processes characteristically result in deposits or large quantities of debris in the channels, ranging in size from mud to large boulders. These channel "lag deposits", which have been deposited in each of the three basins studied, are susceptible to remobilization during future events. They also contribute significantly to the future susceptibilities of the basins.

An additional indicator of future basin susceptibility to flows is the ratio of debris removed during the last events to the amount of debris available in the basins. Unfortunately it was not possible to accurately estimate the volume removed during the last storm. Consequently, only a rough estimate can be made by inspection of the basins. However, it does appear that no more than 5 to 10 percent was removed during the July 1977 event; thus 10 to 20 more events of a similar magnitude are possible even if no more unconsolidated debris accumulates on the steep slopes through the weathering and mass-wasting processes.

D. Summary Statement About the Debris-Flow Basins

The presence of typical debris-fan landforms below the basins (the area on which the houses are built) indicates that debris flows have occurred for a long period of time. Study of the basins suggests that the potential for future flows now exists and will continue for an indefinite period of time into the future. Both past and existing indicators show that all three basins are excellent active debris flow source areas. Abundant material rich in both clay and rock is present on steep slopes and only a small percentage of the available material was involved in the recent events. Thus it can be stated with certainty that given the necessary precipitation conditions, debris flows will continue to discharge large volumes of material onto the fans and into the building area.

Construction of structures to control the debris flows could mitigate future damage to existing buildings. Such mitigation would require knowledge about the dynamics of the moving flows so that the sizes and strengths of the mitigating structures can be rationally and economically designed.

CHAPTER III. DEBRIS-FLOW DYNAMICS

A. Formation and Mobilization of the Debris Flows

As discussed in Chapter II, all three basins contain sufficient debris for future events of magnitudes similar to the last one. The formation and movement of the flows require certain combinations of geologic and hydrologic conditions. As a result of detailed field study of each of the three drainage basins, it is thought that the following sequences of events produced the recent flows.

The basins consist of two distinct parts--an upper area of moderate (8° to 20°) surface slopes and light to moderately heavy vegetation; and a lower, steep area (25° to 40°) with much unconsolidated debris and minimal vegetative cover (Figure 1). During intense rain over the entire basin, these two areas respond and contribute differently to the overall basin-erosion process.

The upper basin areas contribute primarily flood waters with some entrained soil, rock, and organic debris. During intense rain, sheet runoff of water is common on the moderate slopes resulting in large discharges of water and fine material into the central channel. In these upper basin areas (above 6600 ft or 2010 m), the process is dominated by impressive water runoff volumes while landslides and other solid-mass movements are uncommon or very localized in nature. The deep, high-velocity water in the upper channels efficiently erodes and transports material (including small rocks), but the ratio of debris volume removed to basin area or to water runoff volume is probably quite small compared to the lower basin area processes.

The lower basins produce the majority of the solid debris that eventually becomes mobilized as flows and is transported to the residential areas. Slopes in the area are steep (25° to 40°) and are nearly devoid of stabilizing vegetation, particularly on south-facing slopes. Rainfall on these slopes quickly saturates, weakens, and removes soil, boulders, and other unconsolidated material and results in intense and rapid erosion, primarily through landslides and debris avalanches. The rain water is incorporated into the debris and, in contrast to the situation on the upper basin, little additional free water is available as runoff. The cascading rock and soil falls into the main channels immediately below the slide and avalanche areas at elevations of roughly 6100 to 6500 ft (1860 to 1980 m) in all three basins. Figure 3 shows a typical debris-avalanche/landslide chute that terminates in the main channel. Debris at some locations in the channels may accumulate to depths exceeding 10 ft (3 m) but because of its initially high strength, probably does not continue to flow down the channel immediately. Therefore, it forms a temporary dam in the channel which stops the water flowing into the channel from above.

Debris flows in these basins begin at elevations of 6100 to 6500 ft (1860 to 1980 m) in the main channels as flood water from the upper basins

