UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Potential for debris flow and debris flood along the Wasatch Front between Salt Lake City and Willard, Utah, and measures for their mitigation

by

Gerald F. Wieczorek, Stephen Ellen, Elliott W. Lips, and Susan H. Cannon
U.S. Geological Survey
Menlo Park, California

and

Dan N. Short
Los Angeles County Flood Control District
Los Angeles, California

with assistance from personnel of the
U.S. Forest Service

Open-File Report 83-635
1983

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

Contents

Illustrations

Tables

(Illustrations and table follow report text.)

INTRODUCTION

Purpose, Scope, and Level of Confidence

In late May and June of 1983, rapid snowmelt in the Wasatch Range induced numerous debris flows and debris floods that impacted populated areas near the mouths of canyons between Salt Lake City and Willard. These debris flows and debris floods resulted from landslides on steep hillslopes along the canyons. A number of landslides shifted, as evidenced by scarps and cracks having small offset, but did not mobilize to flow downslope into the canyon bottoms. These landslides, herein called partly-detached landslides, remain perched in metastable condition. The purpose of this study is to evaluate the potential for these partly-detached landslides to generate debris flows and resulting debris floods that travel to the canyon mouths. We evaluate this potential for the near future, that is, at least until the end of the summer cloudburst season and through the subsequent winter and spring thaw. We also discuss the recurrent long-term potential for these processes. We then discuss means of mitigating the hazards caused by these processes beyond the canyon mouths.

This report constitutes a preliminary appraisal of the potential for debris flows and debris floods and of the measures appropriate to mitigate hazards posed by these processes. Our appraisal is based on approximately one week of reconnaissance investigation by our team, in addition to earlier observations and measurements by other investigators. Because we were not granted time for careful and systematic study, and because recent aerial photographs essential to our investigation covered only small portions of the area, our appraisal varies in quality from place to place. The resulting differences in our level of confidence are shown in Figure 1, but throughout the area we have low confidence in our appraisal of small range-front canyons and draws, such as those shown by symbol on Plate 1, because we focused on the larger canyons. We recommend methods for more accurate evaluation of potential and mitigation measures later in the report.

Historical Setting

Recurrent offset along the Wasatch fault during geologic time has produced elevation differences across the Wasatch Front that have generated especially active erosional processes, including debris flows and debris floods. The geologically-recent products of these processes are the fans and other Quaternary canyon-mouth deposits along the Wasatch Front, such as mapped by Miller (1980). Historic records, particularly from the early 1900's, document many debris flows and debris floods from these canyons (especially Croft, 1967, 1981; and Woolley, 1946). The impact of these processes during the 1920's and 30's prompted the establishment of the Davis County Experimental Watershed and the consequent construction of extensive erosion-control measures in the headwaters of many canyons and mitigation structures near canyon mouths. When seen in this historic context, the debris flows and debris floods of the past months are only one episode in a long history of similar phenomena.

Conditions and Events of This Spring

The debris flows and debris floods of May and June of this year were triggered by abnormal snowfall and weather conditions. Six such conditions have been recognized by Marsell (1971) as contributing to the flooding that accompanied snowmelt during 1922 and 1952 along the Wasatch Front. These are: (1) heavy winter snowpack; (2) saturated soil mantle at the start of winter resulting from heavy, late-autumn rains; (3) low temperatures during late winter and early spring, permitting retention of the deep snow cover on the low watersheds; (4) sustained high temperatures once melting started; (5) additional precipitation, especially warm rain, which increased the rate of melting; (6) streams within a drainage basin reaching peak flow simultaneously. These conditions were generally observed this year along the Wasatch Front. Snow depth at 8,000 feet elevation in Farmington Canyon (upper-snow sensor station) had a water equivalent of 51.8 inches on 5/27/83, compared with a mean of 12.4 inches (about 400% of normal) (U.S. Department of Agriculture, June, 1983). Snowline receded rapidly from mid-May through June because of an extended period of exceptionally warm temperatures; snowline on 5/27 was at approximately 6,500 feet elevation along the Wasatch Front in Davis County and by 6/19 had receded to approximately 7,900 feet elevation (Thom Heller, U.S. Forest Service, oral commun., 1983).

According to Heller, most landslides that mobilized into debris flows occurred in the recently-thawed zone near snowline, even before the major debris flows and debris floods of Memorial Day. Following Memorial Day, Paul Winkelaar of the U.S. Forest Service and Bruce Kaliser of the Utah Geologic and Mineral Survey followed the initiation of debris flows, observing that debris flows generally mobilized near the receding snow line. As late as our reconnaissance in late June, we observed small debris flows near the snow line.

Most of the landslides that mobilized as debris flows occurred in areas underlain by bedrock of the Farmington Canyon complex. The gneiss and schist that constitute most of this unit weather deeply into coarse-grained granular soils overlying decomposed weathered bedrock that includes zones of clayey material. Large old landslides have been recognized in ground underlain by this unit (Olsen, 1981). The landslides that mobilized as debris flows failed either at the base of the granular soil or within the weathered bedrock.

THE PROCESSES OF DEBRIS FLOW AND DEBRIS FLOOD

Abundant coarse-grained sediment can be transported and deposited by two processes, debris flow (Varnes, 1978) and debris flood [1]. Both processes commonly occur during periods of rapid addition of water to the landscape, either by rainfall or snowmelt. In debris flow, water and soil materials including rocks combine to form a muddy slurry much like wet concrete, considerably more viscous than flowing water, that moves down-canyon with a front armored with coarse-grained materials such as boulders (Fig. 2). Debris flows may leave levees along the edges of the flow that indicate the lateral and vertical dimensions of the flow front. In debris flood, soil materials with a greater relative proportion of water are transported by fast-moving flood waters. Deposits formed by debris flood can be distinguished from those of debris flow by the greater degree of sorting that generally characterizes water-borne deposits (Fig. 3A). Debris flow deposits, in contrast, are characteristically poorly sorted, showing rock fragments suspended randomly in poorly sorted matrix typically consisting of silty sand with a small but significant content of clay (Fig. 3B). Debris flow and debris flood may well form a continuum; as water content of a debris flow is increased, its plastic strength decreases abruptly and its viscosity approaches that of flowing water with entrained sediment.

---

[1] In the technical literature, debris floods are also referred to by a number of other terms, including waterflood with large sediment load (Costa and Jarrett, 1981), sediment flow (Ikeya, 1981) and mud flood (NRC, 1982).

Debris flows apparently can form in at least two fundamentally different ways. Where cloudbursts are common, as along the Wasatch Front, overland flow and flood waters can scour materials from the ground surface and from the channel, thereby increasing the proportion of soil materials to water until debris flood becomes debris flow. Alternatively debris flows can mobilize directly from shallow landslides in which the water content has increased sufficiently to permit flow (Fig. 4). Similarly, debris floods can originate either by progressive incorporation of materials by flood waters or by dilution of debris flows (Fig. 4).

Both debris flows and debris floods contributed to the damage in the area between Salt Lake City and Willard this spring. All of the observed debris flows originated directly from landslides, most from high on the hillslopes; some, such as at Rudd Creek, incorporated significant amounts of material in their passage down channels. Many of the debris flows came to rest before reaching the bottoms of major canyons. Other debris flows reached the canyon bottom but proceeded only short distances down-canyon, contributing material to debris floods that proceeded beyond canyon mouths. A few debris flows, such as those at Ward and Coldwater Canyons, traveled to canyon mouths (but not far beyond) where they deposited. Only at Rudd and Facer Canyons did debris flows clearly deposit beyond canyon mouths. In cases where debris flows did not reach canyon mouths, it is clear that they contributed directly to the debris that caused damage; only those canyons having landslide scars produced significant debris, and significant channel modification could be traced directly to debris-flow scars.

POTENTIAL FOR DEBRIS FLOW AND DEBRIS FLOOD

Method Used For Evaluation

We conceive the potential for debris flow and debris flood in the area as consisting of both an immediate short-term potential remaining from the events of this spring, and a recurrent long-term potential that is documented by an extensive history of debris flows and debris floods.

Short-term potential

The rapid snowmelt of this spring has influenced the present potential for debris flows and debris floods in two principal ways: it has left high ground-water levels in the hillsides, and it has left landslide masses, partly-detached but not as yet mobilized as debris flows, perched on the hillsides. Both of these effects appear to increase the potential for further landslide movement that can lead to debris flows and debris floods.

Ground-water levels

High ground-water levels are known to decrease the stability of hillslopes and hence to drive landslide movement. The present ground-water levels are generally lower than at the time of rapid snowmelt, but they probably are higher than common for this time of year. Hence the likelihood is above average that ground-water levels could be increased to critical values by a summer cloudburst, resulting in the movement of landslides that may subsequently mobilize as debris flows.

Our knowledge of ground-water levels comes from piezometers installed and monitored by a team from Utah State University at Logan, supervised by Prof. Roland Jeppson and led by graduate student Robert Pack. Their measurements at the time of this writing indicate that water levels in general are declining but that levels in and near some landslides remain high. Because the piezometers have only recently been installed, we have no knowledge of water levels in years of more normal climatic conditions. Based on this limited information, we anticipate further gradual decline of water levels in hillsides of the area so long as significant rainfall does not occur. Heavy rainfall, however, has the potential of quickly raising water levels to critical values in at least some areas, especially if such rainfall occurs before drainage from near-surface materials has lowered water levels to more normal values.

Partly-detached Landslides

Limited movement of shallow materials during and after snowmelt has left a number of landslide masses, bounded by cracks and low scarps, perched on hillsides. These masses generally appear to be shallow (less than 5 m deep), but some occupy large portions of hillsides and hence are large in volume. We monitored movement of one such mass in Ford Canyon (Fig. 6) during the week of 6/22 to 6/29/83 and detected no significant movement (less than 5 mm). This monitoring, combined with the piezometric measurements, suggests that most of these masses have probably ceased movement. These partly-detached masses, however, are probably less stable now than before movement (under similar ground-water conditions), and they are probably less stable than nearby unslid materials. Increases in ground-water levels accompanying a rainstorm consequently could be expected to induce movement of these partly-detached landslides before failure of unslid parts of the hillside. Hence the partly-detached landslides appear to be the most likely sources for debris flows in the near future, at least through the summer cloudburst season and through the following winter and spring. We do not know how long the partly-detached landslides may remain significantly more susceptible to movement than other parts of the hillslopes.

Evaluation of travel distance

We have evaluated the potential for debris flow of a given partly-detached landslide to reach the canyon mouth by estimating its potential travel distance through comparison to debris flows that reached canyon mouths this spring. We base estimates of potential travel distance on our observations concerning recent debris flows in the area and on theoretical considerations. Our reconnaissance observations suggest that the ability of a given debris flow to sustain movement depended in large part upon its volume and the gradient of the channel down which it traveled. Theory of mechanics of debris flow indicates that flow can be sustained only so long as a critical thickness is maintained in the channel; this thickness depends upon strength of the slurry and channel geometry (Johnson, 1970). For channels of more-or-less similar cross section, and for materials of similar properties, maintenance of this critical thickness could be expected to depend in large part upon volume of the debris flow and channel gradient. Thus our observations appear consistent with theory, and these together form a basis for crudely estimating travel distance of debris flows down canyons of the Wasatch Front.

We conceive a given debris-flow volume to consist of contributions both from a landslide at the head of the debris-flow path and from materials scoured from the channel. Both of these sources are either documented (Croft, 1967, p. 8) or observed by us this year as capable of contributing significantly to debris-flow volume.

Contributions from channels

Careful evaluation of the potential contribution from channels throughout the area is too complex a task for our limited investigation. Consequently we assume that, for similar initial landslide contributions, the channel contribution will be similar in canyons of similar size, shape, gradient, surficial deposits, and bedrock geology, the latter governing the kind of surficial materials available; comparatively large initial landslide contribution can be expected to induce much greater channel contribution. Most major canyons of concern, those between Holbrook and Beus Canyons, are similar in size, shape and gradient and are underlain by relatively uniform schists and gneisses of the Farmington Canyon complex (Davis, 1983), so it seems reasonable to expect a similar level of channel contribution from these canyons. Canyons in the area between Beus Canyon and Perry Canyon are underlain by a variety of units, including the Tintic Quartzite, Ophir Formation, and Maxfield Limestone as well as the Farmington Canyon complex, so we are less confident in our appraisal of channel contribution from these canyons, as indicated in Figure 1. Willard and Facer Canyons include large areas of Quaternary alluvium, so these canyons appear to have the potential for abnormally large channel contribution.

Contributions from landslides

The contribution to be expected in the short term from landslide source areas is determined by the volumes of the partly-detached landslides. We have assumed that simultaneous failure of non-adjacent landslides is unlikely, so the largest partly-detached landslide within each canyon represents the greatest threat. Figure 5 shows photographs of some partly-detached landslides, and Plate 1 shows by symbol the locations of the largest partly-detached landslides in each canyon.

Using this reasoning, we have compared the volumes of the largest partly-detached landslide in each canyon to the volumes of debris flows that reached the mouths of canyons having similar geometry and materials. Where volumes are less than these standards, we anticipate that debris flows will die out before reaching the canyon mouth but will contribute material to the stream to be transported to the canyon mouth as a debris flood. We used the estimated volume (15,500 m^3) of the debris-flow scar in the headwaters of Ward Canyon (Fig. 6) as a standard for major-size canyons, such as Parrish and Centerville, because this debris flow appears to have barely reached the canyon mouth and because the size, shape and gradient of this canyon are similar to many of the major canyons. We used a smaller volume of 3,600 m^3 as a standard for smaller canyons, such as Rudd, that are locally called half canyons. We based this standard on the volume of the main debris-flow scar in Hornet Creek, from which debris flow traveled to the half-canyon mouth (at confluence with Steed Creek). Hornet Creek served as a useful standard because its size, shape and gradient are similar to other half canyons.

Volumes both of debris flows that occurred this spring and of partly-detached landslides were estimated from photographs taken from helicopter, which were calibrated visually against approximately measured volumes of debris-flow scars on Rudd, Ward and Ricks drainages. The volumes on Ward and Ricks drainages were estimated from tape-and-compass sketch maps (Fig. 6).

Ratings derived by this method are listed in Table 1 and shown on Plate 1 for each major canyon and for many half canyons and minor canyons. Half canyons and small canyons without designated relative potential have low relative potential. These ratings are discussed for many major canyons later in this report.

Recurrent longer-term potential

Potential for debris flow and debris flood in the area has existed long before the changes brought by rapid snowmelt this spring. This fact is documented by historic records (Croft, 1967, 1981; Woolley, 1946) and by mapping of prehistoric debris flow and alluvial fan deposits (Miller, 1980). Observers of many events in the early 1900's attributed the abundant debris-flow activity of this period to rapid runoff induced by overgrazing and other man-induced effects on the watershed, rather than to landslides (Croft, 1967, 1981). All of the debris flows that occurred this spring in the area between Salt Lake City and Willard, however, were directly traceable to landslides. Hence they were not induced by the rapid-runoff erosional process envisioned by Croft, although such processes are recognized as capable of producing debris flows in regions similar to the area under consideration (Pat Glancy, oral commun., 1983). Thus it appears that debris flows and debris floods are recurrent processes in the area, processes that were probably accelerated by man's activity in the late 1800's and early 1900's, but processes that should certainly be anticipated in the future.

We evaluate the potential for recurrent debris flow, a potential independent of changes brought by the rapid snowmelt of this spring, by considering several lines of evidence. We consider a canyon to have the potential for recurrent debris flow, and hence high relative potential, where evidence of more than one historic (including 1983) or prehistoric debris flow is recognized at or beyond the canyon mouth. We anticipate less frequent debris flow, and thus a moderate relative potential, from canyons where there is either evidence of only one past debris flow at the canyon mouth or where we recognize old debris-flow scars or paths that suggest debris-flow volume sufficient for transport to the canyon mouth.

In similar manner we evaluate potential for recurrent debris flood, and hence high relative potential, where alluvial fans at canyon mouths, as mapped by Miller (1980), suggest a succession of past debris floods, where historic accounts suggest at least one debris flood, or where old debris-flow scars or paths recognized in aerial photographs suggest addition of significant volume of debris to the canyon bottom.

Ratings of potential for recurrent debris flow and debris flood are shown in Table 1 and Plate 1. Not all canyons rated on Plate 1 are described in Table 1. Ratings for many canyons are discussed later in this report.

Methods Recommended For More Accurate Evaluation

Although we believe our method of evaluation is sound and appropriate for this preliminary stage of investigation, the evaluations derived using this method are based on incomplete information. The evaluation of potential for debris flows and debris floods could be substantially improved if the same method were applied systematically and carefully over the entire area, using 1) aerial photographs of the entire area taken after the Memorial Day events but before foliage appeared, 2) more careful estimates of partly-detached landslide volumes, 3) analysis of canyon bottoms and other potential debris-flow paths for material available for incorporation by debris flow, and 4) more complete inspection of canyon mouths and bottoms for evidence of prehistoric debris flows. Examination and incorporation of such information could raise the ratings for many canyons. For example, at the time of this writing, we found evidence in aerial photographs of at least two partly-detached landslides not recognized in helicopter reconnaissance; the recognition of these masses changed the rating of debris-flow potential for two canyons from moderate to very high. Such fundamental information must be systematically incorporated into this method for it to yield reliable reconnaissance evaluations of the potential for these processes.

Such improvements form only the beginning of the research appropriate for careful evaluation of the potential for debris flow and debris flood. Studies needed for careful evaluation of potential should address the following questions:

1) Relations between rainfall (or snowmelt), ground-water levels, and landslide movement. Such relations would permit prediction of timing of debris flows. Real-time prediction and warnings could then be made based on telemetered rainfall, water-level, or ground-movement information.
2) Stability of the partly-detached landslides. Are these masses in fact significantly less stable than nearby hillslopes, and how long will they remain so? These questions should be approached through detailed site-specific studies including stability analyses of the landslides.
3) The process of transformation from landslide to debris flow. Understanding developed through such study could help evaluate the potential for debris flow of the partly-detached landslides.
4) Incorporation of channel materials by debris flow. Possible variations in materials available for incorporation is one of the major uncertainties of our analysis.
5) The transition from debris flow to debris flood. Understanding of this transition would permit more accurate prediction of the nature of flow from canyon mouths.
6) Factors that control debris-flow runout. Understanding of runout would help in prediction of areas likely to be affected beyond canyon mouths.
7) Recurrence of debris floods and debris flows at canyon mouths. Systematic

field investigation and dating of deposits would help define the expectable frequency of events from each canyon.

MITIGATION MEASURES FOR DEBRIS FLOWS AND DEBRIS FLOODS

Approach

Because of the large number of watercourses involved and the lack of accessible data and design parameters, detailed engineering design for each site threatened by debris flow or debris flood is beyond the scope of this report. Mitigating measures and suggested watercourse improvements are offered only for watersheds evaluated as having very high potential for debris flow or debris flood. Because this report is incomplete, suggestions for further studies are offered.

In order to assess practical measures, it was necessary to briefly review existing systems and their function during the recent events. It was also appropriate to review existing hydrologic data, debris-production potential, and design quantities.

Existing measures

Old systems consisting of debris basins and levees still exist in the sparsely populated areas. Most of the systems no longer receive regular maintenance. Many have been abandoned or covered by development. A U.S. Forest Service report (1951) indicated 24 such structures in existence.

More recent systems consist of a series of street culverts connected by natural channels. These systems apparently have been developed piecemeal over an extended period of time with no specific criteria or comprehensive plan. Some of the earth channels are included in landscaping; others are treated as necessary nuisances. In many cases the channels have been diverted from their natural path to follow the rear lot lines, where they are encroached upon and neglected. Several stream channels that would naturally cross developed areas obliquely have been realigned to follow rectangular lot lines by incorporating a series of steps or doglegs. There also are systems that decrease in capacity going downstream.

The most recent systems appear to be covered laterals under streets. Some have covered conduits discharging onto farmlands; others discharge into open ditches that meander through the older downstream developed areas.

Methods used for evaluation

Hydrologic data available

Recent hydrologic studies in the area have been performed by Gingery Associates, Inc. (1979) and by the U.S. Army Corps of Engineers (1969, 1974, 1978). Design unit runoff rates differ substantially among the studies, presumably due to different methods of evaluation utilized. However, all studies were based on clear water; each study acknowledged the potential for debris but did not quantitatively include it as bulking of the design flow rates or as mass volumes to be dealt with. The runoff rates we used to estimate required channel capacities were based on Gingery and Associates (1979), but these rates were tripled for debris flows and doubled for debris floods to account for the effects of debris. Flow rates for canyons not included in the Gingery report were estimated from canyons of similar size included in the report.

Debris production anticipated

We found very little documentation or study of anticipated debris production. The most useful study was conducted by the U.S. Forest Service (1950); in this study, volumes of debris deposits were plotted with respect to drainage areas for light, moderate and severe events. The reported production from Rudd Canyon in the 1983 event nearly doubled that indicated by the severe curve. We replotted these curves and compared them to existing plots for Los Angeles County (1970). The light and moderate curves looked reasonable; they are nearly parallel and decrease as the drainage area increases, as shown in Figure 7. The severe curve showed a substantial skew and increased with increasing area. For the purpose of this study, the severe curve was adjusted to the position shown in Figure 7 using the production estimated for Rudd Canyon this spring as a base and drawn similar to the others.

Watersheds judged to have a very high relative potential for debris flow (A) are assumed to have a production potential in accordance with the severe curve. Watersheds judged to have a very high relative potential for debris flood (a), but a lower potential for debris flow, are assumed to have potential in accordance with the moderate curve.

Slopes of deposition

Published research addressing the gradients at which debris flows and debris floods begin deposition in this area were not available. Studies in Japan indicate that debris-flow deposition there may begin at gradients between 10% and 25% and ends at gradients of about 5% (Ikeya, 1981; Mizuyama, 1981; and Daido, 1971). Profiles plotted for all canyons having very high potential for debris flows or debris floods revealed that the upper portion of the fans, except for Facer and Willard Canyons, begin at 10% gradient and appear to terminate at 4% to 5% gradient. At Facer Canyon, debris-flow deposits begin at 17% and terminate at 6%. The fan at Willard Canyon also terminates at 6%, but the upper portion of the fan is modified by a man-made basin. On the basis of this information, we assumed that debris flows would begin to spread and deposit at the canyon mouths or where gradient decreased to 10% beyond canyon mouths. It was further assumed that debris floods would begin deposition at lesser gradient and would continue to transport and deposit debris downstream until the gradient diminished to about 4%.

General mitigation methods

Mitigation measures considered and discussed here are those applicable at the canyon mouth or below. Upstream watershed treatments and in-canyon stabilization structures are not addressed because these measures require more time and information than was available, and because, while such measures may help reduce the frequency of future events, they do not entirely solve the problem. The measures considered here control the debris moved by debris flow or debris flood either by trapping the debris high on the fan or by transporting it to locations where it will deposit with the least amount of damage.

Debris basins

The most common method of entrapment is by debris basins. Local experience with debris basins has been less than satisfactory (Croft, 1967, 1981), but their poor performance may result at least in part from inappropriate design or construction. Basins that remain today, such as those at Willard, Baer, Shepard, Steed and Ricks Creeks, all appear to be long and narrow with the long dimension parallel to the stream. They do not appear to have had low-flow drains and so probably acted as dams when first built. Their net effect was to function as a stabilizer. It is probable that bed load carried in the normal spring and thunderstorm flows was deposited high in such basins, where the stream entered the still water or left the confining canyon. Sufficient energy was probably not available to carry debris into the heart of such basins. Large storm flows would then be able to flank the upper basin walls. Eventually water probably eroded the upstream deposits and the basin filled to the spillway and stabilized the stream bed.