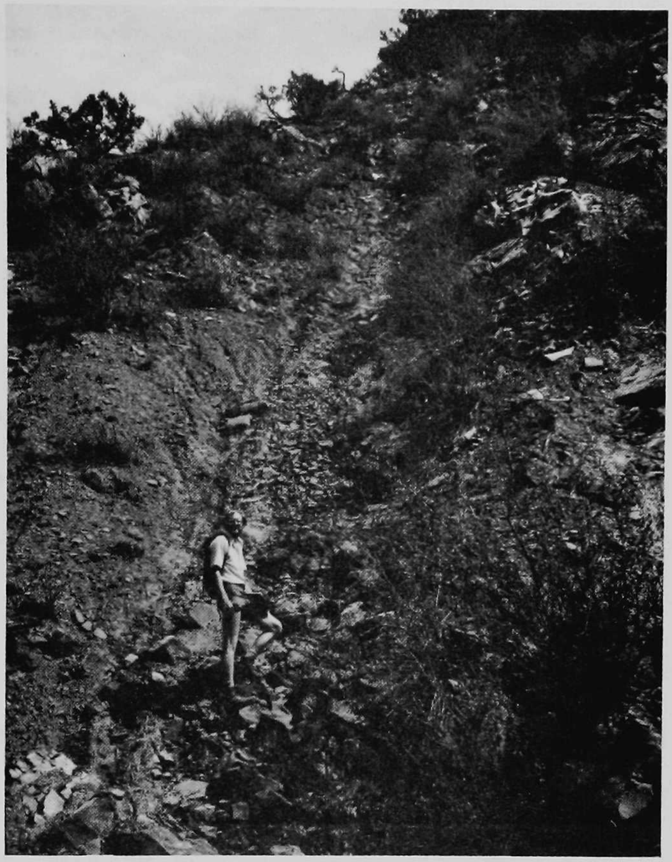


Figure 3. A typical debris-avalanche chute at an elevation of about 6,300 ft (1,920 m) in Gulch A. Areas such as these provided the major source of debris to flood waters in each of the 3 drainage basins.

meets the debris dams formed in the lower channels. The internal shear strength of the debris dams is reduced as flood waters infiltrate the material. This enables the debris dam to flow down the channel as a viscous fluid mass which is mantled with large boulders. Additional solid material can be entrained into the flow through addition of channel lag deposits that normally accumulate in the drainages between major debris-flood events.

This process of avalanching, damming, and debris-flow formation can occur within a basin several times during any particular episode of erosion and can produce several distinct flow surges that may reach the upper debris fan at intervals of several minutes or less. Torrential flood waters will follow the debris surges and cause erosion and random dispersion of material on the fans. The entire process continues until there is insufficient free water available to provide mobility to the flows. Debris-flow surges that become immobile due to loss of water were found in the channels at several locations (Figure 4).

This sequence of events (Figure 5) requires only the conditions described in the previous chapter, all of which are available during an intense rainstorm. Although parts of the upper basins experienced a forest fire in 1976, this probably did not affect the severity of the debris flow significantly. The partially denuded slopes may have increased the runoff rate, but if

Figure 4. A typical debris-flow surge in the main channel. This particular surge evidently lost its lubricating internal water during the waning stages of runoff and stopped in the channel. Note that the largest boulders are transported on top of this flow, approximately 6 ft (1.8 m) above the channel bottom.