The appropriate basin configuration is more nearly square in plan view, with a low-flow drain designed to carry the normal runoff. The basin bottom should slope gently upward (approximately 3%) to intersect an extension of the normal canyon-bottom slope of 7-10% or more. Dewatering facilities are necessary so that debris may be cleared shortly after an event. Spillway systems must be designed to handle the full bulked flow. Basins must be located carefully and either equipped with stabilized channels or energy dissipators downstream so as not to scour downstream channels. A conceptual sketch of a typical basin applicable to this situation is shown in Figure 8. Structures of this nature have a high initial cost and require annual maintenance, but they have a reduced cost of clean-up as compared to the alternative of spreading the debris over several acres. These structures could be compatible with park and recreation areas. Structures of this nature require detailed design beyond the scope of a quick-fix approach, but in many cases they offer a viable long-term solution.

Where a well-incised watercourse is available, an alternative is to provide a row of smaller, simpler storage structures. These storage structures must be adequately protected from failure so that failure of one does not trigger failure of others downstream. They also require frequent cleaning. One such structure, shown in Figure 9, is a rail-and-timber barrier used by the Los Angeles County Flood Control District (1970). This structure should not be used where anticipated flow is more than 2 feet over the top of the structure or where large boulders are anticipated. Sufficient planks should be deleted in the lower center to provide for the normal flow. Another type of structure can be created utilizing a road fill as a dam. In major storms with debris involved, such fills will initially act as dams and should be so protected. The fill must be a partial dip crossing designed as a broad-crested weir and spillway section. The best structure for the road fill is probably a concrete crib-and-sill structure on the downstream face filled with rock. Compacted road fill should be placed on filter fabric and the upstream face should be protected with a mat or flexible lining. In lieu of the concrete crib structure, the backfill could also be soil cement with both faces protected by a flexible lining tied to the backfill at close intervals. A third alternative would be compacted earth with a rigid reinforced concrete spillway section. These last two methods both require an energy dissipator at the bottom. In any of these road-fill designs, the street section must be entirely concrete and tied to the lining. The culvert is a low-flow drain and should be designed to carry the normal stream flow. The upstream structure in such a system should also have a tree catcher. A sketch depicting such a facility is shown in Figure 10, and a typical tree catcher is shown in Figure 11.

Transport of debris along channels

Downstream from debris basins, the intent is to transport the remaining debris until it can be deposited with minimal damage. It should be noted that there are definite drawbacks associated with the transportation of debris. There is constant deposition or degradation occuring in natural channels. A given flow rate at a given velocity has the capacity to carry a given amount of debris. Should a greater amount of material be available from steeper upstream reaches, deposition will occur. Should the upstream area be void of material, the water is said to be hungry and degradation will take place. The situation not only changes from storm to storm, but within a storm, and generally is unpredictable. Consequently, watercourses must be watched and emergency action taken as necessary.

Transportation of debris also has a detrimental effect on improved conduits. The inverts of conduits, both concrete and steel, are subjected to abrasion. Steps must be taken to protect, inspect, and replace the inverts as required.

A reduction of deposition or degradation can be accomplished by straightening channels, uniformly grading when possible, and protecting banks and curves from erosion and undercutting. Channels should be uniform in width and wide enough to negotiate a bulldozer with a front-end loader. Channel walls parallel with the flow or on sweeping curves can be built or protected with grouted rock riprap, rail and timber, flexible or semi-flexible mats, or reinforced concrete blocks. Constructing two-step flood plains where room and grade permit is also recommended. Road crossings normal to streams should be depressed and protected, and yards downstream should be landscaped to include a berm or wall with several feet of return in the downstream direction. Examples of these types of improvements are shown in Figures 12, 13 and 14.

Figures 12A and 12B show temporary rail-and-timber revetments. Both types are limited to 4 feet in height and extend 1 foot below ground level. The structure shown in Figure 12A is free standing and does not require or permit backfill against the wall. The wall in Figure 12B requires loose dumped or slightly compacted backfill. The structure shown in Figure 12C is intended as a retaining wall and may be considered semi-permanent. During storm situations all three of these structures must be watched for undercutting.

The watercourse improvements shown in Figure 13 provide increased flow area and are appropriate in the steeper portions of the watershed (gradients of 6% to 7% or more). These methods by themselves are probably not sufficient in the more gently-sloping areas, but they may be incorporated along with flood-proofing measures shown in Figure 14.

Where diagonal crossings are encountered, flow in excess of channel capacity should be diverted to streets, allowing deposition to take place on public property. Appropriate street designs for this situation are those with inverted crowns and minimum 4-foot-wide concrete paving in the center. Depending on the slope, residents may have to flood-proof their property. An attractive way to accomplish this would be a concrete-block wall up to 3 feet high having removable timber stop logs, as shown in Figure 14. Block walls are also appropriate at rear and side yards where there are no alternate water paths. Berms of loose fill, like those now in place, are acceptable only in emergencies, as they are easily eroded by water not carrying its full capacity of sediment. Prior to making or increasing diversions into streets, the jurisdictional agency should evaluate local laws or ordinances and consult with their legal advisors with respect to future liabilities as a result of the diversions.

Mitigation measures are discussed below for each drainage area classified as having very high potential for debris flow (A) or debris flood (a).

Recommendations for further studies

The mitigation measures cited herein are primarily conceptual in nature. In most cases the recommended measures will not handle the full debris potential. These measures are based on estimated production rates and estimated bulking factors, determined from a limited amount of research, and they are presented only for canyons rated as having very high potential for debris flow or debris flood. Detailed research and engineering studies are appropriate for all the frontal canyons. These studies should determine the quantity of debris to be anticipated and methods for dealing with this material.

The flood plains and canyons of the Wasatch Front are under the jurisdiction of the U.S. Forest Service, three counties, and numerous cities and communities. None of these entities has exclusive control over a complete watershed and none has the staffing or financing to undertake studies of this nature. It is therefore recommended that a special district be formed, preferably by state charter, to coordinate watershed management and research and to oversee technical studies. This organization would also serve as the clearing house for all reports and data regarding these watersheds.

FEMA (Federal Emergency Management Agency) and FIA (Federal Insurance Agency) should be requested to review the hydrology of the area and to consider authorizing new studies to determine bulked flow rates, to quantify debris potential (both rate and volume), and to investigate the mechanics and locations of potential deposition. Programs should then be adopted to address these problems and to monitor the watershed reactions to verify the studies and solutions. The reestablishment of recording gages for both precipitation and runoff is appropriate to assist in monitoring the watersheds. The National Weather Service may be able to assist in instrumenting the watersheds and in applying their watershed-runoff forecast model.

The jurisdictional agencies would be advised to adopt a program of inspection and repair of existing systems. This inspection should include drainage ways that are the responsibility of property owners. The agencies might also wish to temporarily prohibit both development on the apexes of alluvial fans and the diversion of streambeds, until the above-mentioned studies are completed. Future development should be designed around streambeds rather than rerouting streambeds to fit development.

CANYON-BY-CANYON EVALUATION OF RELATIVE POTENTIAL FOR DEBRIS FLOWS AND DEBRIS FLOODS TO REACH CANYON MOUTHS, AND MITIGATION MEASURES

(Canyons listed in sequence from south to north along Wasatch Front)

City Creek

Following a three-hour rain over Salt Lake City on September 11, 1864, a debris flow[2] "as thick as molasses" issued from City Creek (Woolley, 1946, p. 87). Based on this episode and other historic accounts of debris flood and possible debris flow (Woolley, 1946), City Creek is rated as having a high debris-flow potential (B) and high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

Mill Creek

Young alluvial-fan deposits identified beyond canyon mouth of Mill Creek (Miller, 1980) suggest a history of recurrent debris floods and a high debris-flood potential (b). Debris flows reached the main channel during the spring

[2] Underscoring in text and in Table 1 indicates authors' interpretation of historical accounts.

of 1983 without extending beyond the canyon mouth, indicating a low (D) debris-flow potential. No specific mitigation measures are suggested for this drainage.

Kenney Creek

This tributary of Mill Creek contains deposits of both historic and prehistoric debris flows reaching Mill Creek (P. Winkelaar, oral commun., 1983). Based on this evidence of recurrent activity, this drainage is rated as having high debris-flow potential (B) and high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

Holbrook Canyon

Historical Setting and Relative Potential

We have no historical evidence of debris flows or debris floods in this drainage. The presence of an exceedingly large partly-detached landslide, estimated to be about 42,000 m^3 in volume, creates a very high debris-flow potential (A) and a very high debris-flood potential (a).

Mitigation Measures

There is no way the maximum possible debris volume can be retained without a full-size debris basin. As much as 140,000 cubic yards (107,000 m^3) of sediment could be expected, based on the curve for a severe event (Fig. 7). The maximum possible bulked flow rate, in many cases, cannot be retained within the natural channel, so overflow and deposition is to be expected. A portion of the material deposited in the 1983 event originated in the developed portion of the watershed.

Street basins, as shown in Figure 10, might be considered as a method of reducing the quantity of debris being transported. These may be most appropriate in the uppermost portion of the developed watercourse. Consideration may also be given to constructing protected dip crossings in the mid-portions of the developed watercourse. Flow conditions may be improved by straightening the channel, replacing doglegs with smooth transitions, and eliminating significant grade changes. Where curves are necessary they should have a constant radius, with the outside levee protected by one of the measures shown in Figures 12 or 13. Obstructions in the natural channel should be removed and brush and dead trees cleared from the flood plain.

The jurisdictional agency may wish to examine the gradient of the watercourse to determine probable locations of deposition and areas where debris can be diverted to, or stored on, public property. The agency may also advise residents in areas where deposition may take place to flood-proof their property. The agency would also be advised to inspect culvert inverts for erosion.

Stone Creek/Ward Canyon

Historical Setting and Relative Potential

Our documentation that a prehistoric debris flow in this drainage reached the canyon mouth, as did a debris flow during the spring of 1983, demonstrates a high debris-flow potential (B). The presence of a small (2000 m^3) partly-detached landslide in this drainage poses very high debris-flood potential (a).

Mitigation Measures

This watercourse has been realigned to fit modern development. It has many abrupt turns and it approaches many culvert entrances at a skew. Backyard encroachments are also present.

A substantial debris-retention capacity can be generated in the canyon. Based on a moderate event (see Fig. 7), a minimum of 70,000 cubic yards (53,500 m^3) could be anticipated. A debris-barrier structure as shown in Figure 9 could be located upstream of the narrows. This site should be more precisely located in the field. Street basins may also be appropriate along with depressed and protected dip crossings. Man-made encroachments into the watercourse should be removed. Doglegs should be replaced with smooth transitions. Where possible the watercourse should be returned to its original location and should be widened to at least 12 feet. The required curves should be protected in accordance with Figures 12 or 13. Diversions into public streets, along with appropriate flood-proofing, may be advisable and should be investigated by the jurisdictional agency.

Centerville Canyon

Because we have no historic or prehistoric evidence of debris flows reaching the canyon mouth, this drainage rates a low debris-flow potential (D). Young alluvial-fan deposits at the canyon mouth (Miller, 1980) indicate a high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

Parrish Creek

Historical Setting and Relative Potential

The debris flow of July 10, 1930, from Parrish Creek destroyed several homes near the mouth of the canyon and caved in one side of the Centerville School (Croft, 1981). The "bouldery alluvium" of the debris flow covered an area of 64.8 acres with an average thickness of 3 ft (1m) (Croft, 1967, p.

16). A subsequent debris flood on August 11 and a debris flow on September 4, 1930, left State Highway 106 under 15 ft (5m) of debris (Woolley, 1946, p. 114). The presence of a large partly-detached landslide, estimated to be about 50,000 m^3 in volume, rates this drainage as a very high debris-flow potential (A), as well as a very high debris-flood potential (a).

Mitigation Measures

This canyon is considered to have a debris potential on the order of 100,000 cubic yards (76,500 m^3), based on the curve for a severe event (Fig. 7). The possibility should be investigated of storing up to one third of the potential debris, using a combination of levees, grading, and the construction of a barrier like that shown in Figure 9. The natural watercourse should also be cleared of obstructions and brush. A determination of overflow paths is appropriate, as is providing flood-proofing advice to residents along these paths.

Approximately 800 feet east of 400 East Street, the low-flow from this creek has been diverted to a storm drain in 540 North Street just west of 500 East Street. During this spring, sandbags were successfully placed to assist this diversion. A debris flow or debris flood would not be so easily handled, and would probably continue southeast down the old flood plain and dry wash. If a debris flow deposited here, additional flow could be deflected in either direction.

Barnard Creek

Historical Setting and Relative Potential

Debris-flow scars and paths on 1953 aerial photography appear to be of sufficient size for debris flows to reach the canyon mouth; however, we have no evidence of debris flows having reached the canyon mouth. Young alluvial-fan deposits (Miller, 1980) indicate a history of debris floods. A partly-detached landslide of insufficient volume for a debris flow to reach the canyon mouth gives this drainage a moderate debris-flow potential (C) but a very high debris-flood potential (a).

Mitigation Measures

This is another situation where the stream is landscaped into yards and follows lot lines down the fan. A debris flood would probably not follow this path; in 1983 a portion of the flow left the stream bed at the private bridge upstream of 550 East Street.

An investigation of methods to direct the streamflow into desired paths is recommended. Some of the methods might be levees or barrier structures, such as shown in Figures 9 and 13. Where flows are directed into streets, it may be advisable to consider inverted-crown streets. Gradients of the flow paths should be determined, and residents of areas of likely deposition should be advised to flood-proof.

A debris production of 40,000 cubic yards (30,600 m^3) might be reasonable from this drainage.

Ricks Creek/Ford Canyon

Historical Setting and Relative Potential

An old photograph near the mouth of Ricks Creek shows mud and debris against the side of a house (Croft, 1967) following a storm on August 13, 1923, suggesting a debris flow beyond the canyon mouth. Another house adjacent to Ricks Creek along State Highway 106 was filled with mud and debris to the level of the window sills in both 1929 and 1930, according to the owners. Although historic citations (Woolley, 1946) do not differentiate debris-flow from debris-flood events along Ricks Creek, and do not differentiate events in Ricks Creek from those in other drainages in this vicinity, the likelihood of debris flows beyond the mouth of this canyon appears high. Based on this historic evidence, a high debris-flow potential (B) is assigned. Because of the presence of small partly-detached landslides on the hillsides of this canyon, the debris-flood potential is rated very high (a).

Mitigation Measures

This canyon is judged as capable of moderate debris production (Fig. 7), on the order of 40,000 cubic yards (30,600 m^3). The situation here has been made more difficult by recent construction. A house and stable have been constructed within the old debris basin, and a tract downstream has diverted the stream to the south, resulting in another dogleg.

The upstream end of the basin can be restored to generate some capacity by grading. The bottom could be graded at 2%, beginning upstream of the house and stable and continuing for approximately 500 feet, and then gradually increasing to daylight. Maximum slope should not exceed 10%. Appropriate flood-proofing should be considered.

Downstream from the basin, a pile of debris on the south side of the stream should be removed. The stream bed should be straightened and widened so that, if necessary, a portion of the bed load could be diverted into the park. The banks on the north side of the stream could be protected.

The berm downstream of the new houses and on the north side of the wash was recently graded, presumably to replace a portion of the old berm removed by the tract. This berm could be recompacted and a gabion or grouted-rock spillway added to discharge excess flows to 1600 North Street.

It should be noted that the gradient downstream of US 106 is only about 3% and therefore subject to deposition.

Davis Creek

The debris flow of August 13, 1923, deposited "bouldery alluvium" over 31 acres with an average thickness of 1.5 ft (0.5 m) (Croft, 1967, p. 16). Miller (1980) maps a debris-flow deposit at the mouth of this canyon. The historic evidence of debris flows indicates that this drainage rates a high debris-flow potential (B). The record of floods in 1878, 1901, 1903, 1929 and 1930 (Marsell, 1971; Woolley, 1946), some of which may have been debris flows or debris floods, gives this canyon a high debris-flood potential rating (b). No specific mitigation measures are suggested for this drainage.

Steed Canyon

Historical Setting and Relative Potential

The debris flow of 1923 deposited "bouldery alluvium" with an average thickness of 3 ft (1m) over an area of 21.6 acres (Croft, 1967). A debris-flow deposit below this canyon is also shown by Miller (1980). We recognized in this channel beyond the canyon mouth an historic, 2m-thick debris-flow deposit with an older debris-flow deposit beneath it. A partly-detached landslide about 25,000 m^3 in volume on Hornet Creek, a tributary of Steed Canyon, combined with a steep gradient of 0.341, gives this drainage a very high debris-flow potential (A) and a very high debris-flood potential (a).

Mitigation Measures

This watershed could have a debris potential on the order of 120,000 cubic yards (91,800 m^3). Capacity for the full amount cannot be provided, as the existing debris basin apparently was reduced in size by construction of the houses on the south.

Capacity can be improved by grading the existing debris cone at a 2% gradient upstream to intersect a continuation of the 10% natural watercourse gradient. Excess material can be used to strengthen levees. A new spillway could be created by grouting gabions to form a gravity dam about 4 to 6 feet high. A 2-foot-by-2-foot opening should be left in the bottom center for low-flow drainage.

Debris floods in excess of the newly-created capacity would be deposited near Jay Drive.

Rudd Creek

Historical Setting and Relative Potential

A series of debris flows during the spring of 1983 deposited approximately 80,000 m^3 of debris over 17.9 acres at the mouth of Rudd Creek. This volume was calculated from an isopach map of the deposit by B. Kaliser, Utah Geologic and Mineral Survey (written commun., June, 1983). Photogrammetric measurements indicate that the landslide contribution to debris flows was only 12,200 to 15,300 m^3 (B. Vandre, oral commun., July, 1983). Hence a large contribution to the debris flow was added by channel scour as the flow descended the steep channel. A large partly-detached landslide mass, estimated to be 70-100,000 m^3 in volume, is situated next to the existing scar. During our investigation a prehistoric debris flow deposit was also observed at the canyon mouth. These factors indicate very high debris-flow potential (A) and very high debris-flood potential (a).

Mitigation Measures

Based on the potential for additional debris flows and and debris floods, it is suggested that the homes lost or severely damaged not be repaired or replaced. The public entity should move to acquire these parcels and begin plans for a debris basin.

In the meantime it is probably best to attempt to direct and confine any debris flows within the existing earthen levees down 100 East and 500 North Streets. Debris floods would probably have sufficient energy to erode and transport some of this levee material. Consequently the lower 4 to 6 feet of the levees should be compacted and faced with a protective medium or shot with gunite. To insure that the flows get into the levee, the existing deposits should be graded to form a bowl emptying into the street. The bowl should encompass most of the block that was severely damaged and should be graded to allow as much room for deposition as possible. The grade of the bowl could be less than 10%. Levees should be graded on both sides of the bowl.

Farmington Canyon

Historical Setting and Relative Potential

On August 13, 1923, a man driving a four-horse team up Farmington Canyon heard a tremendous roar up the canyon and rushed up the mountain-side just in time to see a mass of rocks, grinding against one another, carry away his team and wagon (Croft, 1981, p. 9). Observers in the canyon reported the crest of the debris flow to be 75 to 100 feet high in that part of the canyon, with a width of 200 feet. The crest further down the canyon was reported to be 30 feet high (Woolley, 1946, p. 107). Near Lagoon resort, about 2 km beyond the mouth of Farmington Canyon, people were rescued from trees where they had sought refuge from the rapidly rising waters (Woolley, 1946, p. 107). Debris-flow deposits have been identified below Farmington Canyon (Miller, 1980). Floods with abundant debris have also occurred historically in 1878, 1926, and 1930 (Woolley, 1946). On August 10, 1947, Halfway Canyon, a tributary of Farmington Canyon, experienced a debris flow estimated to be 210,000 cubic yards (161,000 m^3) in volume. This flow damaged an instrument house and knocked a bridge from its foundation (Croft, 1981). A partly-detached landslide estimated to be 40,000 m^3 in volume poses a very high debris-flow potential (A) and a very high debris-flood potential (a) within the Farmington Canyon drainage.

Mitigation Measures

This canyon is one of the largest on the front. The method used to determine potential for sediment indicates a volume of 170,000 cubic yards (130,000 m^3). The ability of the existing basin to be restored to handle this full volume is questionable, but it will handle a substantial portion with clearing and/or grading.

It is recommended that as much capacity as possible be generated by removing material and regrading the basin. For this canyon, like the others, the upslope grade of 10% should be maintained. The use of the area within the basin as a disposal site for materials from other areas should be halted immediately. Prior to excavating the basin, the level of protection to be offered, or the elevation to which future deposits will be removed, should be determined. An outlet should be drilled through the dam at an appropriate level and a dewatering system constructed to drain future deposits. The dam appears to be in good shape, but a close inspection is recommended.

Shepard Creek

Historical Setting and Relative Potential

We have no evidence of debris flows having reached the mouth of this canyon, although several debris flows did reach the main channel during the spring of 1983. Young alluvial-fan deposits are recognized at the mouth of this canyon (Miller, 1980). Because of the relatively small estimated volume of partly-detached landslides in this drainage, a low debris-flow potential (D) but very high debris-flood potential (a) is assigned.

Mitigation Measures

This watershed is judged to have a moderate debris-production potential, on the order of 50,000 cubic yards (38,200 m^3). The existing basin just upstream from the highway has not been maintained and may have been the source of some of the debris deposited downstream. Additional capacity can be achieved by cleaning or grading the basin. The spillway could be notched several feet deep for low-flow conditions and the grading begun at the bottom of the notch. As in other basins, a gentle slope at the downstream end, graded to intercept the extension of the upstream slope, is recommended. An additional problem is the drainage system immediately downstream from the basin. The spillway flow rushes through a culvert, discharges into a skewed rock inlet for another culvert, and then, a few feet later, discharges at high velocity into a small landscaped channel meandering between two houses. This spring, undercutting has affected the inlet to the landscaped channel, a clump of trees and a berm. The northern-most house appears to be built in the old watercourse. Any appreciable volume of debris would render this system useless and jeopardize the house.

The most appropriate solution would be to reactivate the basin and construct an improved channel to, and preferably under, the road. Because of the high velocities involved, a non-erodable invert is in order.

Baer Creek

Historical Setting and Relative Potential

We observed historic or possibly prehistoric debris-flow deposits beyond this canyon mouth. This drainage has a history of floods in 1912, 1923, 1927, 1945, and 1947 (Croft, 1981). A partly-detached landslide, about 20,000 m^3 in volume, poses very high debris-flow potential (A) as well as very high debris-flood potential (a).

Mitigation Measures

An old basin exists just above Mountain Road. This basin, like the others, could be regraded to pick up some additional capacity but probably could not accomodate the full 120,000-cubic-yard (91,800 m^3) debris potential. The bottom of this spillway should be inspected, as the plunge pool may have had some rocks plucked out.

Recent grading above the basin has resulted in the construction of a levee that actually makes it easier for a debris flow to leave the streambed. Downstream from Mountain Road, the watercourse is well-defined, and the adjacent property is topographically high and has large setbacks from the channel. A debris flood would probably continue downstream through this reach of 10% gradient until the gradient diminishes to 4%, where deposition would probably take place.