Figure 5

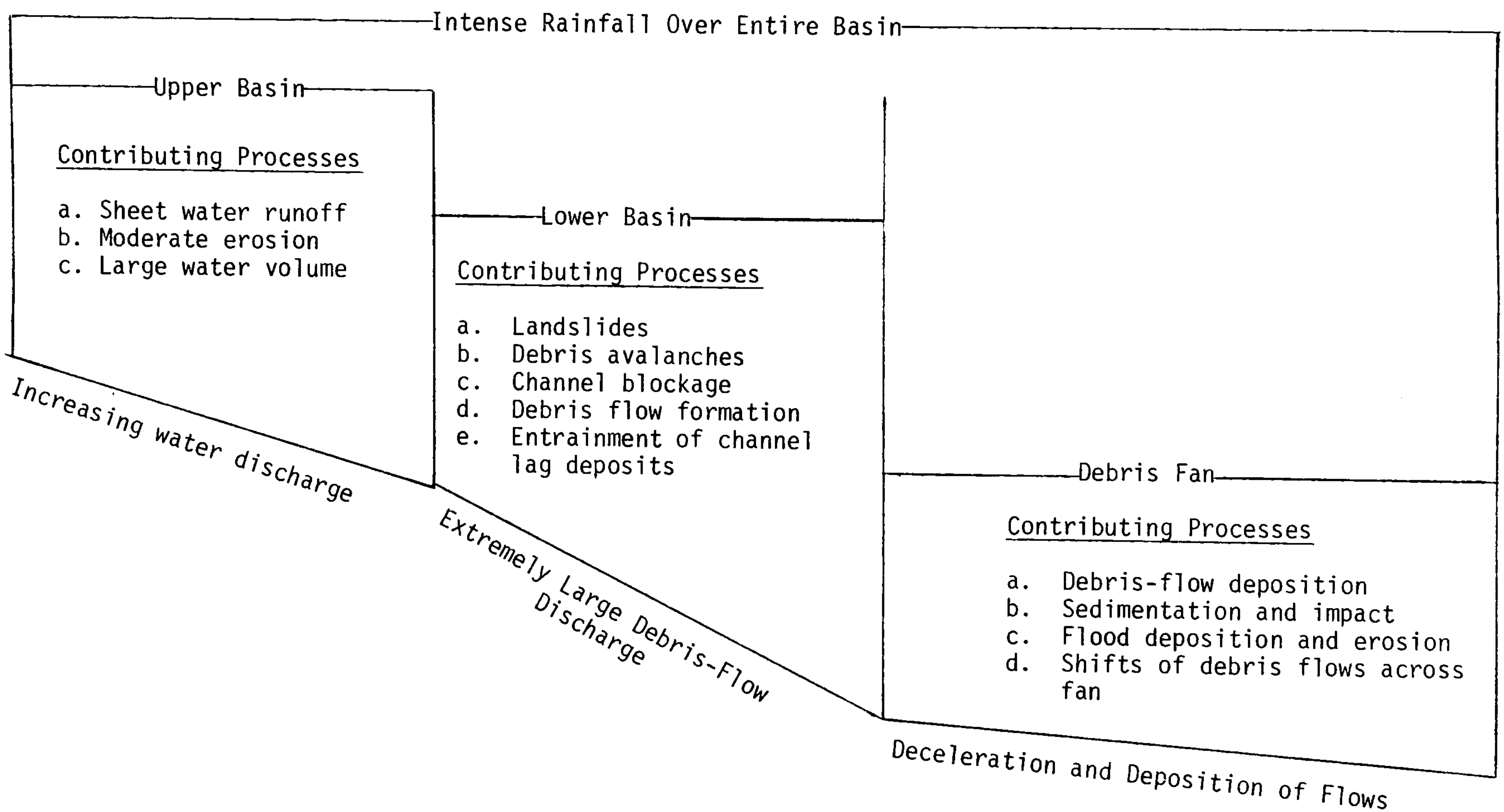


Figure 5 summarizes the discussion of debris-flow formation in the basins studied at Glenwood Springs. Large water volumes from the upper basins meet debris in the lower channels. The debris is then mobilized because of the lubricating effect of the upper flood waters and continues down the channels onto the debris fans as debris-flow surges followed by flood water.

ponding and release of debris dams is a major source of the flows, the events probably would have occurred even if discharge from the upper slopes had been less.

B. The Flow of Debris

Field investigations made shortly after the July 24, 1977, events revealed the following facts that provide significant information about the dynamics of the debris-flow process:

(1) A thick deposit of mud was widespread on the upper fan surfaces.

(2) Boulders of various sizes were imbedded in the mud matrix.

(3) The largest boulders were found near the upper parts of individual debris-flow lobes.

(4) Distinct lateral levees were deposited in channels and on parts of the upper fan surfaces, presumably marking the lateral limits of the flows.

(5) Debris-flow surfaces (as inferred from the positions of levees in channels) were tilted at locations in channels where the debris were forced to flow around curves.

(6) Debris-flow cross-section sizes and shapes could be

accurately measured at many channel locations.

(7) The distinct U-shape of the debris-flow channels was modified by subsequent flood waters that incised a V-shaped notch into the channels.

These features are characteristic of debris flows in general and can be described satisfactorily if the mechanics of the flows are understood. Johnson (1970) proposed a detailed mechanical description of how debris flows move and are able to transport large boulders. He indicates flows are able to transport boulders near their upper surfaces because they possess a finite shear stength as well as the ability to flow as a viscous fluid. Large boulders are often transported near the tops of the debris flows, in contrast to boulder transport in floods which takes place near the bottom of channels (Figure 4). A certain percentage of clay must be present in the mud in order to give the material strength and enable it to transport boulders. In addition, the sizes of boulders transported appear to be limited only by channel size and the available material. Inspection of deposits in the channels and on the fans at Glenwood Springs showed that some boulders weighing 5 to 10 t (4500 to 9000 kg) were transported on or near the upper surfaces of flows more than 5 ft (1.5 m) deep. This particular mode of transport is very important to consider if structural protection from flows is planned because rock impact to a structure could occur several feet above ground level. Regardless of whether a previous channel exists, debris flows can move across unobstructed fan surfaces in almost any direction. This can occur because the flows tend to build their own channels as levee material is deposited at the lateral boundaries of the flows. This process is discussed in detail in the Appendix. Furthermore, a previous flow surge can stop within an existing channel and deflect a succeeding flow to a new direction. As a result, the potential hazard from boulder-laden flows several feet high may be spread randomly over an entire debris fan surface, regardless of man's attempts to channelize the flows. This important point is discussed further in Chapter V.

Debris-flow velocity is an important factor when defense against the flows is considered because it enables rough calculations of the dynamic pressures and discharges. There is very little information about debris-flow velocities reported in the literature, but we have exceptionally good data on the Glenwood Springs flows obtained from eyewitnesses to the events and from calculations.

Mr. Julian Vogt, who observed the muddy, boulder-laden flow near his house on Bennett Avenue, estimated the flow velocity to be approximately 5 mph (8.0 km/hr) or slightly more (7 ft/sec, 2.1 m/sec). His house is located on the unconfined debris fan approximately 500 ft (150 m) below the mouth of Gulch A. The fan gradient at this location is roughly 7°. Flow depth in this area, as inferred from mud marks on trees and buildings (Figure 6) was approximately 5 ft (1.5 m). Mr. Charles Stoddard also observed flows near his house, located on Palmer Avenue, approximately 200 ft (60 m) below the mouth of Gulch B. He estimated flow velocity of roughly 10

Figure 6. The maximum depth of flowing debris, as indicated by distinct mud lines on trees, was about 5 ft (1.5 m)

mph (15 ft/sec) or 16 km/h (4.5 m/sec.). Although this is somewhat greater than the velocity reported by Mr. Vogt, it is to be expected because the property is nearer to the mouth of the channel and the surface gradient in this area is roughly 14°. Flow depth at this location was at least 5 ft (1.5 m). In both locations, large boulders were transported by the flows, as discussed below, although it appears that flood waters which followed each debris-flow surge dispersed the debris and removed some of the finer sediment.