It is recommended that the basin be excavated at a gradient of 2% to 3%

to intersect the upstream gradient of 12%. The excavated material could be used to increase levee heights and to redefine the streambed. An investigation should also be undertaken to determine the likely areas of deposition, and the residents of these areas should be advised to flood-proof.

Holmes Creek/Webb Canyon

A cloudburst on July 28, 1917, brought a debris flow down the canyon that covered a water-system intake with boulders and mud and swept debris onto farms near the mouth of the canyon (Woolley, 1946, p. 104). Young alluvial-fan deposits are also recognized at the mouth of the canyon (Miller, 1980). No debris-flow or landslide activity was observed in the spring of 1983. This drainage rates a moderate debris-flow potential (C) and high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

South Fork Kays Creek

A reporter from a Kaysville newspaper described a debris flow of August 8, 1912, as a rush of water laden with millions of tons of dirt and boulders which emerged from the canyon, crossed a road, and came to rest as a deposit ten feet thick and 300 feet wide (Croft, 1981). Another debris flow reached the canyon mouth during August of 1930 (Croft, 1981). Other debris-flow or debris-flood events are reported to have occurred in 1923, 1927, 1945, and 1947 (Winkelaar, written commun., June, 1983). Because of this abundant historical evidence, this drainage is rated as having a high potential for debris flow (B) as well as a high potential for debris flood (b). No specific mitigation measures are suggested for this drainage.

Middle Fork Kays Creek

Two debris-flow scars recognized in 1953 photography had estimated volumes sufficient for the debris flows to reach the canyon mouth. Debris-flood deposits from the 1947 storm, as well as the presence of young alluvial-fan deposits (Miller, 1980), give this drainage a rating of moderate debris-flow potential (C) and high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

Waterfall Canyon

A deluge of boulders, rocks, and gravel was deposited in a 200-acre triangular mass near Mount Ogden Park during a storm on August 13, 1923. The source of this debris was related to an area that had been virtually stripped of vegetation several years earlier by overgrazing (Croft, 1981, p. 8-9). Although the description of this event resembles a rock avalanche more than a debris flow, it is possible that a debris flow from the upper part of the drainage, which is underlain by the Farmington Canyon complex, could have flushed out the bouldery talus from the Tintic Quartzite located in the lower part of the drainage. Without field investigation to document the source of this historic event, we conservatively assign this drainage a moderate potential for debris flow (C) and a high potential for debris flood (b). No specific mitigation measures are suggested for this drainage.

Ogden Canyon

On July 30, 1888, several landslides occurred in Ogden Canyon and heavy torrents (possibly debris flows) occurred in side gulches. The Ogden River carried a great deal of debris (Woolley, 1946, p. 91). Debris flows were documented on tributaries of Ogden River in 1923 (Croft, 1981) and in 1980 (T. Heller, oral commun., June, 1983). The history of several debris flows in tributaries gives this large drainage a moderate debris-flow potential (C) and a high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

Coldwater Canyon

A debris flow from this canyon during the spring of 1983 was judged to have just reached the canyon mouth, according to our helicopter reconnaissance and to on-the-ground inspection by Tom Pierson of the U.S. Geological Survey (oral commun., June, 1983). This event, in addition to a prehistoric debris-flow deposit mapped at the canyon mouth by Miller (1980), results in this canyon having high debris-flow potential (B) and high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

Willard Canyon

Historical Setting and Relative Potential

The debris flow from Willard Canyon of August 13, 1923, destroyed the Willard Municipal Power Plant, about a quarter of a mile below the canyon mouth, by depositing a 50-ton boulder inside the powerhouse. Smaller boulders and debris went down into the town (Croft, 1981, p. 6). During the cloudburst of July 31, 1936, the main road was buried under mud for nearly two blocks; seven homes were partially buried and basements were filled with mud. During 1936, successive episodes of debris flow caused the filling and overflowing of debris-retention structures (Woolley, 1946, p. 118). A partly-detached landslide of about 10,000m^3, in combination with a stream gradient of 0.195 (compared to 0.126 in Ward Canyon), are judged sufficient to deliver a debris flow to the canyon mouth. Accordingly, the canyon is rated as having a very high debris-flow potential (A) and a very high debris-flood potential (a).

Mitigation Measures

This watershed is judged to have severe debris potential, as much as 130,000 cubic yards (99,500 m^3). The basin here could be regraded to gain capacity. As the upstream gradient here is only 6%, it may be beneficial to steepen this grade by redeveloping the stream bed and building levees upstream. As Croft (1967) indicated, this basin can easily be flanked by future flows. The spillway at the basin should be investigated for loss of rock due to plucking.

It is recommended that future studies consider a new basin in the vicinity of the fan apex. Because it is understood that diversions from the adjacent frontal areas are currently proposed, it is recommended that downstream liabilities resulting from diversions be reviewed.

Facer Canyon

Historical Setting and Relative Potential

We observed a sequence of prehistoric debris-flow deposits beyond the canyon mouth, and a debris flow this spring extended beyond the canyon mouth. A young alluvial-fan deposit at the canyon mouth (Miller, 1980) attests to a history of debris floods. A large partly-detached landslide, estimated to be about 30,000 m^3 in volume, combined with a very steep gradient of 0.307 within the canyon, poses a very high debris-flow potential (A) and a very high debris-flood potential (a).

Mitigation Measures

A basin was recently graded at the base of the fan. A large tree and a clump of brush in the streambed upstream of the basin would probably deflect future debris flows to the north. The obstructions should be removed and the basin enlarged to the north, with an appropriate capacity on the order of 80,000 cubic yards (61,200 m^3). A spillway protected by gabions or grouted rock should be located in line with the canyon.

Threemile Creek/Perry Canyon

On August 13, 1923, a debris flow from Perry Canyon, a few miles north of Willard, deposited gravel, water, and mud on the highway and on orchards below (Croft, 1981). Miller (1980) has mapped alluvial fan deposits at the mouth of this canyon, attesting to a history of debris floods. Consequently we assign this drainage a moderate debris-flow potential (C) and a high debris-flood potential (b). No specific mitigation measures are suggested for this drainage.

ACKNOWLEDGMENTS AND RESPONSIBILITY

The conclusions expressed in this report are based in part on work undertaken before our arrival. Paul Winkelaar of the U.S. Forest Service contributed an inventory of landslides and channel effects mapped from helicopter, and a team from Utah State University in Ogden, under the direction of Roland Jeppson, Robert Pack, and Richard Hawkins, installed and monitored piezometers in and near a number of the landslides. The information gathered by both of these efforts was invaluable to our evaluation; the piezometer arrays and data, in addition, provide a means by which future movement of these and other landslides in the area can be anticipated.

Paul Winkelaar, Gary Kappesser, Bruce Vandre, and Earl Olson of the U.S. Forest Service contributed maps of old landslides and of glacial deposits and features, literature on debris-flow and debris-flood events in the area, hydrologic information, and pre-1983 aerial photographs of much of the area. Tom Pierson of the U.S. Geological Survey in Vancouver, Wash., offered his descriptions of debris-flow events of this spring. Thom Heller of the U.S. Forest Service helped extensively in the field. Klaus Gurgel and the cartographic team at the Utah Geologic and Mineral Survey assisted in map preparation. Personnel from FEMA (Federal Emergency Management Agency), particularly Bob Ives, Gary Connely, Sylvia Meyer, Robyn Roberts, and Nick Saavedra, facilitated logistics for our work, typed manuscripts and drafted figures. Bruce Kaliser and Don Mabey of the Utah Geologic and Mineral Survey briefed us on the scope of the problem and facilitated contacts to begin our studies. Jessica Vasquez and Lauren Herzog of the U.S. Geological Survey in Menlo Park, Calif., assisted with the typing of drafts and compilation of the final manuscript.

Wieczorek, Ellen, Lips and Cannon of the U.S. Geological Survey are responsible for the evaluation and discussion of the potential for debris flow and debris flood to reach canyon mouths. Short of Los Angeles Flood Control District is responsible for evaluation and discussion of mitigation measures. Wieczorek served as team leader and coordinator, compiled historic information, and wrote sections on assessment of the potential for each canyon. Ellen and Wieczorek conceived the comparative approach used to evaluate the potential for debris flows and debris floods to reach the canyon mouths. Ellen organized the report and wrote the sections on processes and potential. Lips evaluated volumes of debris flows and of partly-detached landslides. Cannon identified partly-detached landslides on aerial photographs and evaluated potential for debris flow from small range-front canyons. Most tasks, particularly the development of the rating system for relative potential, were developed by team effort.

References Cited

Costa, J. E., and Jarrett, R. D., 1981, Debris flows in small mountain channels of Colorado and their hydrologic implication: Bulletin of the Association of Engineering Geologists, v. XVIII, n. 3, p. 309-322.

Croft, A. R., 1967, Rainstorm debris floods, a problem in public welfare: University of Arizona, Agricultural Experiment Station, Report 248, 35 p.

Croft, A. R., 1981, History of development of the Davis County Experimental Watershed: U.S. Department of Agriculture, Forest Service, Intermountain Region (Region Four), Odgen, Utah, 42 p.

Davis, F. D., 1983, Geologic map of the central Wasatch Front, Utah: Utah Geological and Mineral Survey, map 54-A, scale 1:100,000.

Daido, Atuyuki, 1971, On the occurrance of mud-debris flow: Bulletin, Disaster Prevention, Kyoto University, vol. 21, part 2, no. 187.

Gingery Associates, 1979, Hydrology report, flood insurance studies for 20 Utah communities.

Ikeya, H., 1981, A method of designation for area in danger of debris flow: International Symposium on Erosion, New Zealand.

Johnson, A. M., 1970, Physical processes in geology: Freeman, Cooper, & Co., 577 p.

Los Angeles County Flood Control District (LACFCD), 1970, Hydrology Manual.

Marsell, R. E., 1971, Cloudburst and snowmelt floods: Environmental Geology of the Wasatch Front, N1-N18.

Marston, R. B., 1958, The Davis County Experimental Watershed story: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Ogden, Utah, 37 p.

Miller, R. D., 1980, Surficial geologic map along part of the Wasatch Front, Salt Lake Valley, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1198, scale 1:100,000.

Mizuyama, Takahisa, 1981, An intermediate phenomenon between debris flow and bed load transport: International Symposium on Erosion, New Zealand, 8 p.

National Research Council, 1982, Selecting a methodology for delineating mudslide hazard areas for the National Flood Insurance Program: National Academy Press, Washington, D.C., 35 p.

Olsen, Earl, 1981, Landslide Hazard Map (Wasatch Range): U.S. Department of Agriculture, Forest Service, Intermountain Region (Region Four) Odgen, Utah, scale 1:24,000.

U.S. Army Corps of Engineers, 1969, Flood plain information; Barton, Mill and Stone Creeks.

U.S. Army Corps of Engineers, 1974, Flood plain information; Farmington Bay Tributaries, Farmington-Centerville, Utah.

U.S. Army Corps of Engineers, 1978, Flood insurance studies, City of Bountiful, Utah.

U.S. Department of Agriculture, Soil Conservation Service, 1983, Water supply outlook for Utah, Salt Lake City, June 1983.

U.S. Forest Service, 1950, Survey Report, Wasatch Front, Utah

U.S. Forest Service, 1951, Survey Report, Wasatch Front, Utah

Varnes, D. J., 1978, Slope Movement Types and Processes, in Landslides: analysis and control: Transportation Research Board, National Academy of Science, Washington D.C., Special Report 1976, ch. 2.

Woolley, R. R., 1946, Cloudburst floods in Utah, 1850-1938: U.S. Geological Survey Water Supply Paper 994, 128 p.

Figure 1 - Map showing level of confidence in evaluations of potential for debris flow and debris flood to reach canyon mouths. Highest level of confidence is denoted by the number 1, lowest by the number 5. Information used for evaluations in the different areas are: 1 - Observations from the air and locally on the ground; relatively uniform geologic materials; 1980 aerial photography; partial coverage by May-June 1983 aerial photography; between Holbrook and Farmington Canyons; 2 - Observations from the air; relatively uniform geologic materials; 1980 aerial photography; between Farmington and Weber Canyons; 3 - Observations from the air; relatively uniform geologic materials; between Weber and Beus Canyons; 4 - Observations from the air; 1980 aerial photography; varied geologic materials; between City and Holbrook Canyons; 5 - Observations from the air; varied geologic materials; between Beus and Perry Canyon.

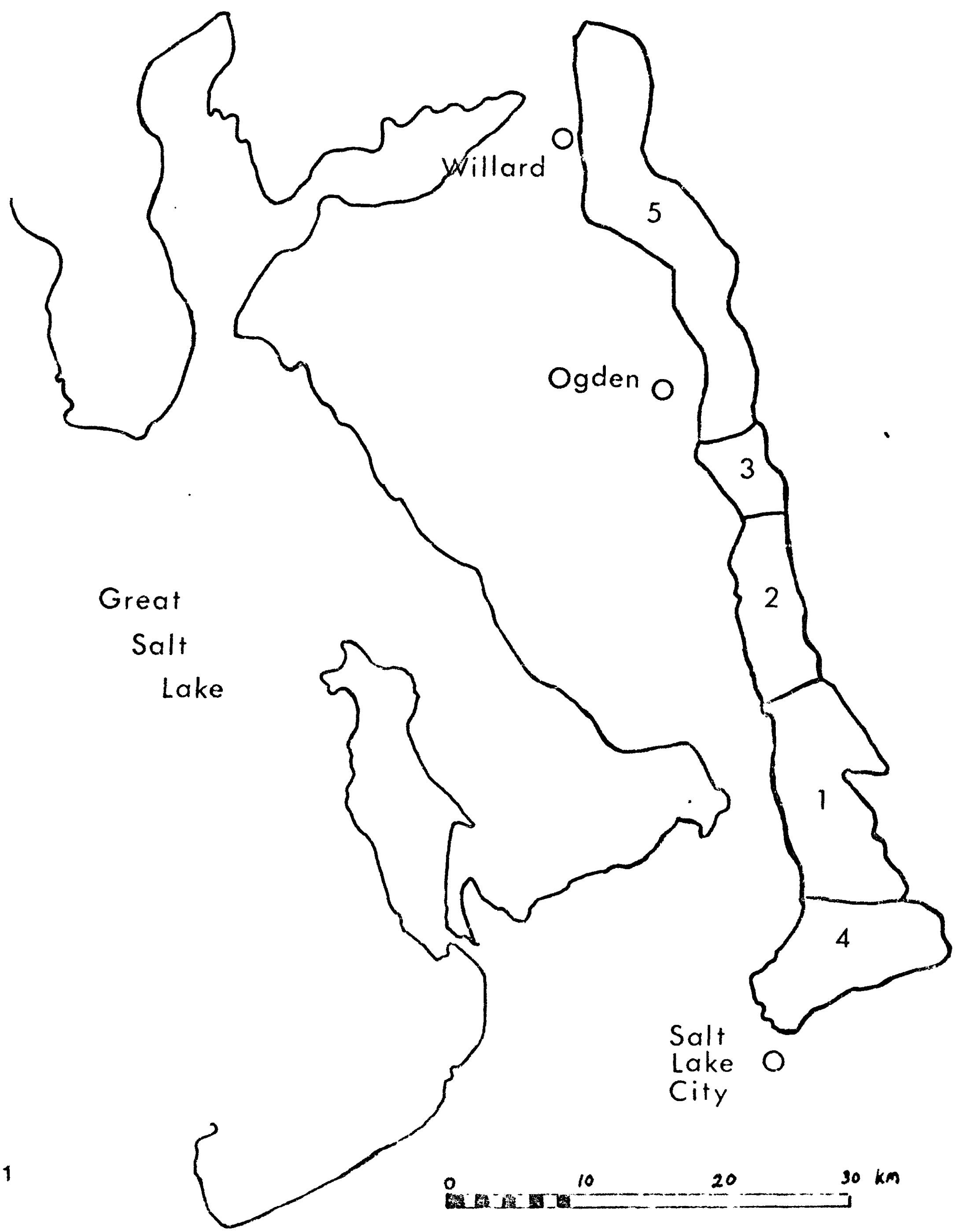

Willard
Ogden
Great
Salt
Lake
Salt
Lake
City
5
3
2
1
4
0
10
20
30 km

figure 1

Figure 2. Sketch of debris flow (from Croft, 1967).

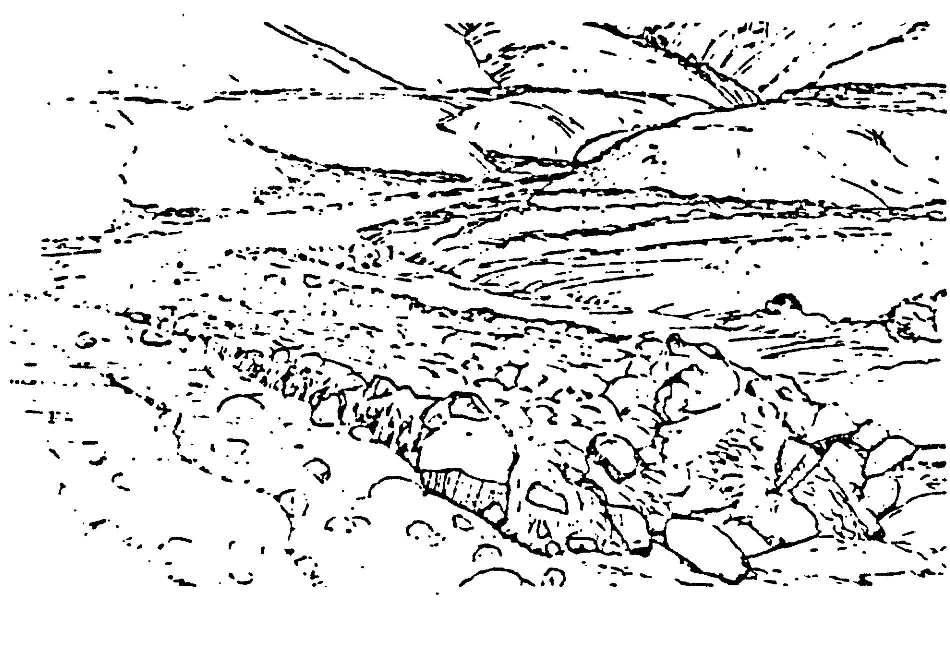
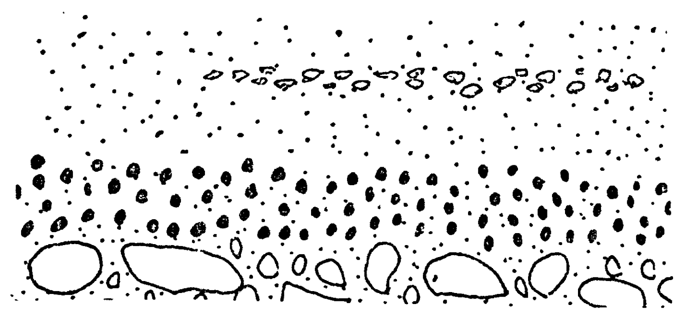


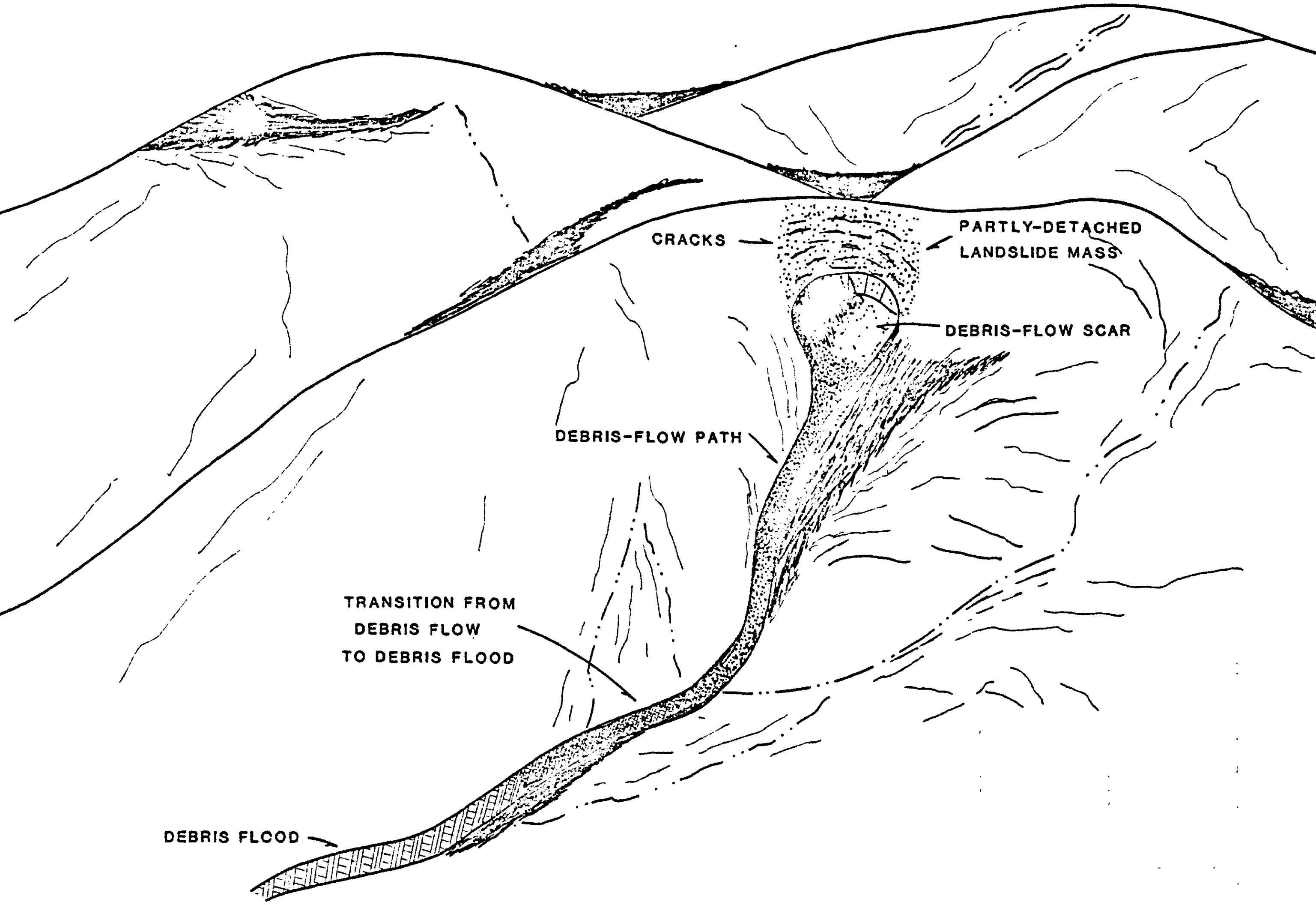
Figure 3. Comparison of deposits left by (A) debris flood and (B) debris flow.



A

B

Figure 4. Oblique sketch of debris flow from canyon wall, showing transition from debris flow to debris flood in main stream channel.



DRN BY Nick Saavedra

FIGURE 4

Figure 5. Photographs of partly-detached landslides in a) Ward Canyon, b) Ricks Creek/Ford Canyon (different landslide than shown in Fig. 6) and c) Steed Canyon. Lines in lower photographs indicate location of cracks used to define boundaries of partly-detached landslides.