Good correlation with these velocity estimates was made by comparing them to calculations of debris-flow velocities made from data collected in the channels. The calculations were not based on any of the commonly used hydraulic engineering formulas (such as the Manning formula) because such formulas cannot be applied to the flow of debris. Details of the calculation method are given in the Appendix; the results of the calculations at various locations in the channels are given in Table 2.

Although the velocities and discharges given in Table 2 are only approximate, the range reported appears to be reasonably consistent in view of the observations of residents of the area. For example, the average velocity of 16.7 ft/sec (5.0 m/sec) obtained from the three cross sections in the lower 500 ft (150 m) of Gulch A is about twice the velocity estimated by Mr. Vogt near his house. However, a significant decrease in velocity is to be expected as the flow traverses the unconfined debris fan, flows through trees and bushes (Figure 6), crosses an irrigation ditch, and encounters reduced gradients. The velocity of 20.6 ft/sec (6.3 m/sec) in the lower channel of Gulch B compares much more closely with the 15 ft/sec (4.6 m/sec) estimate of velocity near the house. However, in this case the house is located on a steep gradient much closer to the mouth of the gully. Closer agreement, as observed, is to be expected in this case. The velocities reported and calculated here are well within the range of those reported by Campbell (1975) which ranged from 2 to 40 ft/sec (0.6 to 12 m/sec).

Table 2: Debris-Flow Velocities and Discharges

Name	Point	Velocity ft/sec (m/sec)	Discharge cfs (m^3/sec)
Gulch A	A	13.1 (4.0)	643 (18.2)
	B	16.0 (4.9)	1167 (33.0)
	C	21.1 (6.4)	1285 (36.4)
Gulch B	D	20.6 (6.3)	1653 (46.8)
Gulch C	E	17.8 (5.4)	1640 (46.4)
	F	22.9 (7.0)	1580 (44.7)
	G	24.4 (7.4)	1990 (56.4)

Note: Reference points refer to those shown on Figure 1.

The discharges given in Table 2 represent instantaneous peak discharges of debris in channels at the fronts of the flow surges. The individual discharge peaks probably lasted considerably less than one minute, perhaps only 10 to 20 seconds. The discharges of debris, although of short duration, exceed flood-water discharges from the larger upper basins by a factor of 3 to 5, even though the upper basins constitute 65 to 93 percent of the total basin areas (Table 1). For comparison to the debris flow discharges of Table 2, water discharges were calculated at the points where the larger upper basins discharge into the smaller lower basins using high water marks and the Manning equation. The water discharges were only 250 to 400 cfs (7.1 to 11.3 m^3/sec) and are approximately equal to what would be calculated for these basins during a "100-year storm" using standard storm discharge methods (such as that used presently by the Soil Conservation Service). This <u>is not</u> meant to imply that the hydrologic methods are inaccurate or provide misleading results when applied to flood runoff. However, it does suggest that the debris-discharge process, as discussed in Section A of this chapter, can magnify the peak discharge temporarily through damming and addition of solid material.

Boulder transport by the debris flows was also studied in detail because it gives a general indication of the destructive potential of the flows. To determine quantitatively the boulder transport capabilities of the flows, the 10 largest boulders were measured at 8 different locations on the debris fan, within 300 ft (90 m) of the buildings reached by the flows. Details of the sampling method are discussed in the Appendix. The mean boulder weights at each sample site and the mean weights associated with each drainage basin are given in Table 3. Note that the boulder weights do not decrease with distance down the fan in Gulches A and B (only one location was sampled below Gulch C). This lack of sorting with distance from a gully is to be expected of debris-flow transport. In contrast, the sizes of boulders moved much lower on the fan (toward the Roaring Fork River) by flood water did appear to decrease with distance from the mouths of the gullies. However, no quantitative data on boulder transport in this area was obtained because subsequent clean-up work had removed much of the debris.

Table 3: Mean Weights of Boulders Moved by the Debris Flows

Name	Point	Weight lb (kg)	Mean Weight lb (kg)
Gulch A	1	2450 (1110)	
	2	3150 (1430)	1990 (900)
	3	1610 (730)	
	4	750 (340)	
Gulch B	5	1610 (730)	
	6	7280 (3300)	4760 (2160)
	7	5400 (2450)	
Gulch C	8	2450 (1110)	2450 (1110)

Note: Locations of numbered reference points are indicated on Figure 1.

The differences in the average boulder weights associated with each drainage basin appear to be related to the sizes of boulders weathered from bedrock outcrops in the drainage basins. Figure 2 illustrates the sizes of boulders available for future flows in a typical basin location.