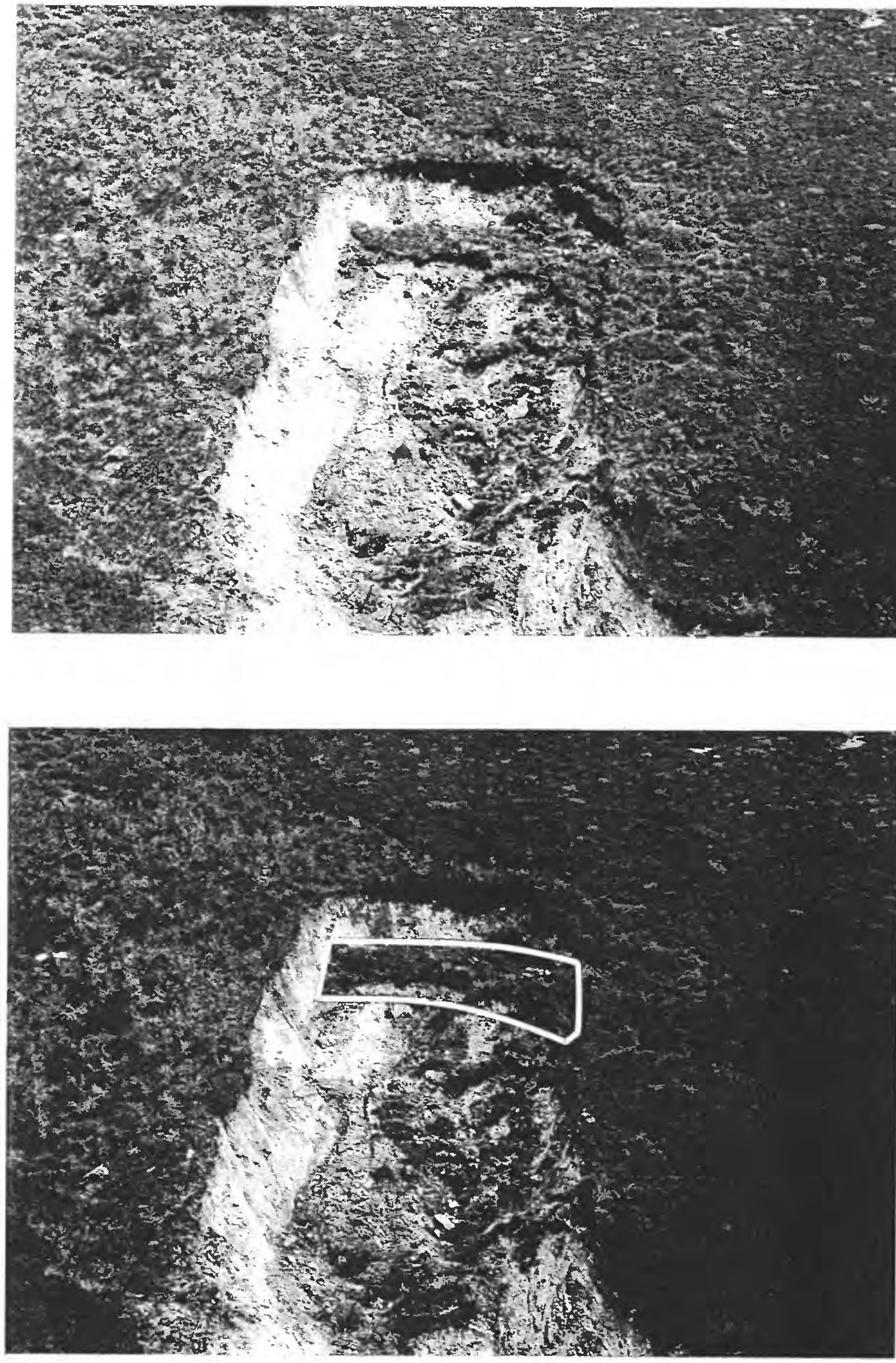


Figure 5A

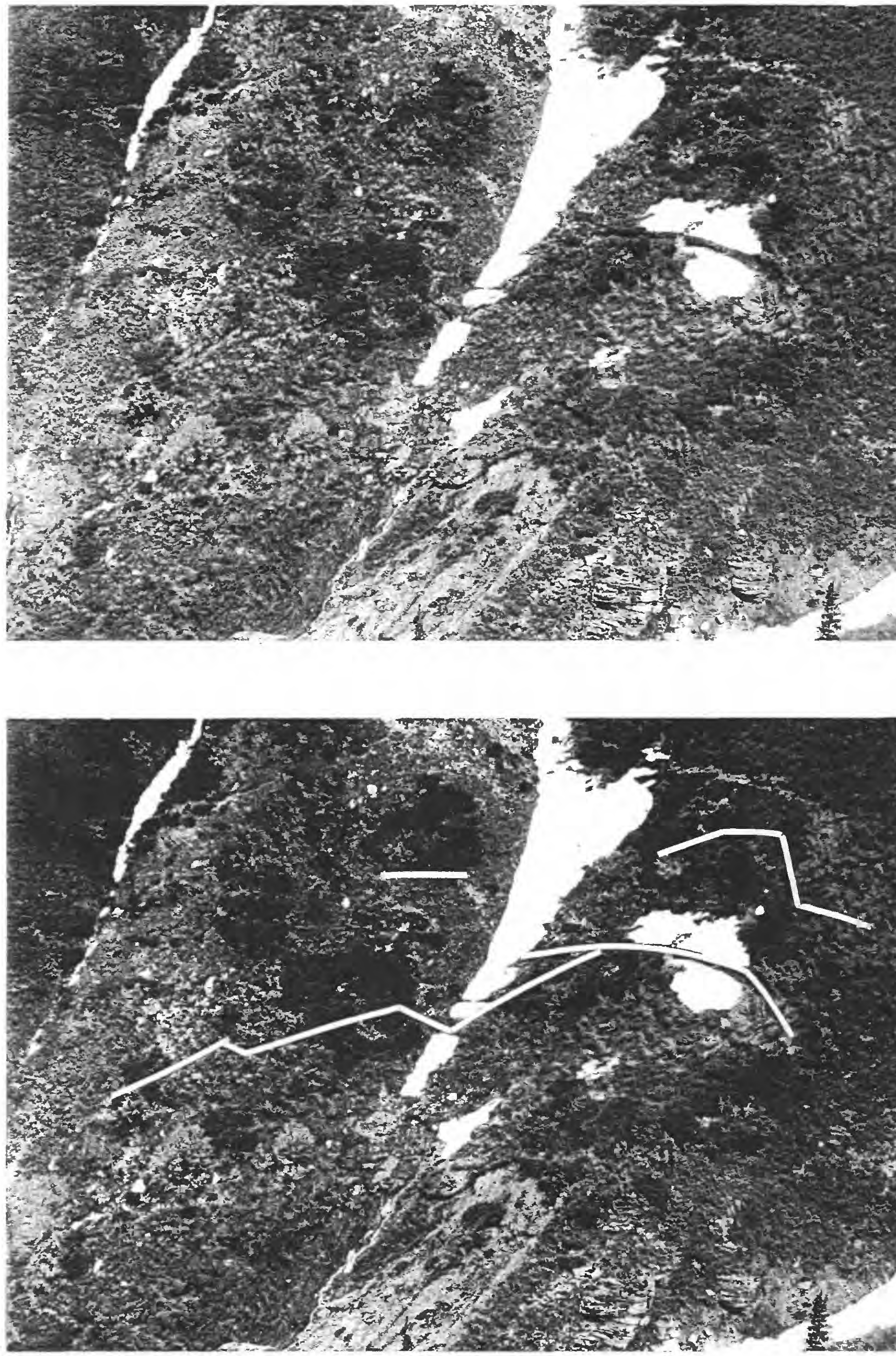


Figure 5B

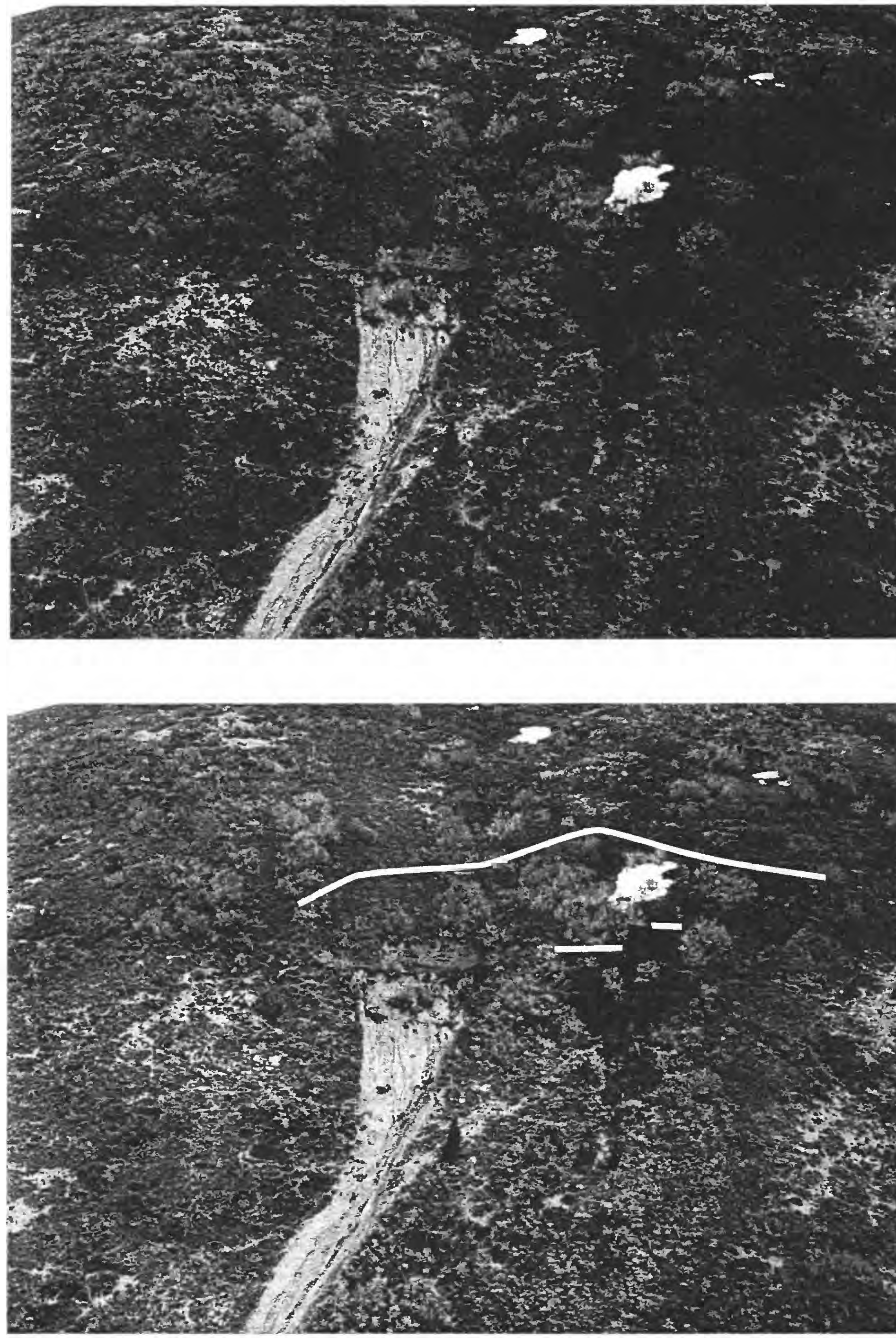


Figure 5C

Figure 6. Sketch maps of Ricks Creek/Ford Canyon landslide complex and of Ward Canyon landslide.