CHAPTER IV DEBRIS-FLOW PROBABILITY

A. Hydro-Geologic Probability Relationships

Regardless of the destructive potential and areal extent of any debris-flow or flood event, the event does not necessarily constitute a significant hazard unless the probability that people are exposed to it is sufficiently high. Flows reaching a developed area an average of once in 1000 years would probably not be considered especially hazardous, whereas flows reaching the same area once very 100 years or less should be considered a significant hazard. Therefore, in order to evaluate the hazard and make recommendations about land use and mitigation, it is necessary to estimate the annual probability (or return period) of debris flows similar in size to those recently observed.

A reciprocal relationship exists between annual probability, P, and return period, T, such that P equals 1/T. The return period is merely a statement of probability and implies nothing about the actual distribution of debris-flow events through time. The fact that an event has just occurred does not reduce the probability that it will occur again soon. In order for this to be true it is necessary for a drainage basin to be susceptible to flows, as discussed in Chapter II.

Because the drainage basins are susceptible to future flows, it can be assumed that a rainstorm of the intensity and duration of that which occurred on July 24, 1977 would also trigger future flows. In this particular case the probability of debris flows is the same or greater than the probability of the rainstorm event. Debris flow probability may be greater because a rainstorm of lesser intensity (and greater probability) may also be capable of triggering future events of approximately the same magnitude.

A first objective, therefore, in determining the debris-flow probability, or fixing a lower limit to the probability, is to estimate the return period of the rainstorm.

B. The July 24, 1977, Rainstorm

The rainfall measured at the National Oceanic and Atmospheric Administration (NOAA) weather station in Glenwood Springs during the several days preceding and including the debris flows is given in Table 4.

Table 4

Date	Rain in Inches (mm)
July 18	0.02 (0.51)
July 19	0.00 (0.00)
July 20	0.00 (0.00)
July 21	0.24 (6.10)
July 22	0.15 (3.80)
July 23	0.00 (0.00)
July 24	1.08 (27.4)

Sufficient rainfall occurred during the three days preceding the flows to wet although probably not saturate, the soil.

It is of more significance that 0.85 in. (21.6mm) of the July 24 rainfall came in about a half hour at the weather station. Rainfall intensities and amounts in the basins are not known, but judging from the comments of observers in the area, rainfall was of a magnitude similar to that recorded in town. In view of the lack of data in the basins it will be assumed that rainfall intensity there was 0.75 to 1.00 in. (19 to 25 mm) during the half hour period.

C. Rainfall and Debris-Flow Probability

According to statistical analysis of NOAA rainfall data, the maximum 1-hour period rainfall to be expected in any given 100-year period at Glenwood Springs is 1.58 in. (40.1 mm). The precipitation intensity observed during the recent storm appears representative of approximately a 100-year return period. Therefore, the debris flows, in accordance with the discussion of section A of this chapter, probably have a return period of 100 years or less.

Interviews with staff members of the Colorado Geological Survey and local residents revealed that flows occurred here 30 to 40 years ago (the exact date is in question). Thus the flows apparently have recurred in considerably less than a century. Subsequently it will be assumed that the flows have a return period of 50 years (annual probability of 2 percent).

CHAPTER V. PROTECTION OF BUILDINGS AND PROPERTY

A. Introduction

As discussed in this report, the debris flows in Glenwood Springs are of a sufficient magnitude and probability to warrant structural protection of buildings and property. This chapter discusses some specific defense measures that could be used below the three drainage basins studied. However the defenses recommended here cannot be applied in blanket fashion to other areas within the town. Because other basins may produce flows or floods with entirely different characteristics, the specific defenses recommended in this study are not applicable and could even increase the hazard severity if applied in these other areas.

I do not believe the defenses recommended can provide complete protection because future flows may differ somewhat from those recently observed. However, if the recommendations are carefully applied they should result in a structural defense system which will greatly reduce the potential damage from future flows and can help in restoring peace of mind to residents in areas exposed to the hazard.

B. General Considerations

The recommendations contained in this chapter consider the mechanical properties and dynamics of debris flows as discussed in detail in Chapter III. Summarizing this information, the factors which must be considered when recommending defenses are:

(1) Several distinct flow surges are possible and may occur in rapid succession in a drainage basin during a single event.

(2) The flows may be several feet deep and often carry large boulders on or near their tops.

(3) A debris-flow surge will not necessarily maintain a uniform velocity. Instead, velocity can be expected to fluctuate quickly in the channel or on the debris fan in response to water content changes, terrain variability, and additional pressure from behind.

(4) A debris flow surge <u>will not necessarily spread laterally</u> like a flood, even on the unconfined surface of a debris fan. Instead, it can remain confined within a channel it builds as it flows across a fan, thus maintaining great flow depth.

(5) Closely spaced trees are quite effective in stopping boulders and large rocks on debris fans (see Figure 7).

(6) Debris flow surges are often followed by muddy, debris-laden flood waters. These waters can erode and redistribute the debris but probably will not cause impact forces as large as the debris flows.

Because of these characteristics, strict channelization of the flows cannot be recommended as a mitigation method. Such channels can quickly become blocked, as illustrated in Figure 4, causing subsequent surges to flow in new directions. This occurred in a small debris flow basin on the west side of the Roaring Fork River during the July 24 storm. A flow surge blocked the existing channel and advanced in a new direction. Channelization of water runoff is necessary as part of the overall drainage plan in the area but will prove ineffective without additional structural control.

Two types of control are discussed below. These are direct protection for buildings against debris impact, and arresting and breaking structures which will lessen the hazard to both buildings and surrounding property.

C. Direct Protection Against Impact

Very little structural damage from debris impact to structures occurred during the recent flows, even though moderate to large boulders were pushed (presumably quite slowly) against buildings. However, it must be stressed that this will not necessarily be the behavior of future flows.

As mentioned earlier, debris-flow velocity can fluctuate greatly on the fan. During the last events the velocities at the buildings at the instant of impact evidently were fairly small. This may have been true for several reasons including (1) varying water content within the flows, (2) dispersal of flows by flood waters so that the actual debris flows did not come into contact with the buildings, (3) deposition of mud and fine-grained material against buildings just prior to arrival of large boulders, thereby providing a "cushion" effect, or (4) deflection of debris-flow surges by previously deposited debris lobes. However, none of of these factors can be depended upon to randomly combine in such a way that damage from future flows will be avoided. It was simply fortunate that it happened this way the last time. Significant dynamic pressures against buildings from debris flows must be anticipated in the future.

The magnitude of the dynamic pressure that should be designed for depends on the unit weight of the flowing debris and the flow velocity. It is assumed that the flow unit weight is 125 lbs/ft^3 (2 gm/cm^3) which is characteristic of some measured flows; however, as discussed earlier, velocity varies over the channel and fan. It can be safely assumed that the velocity decreases with distance from the mouths of the channels. Calculations in the channels and eyewitness reports suggest that it is reasonable to assume a design velocity of 15 ft/sec (4.5 m/sec) for the

Figure 7. Closely spaced trees were quite effective in stopping boulders on the debris fan.

first 300 ft (90 m) below the channels, and a velocity of 10 ft/sec (3.0 m/sec) for the next 300 ft (90 m) (Figure 1). To be safe, buildings within this 600-foot-wide (180-meter-wide) area should be designed specially for debris impact as follows:

(1) Uphill walls of all new buildings located within 600 ft (180 m) of gully mouths should be reinforced to a height of 6 ft (1.8 m) above ground level. Windows and doors within this reinforced section should also be reinforced.

(2) Design-load requirements for the reinforced parts of buildings are a) 900 lbs/ft^2 (43 kPa) over the entire wall area for buildings located within the upper 300 ft (90 m), and b) 400 lbs/ft (19 kPa) over the entire wall area for buildings located 300 to 600 ft (90 to 180 m) from the gullies.

This is the minimum that should be done for debris-flow protection in this area. It is recommended that this be required for any new buildings and be encouraged as modifications to old structures, if possible.

Although reinforced building walls will protect buildings and occupants who are inside when the flows occur, they do nothing to protect landscaping. For property protection the flows must be altered before the residential area is reached.

D. Arresting and Separating the Solid Debris Mass

Debris flows can be made relatively ineffective and harmless if the large boulders and other solid material can be stopped and separated from the flows. As indicated on Figures 6 and 7, closely spaced trees worked quite effectively in stopping some of the larger boulders before they reached the building area. Unfortunately, trees provide only localized protection on the fans.

It is recommended that a structural catching fence, possibly constructed as a combination of steel and reinforced concrete, be built above the irrigation ditch to stop the large boulders (Figure 8). Structures similar to the one proposed are often used in the Austrian Alps to protect populated areas against debris flows and floods. Vertical members in the structure should be spaced 1.5 ft (0.5 m) apart, thereby allowing passage of smaller boulders while retaining the larger ones. The fences should be designed for a dynamic load of 900 lbs/ft^2 (43 kPa) over the entire surface.

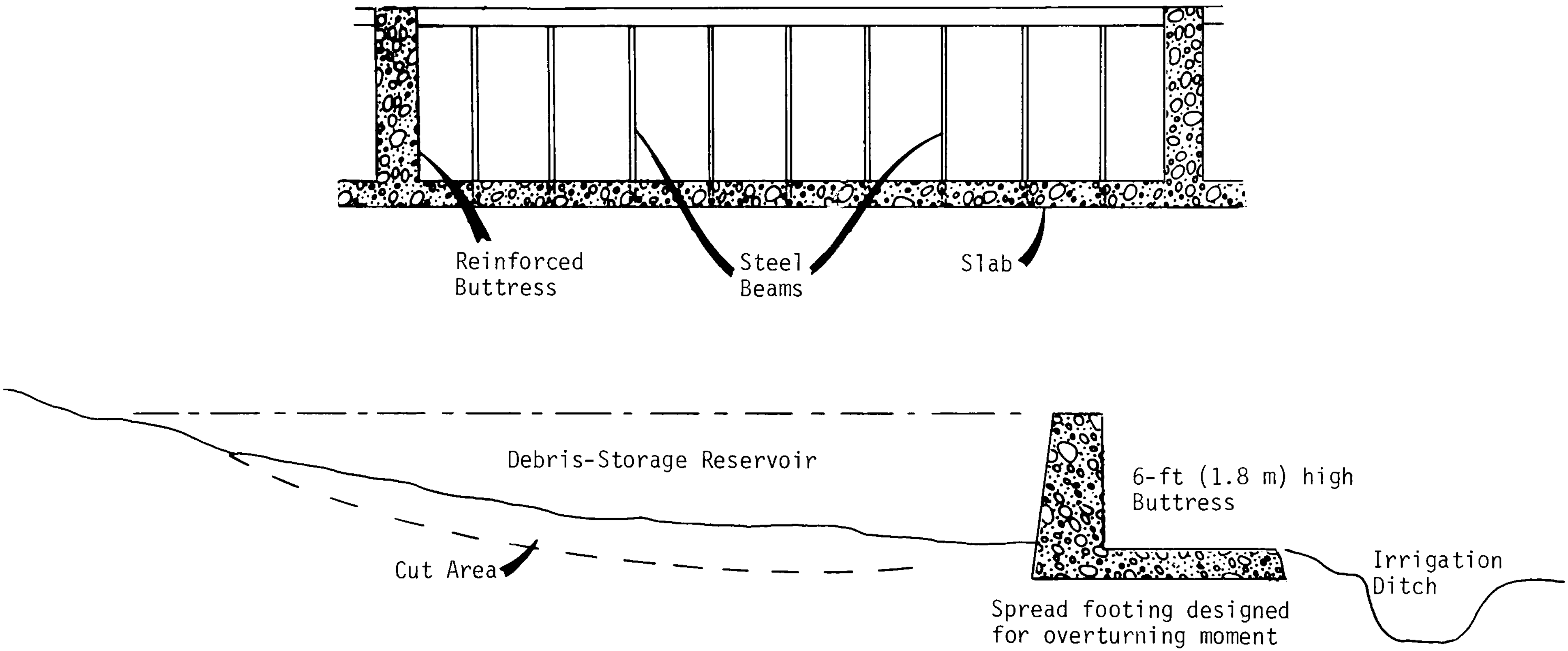
Flood water following each debris flow surge will tend to flush some of the finer material and rocks through the fence and into flood drainage channels below the structure. However, the integrity of the debris flow will be broken and it will no longer have the ability to flow randomly over the fan surface.

Obvious problems exist with catching and arresting fences. In order

Figure 8

Structural Defense for Arresting and Separating Debris Flows
(Diagrammatic Sketch)

Fence 6-8 ft (1.8-2.4 m) high with vertical bars 18 in. (50 cm) apart



Effect: Large boulders and debris are stopped; smaller material and mud is washed through and over structure and continues as a debris flood rather than as a debris flow.

to remain effective they must be carefully cleaned of their boulder load after each event. Therefore, access must be provided to the debris-catchment area. In addition, it may prove difficult to design a foundation that will satisfy the load requirements. Careful study of the bearing capacity of soil must be made to insure safe construction. Finally, there is and will always remain the possibility that the catching reservoir will fill and flows will spill over the top. Even if this does happen the total amount of debris reaching residential areas will be greatly reduced and the chance that a flow surge will reach a building will also be reduced.

In order to be safe it is recommended that both direct protection and arresting structures be used in this area, and that both be combined with a storm drainage plan to convey the associated flood waters. It is also recommended that trees be planted on both the uphill and downhill sides of the catching fence. This should tend to make the structure more visually acceptable and will also assist in the interception of debris.

E. Economic Considerations

Estimates of the total cost of damages and clean-up of the recent flows are as great as $2,000,000. Using this figure and assuming the annual probability of flows of this magnitude is 2 percent, then the average annual cost to the City of Glenwood Springs and its residents can be calculated simply as ($2,000,000.) times (0.02) or $40,000. This is the annual cost of "doing nothing," cleaning debris as it is deposited, and repairing property. This cost could be substantially reduced, perhaps by 90 percent or more, if the recommended defenses are built.

As a very rough estimate, the catching fences would cost no more than $100,000. This initial cost, amortized over a 25-year period at 9 percent is equivalent to an annual cost of $10,180 for 25 years. After this time the annual cost would consist only of cleaning and maintenance which would be neglibible compared to the construction cost. Based upon these very rough calculations, it appears that the most economical decision would be to construct defense facilities.

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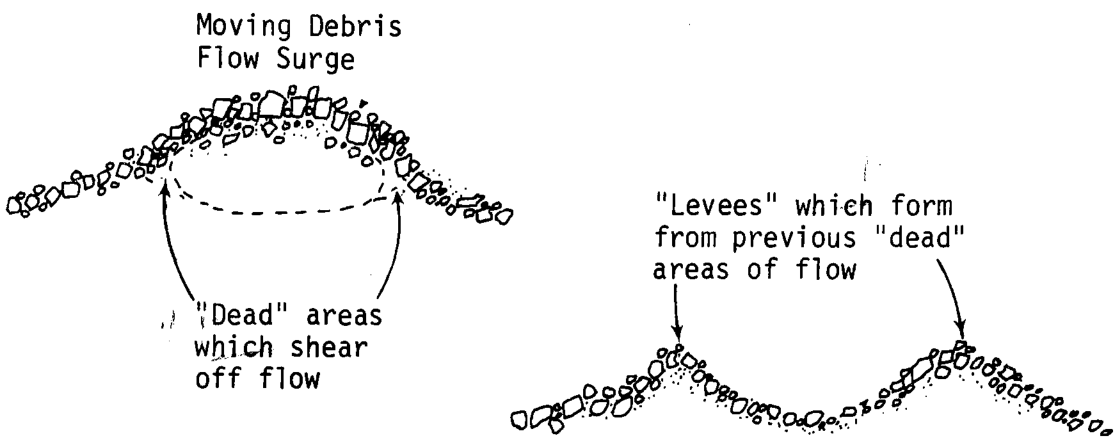
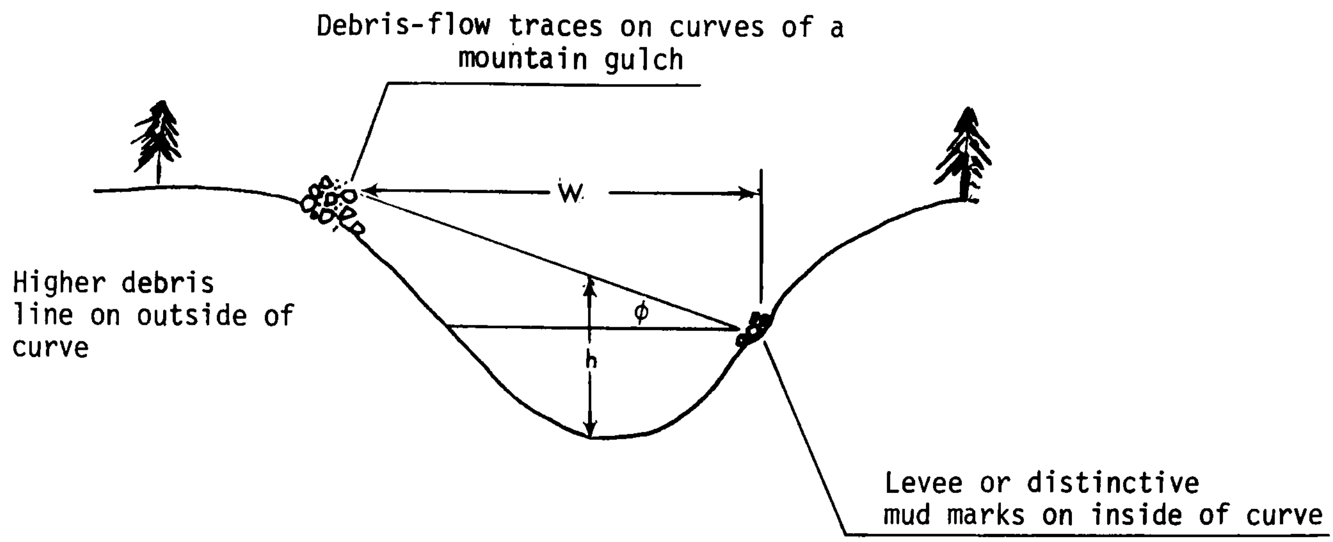
APPENDIX

1. Flow and Deposition of Debris on a Debris Fan



A debris flow efficiently transports debris and large boulders on an unconfined fan by forming its own channel. Lateral areas on the sides of the flow confine the moving mass and are sheared from it as the flow passes, leaving distinctive lateral levees that are often studded with boulders. Therefore, these channels should not be considered strictly as erosional features, but are actually intermediate regions between two depositional features.

2. Velocity and Discharge Calculations in Channels Above the Fan



Debris-flow velocity, V, and discharge, Q, were calculated by measuring the amount of "tilt," ϕ, of the flow as it flowed around a curve in a channel of radius of curvature R. Velocity was calculated as

$$V = \sqrt{gR \tan \phi} ,$$

where g is the gravitational acceleration. Discharge was calculated as

$$Q = A \frac{V}{2} \left(1 + \frac{R - W}{R}\right),$$

where the parabolic cross-section area, A equals $\frac{2}{3}Wh$.

3. Sampling of the Weights of Boulders Carried by the Flows

Boulder weights were estimated by an approximate but uniform method applied throughout the depositional areas sampled. A site included an area of roughly 1000 ft^2 or somewhat less particularly if the site was the front of a flow surge. On each site the 10 largest boulders were measured by determining the intermediate diameters, I, of each. The volumes of the boulders were estimated by assuming volume equal to I^3. Weight was estimated by multiplying the volume by 168 lbs/ft^3, the approximate unit weight of the rock.

The boulder weights tabulated at each sample site in Table 3 represent the mean value at each site, not the maximum value. Mean values were used to reduce the probability that the largest values measured and used in calculations were from boulders not actually moved by the recent flows.

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