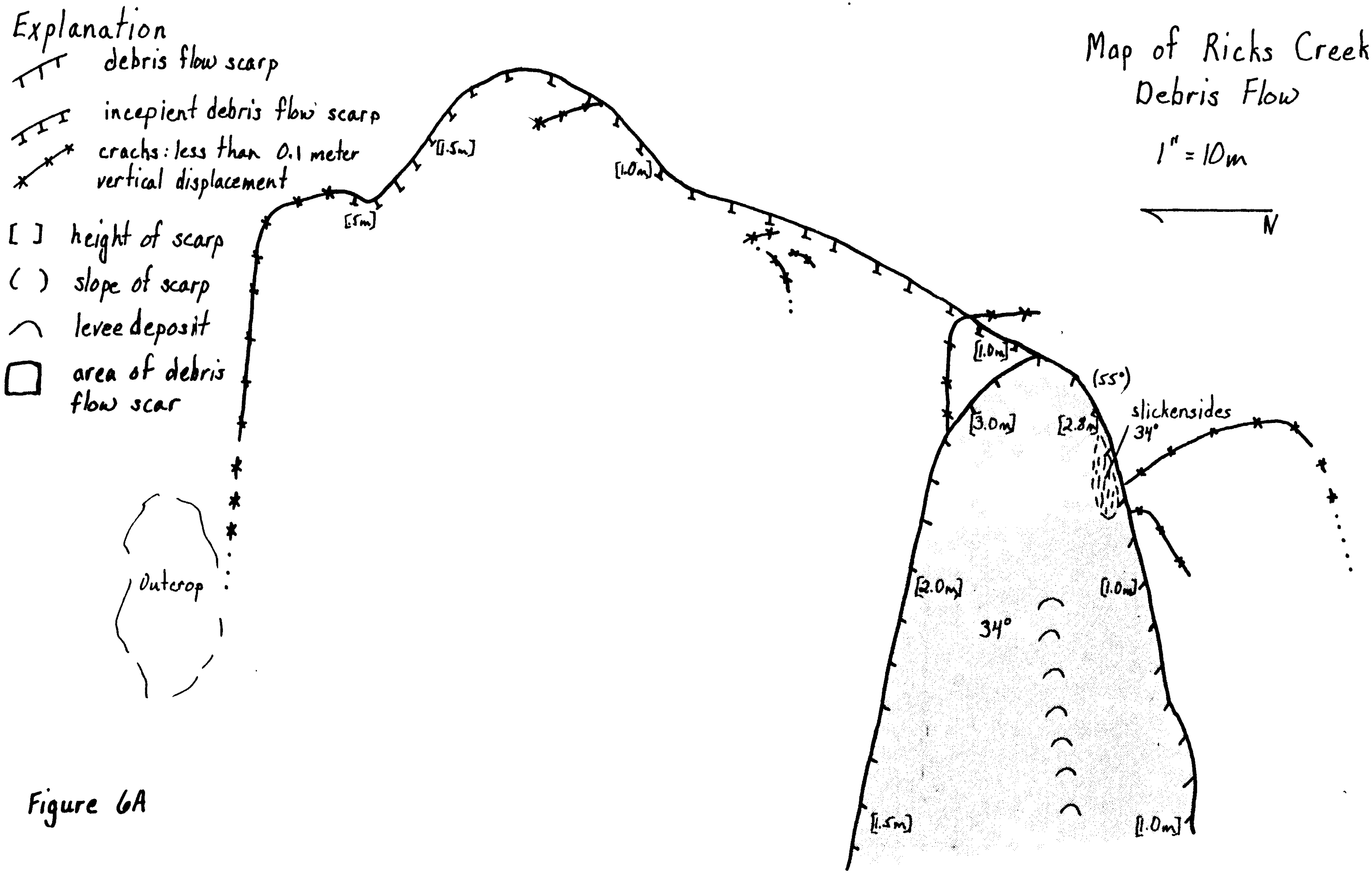
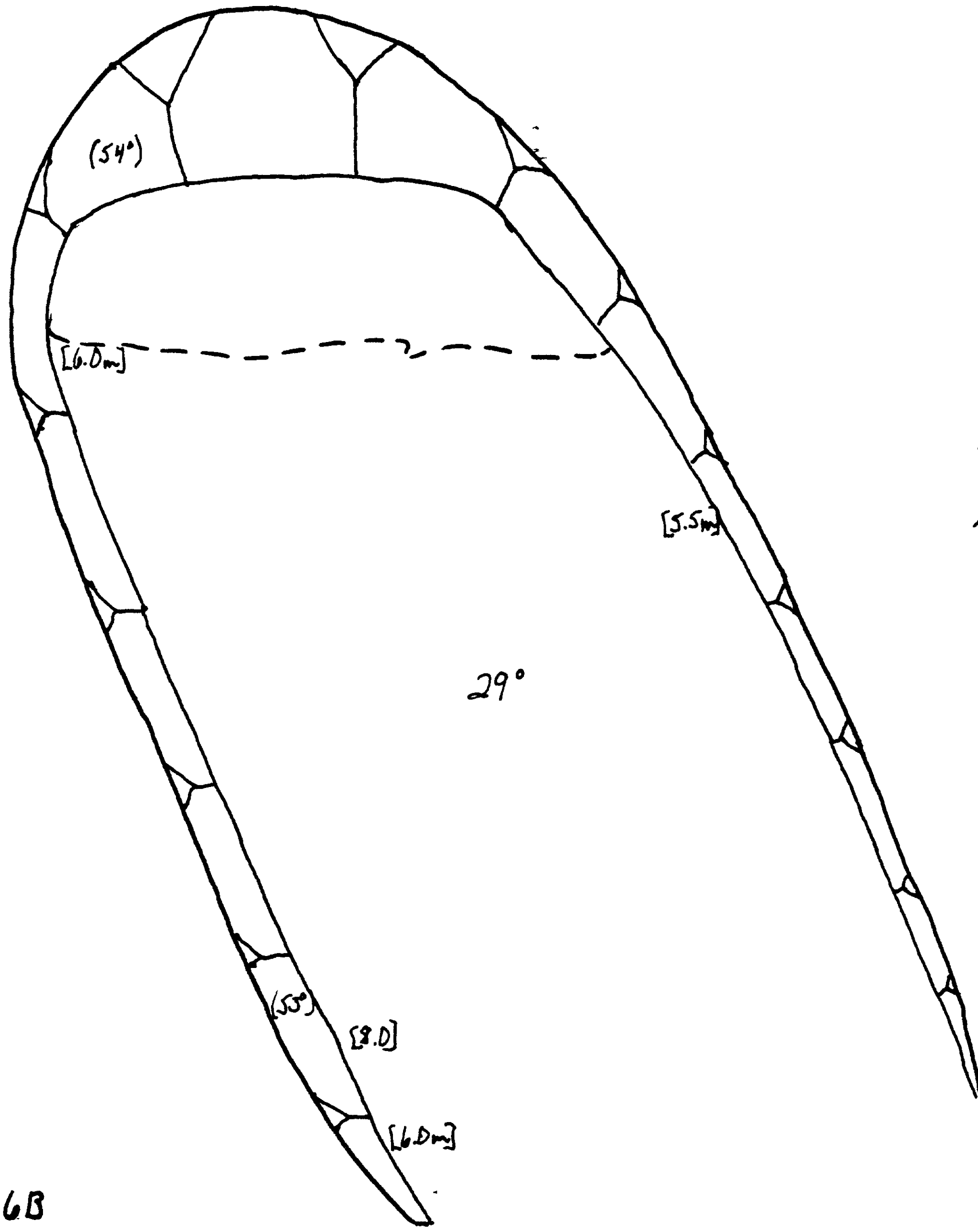

Map of Ricks Creek
Debris Flow
1" = 10m
N
Explanation
debris flow scarp
incepient debris flow scarp
cracks: less than 0.1 meter
vertical displacement
[ ] height of scarp
( ) slope of scarp
levee deposit
area of debris
flow scar
[.5m]
[1.5m]
[1.0m]
[1.0m]
(55°)
slickensides
34°
[3.0m]
[2.8m]
[2.0m]
[1.0m]
34°
[1.5m]
[1.0m]
Outcrop

Figure 6A



Map of Ward 3
Debris Flow
1" = 10m

N

Explanation

debris flow scarp

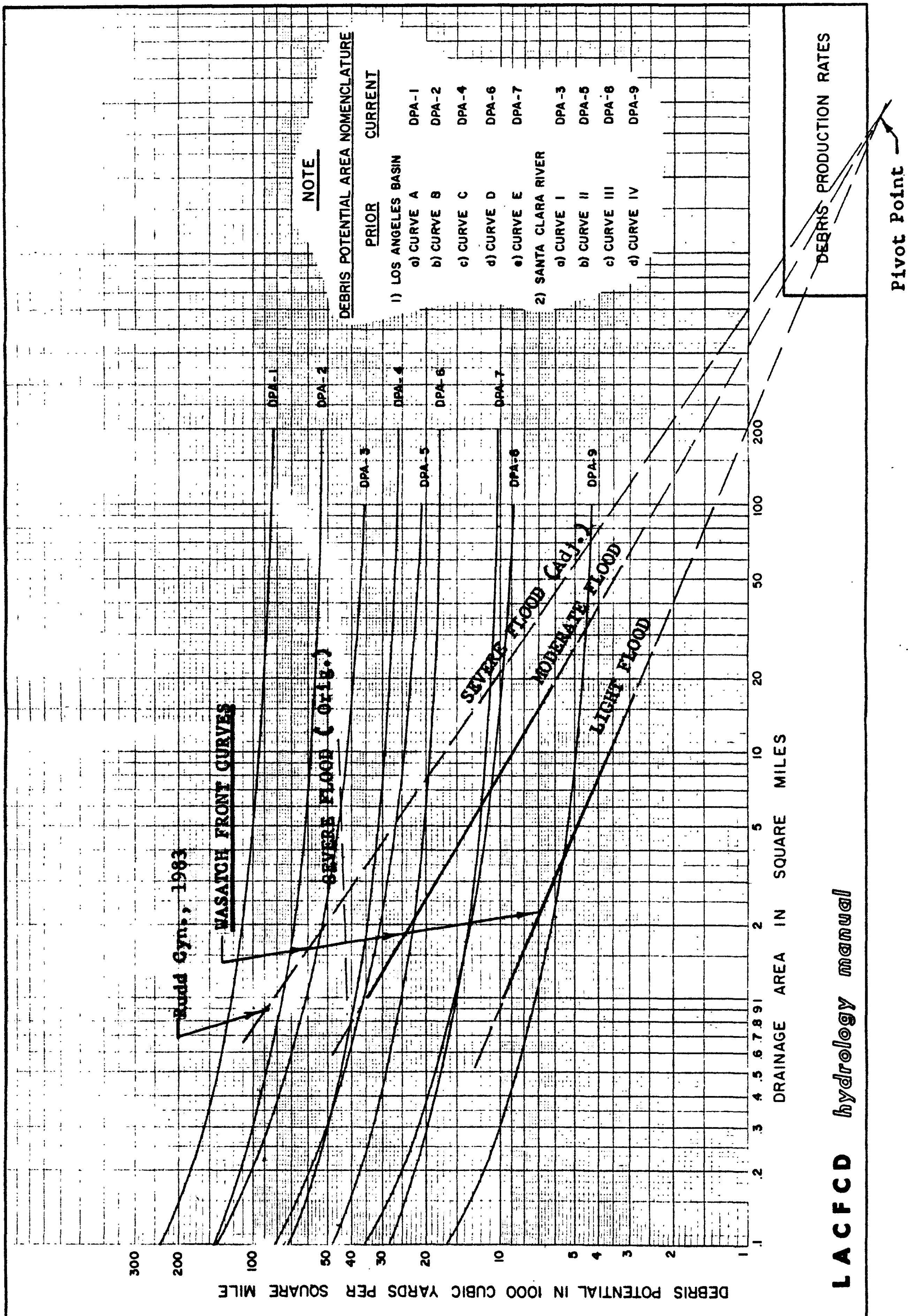
[ ] height of scarp

( ) slope of scarp

front edge of partly detached landslide

Figure 6B

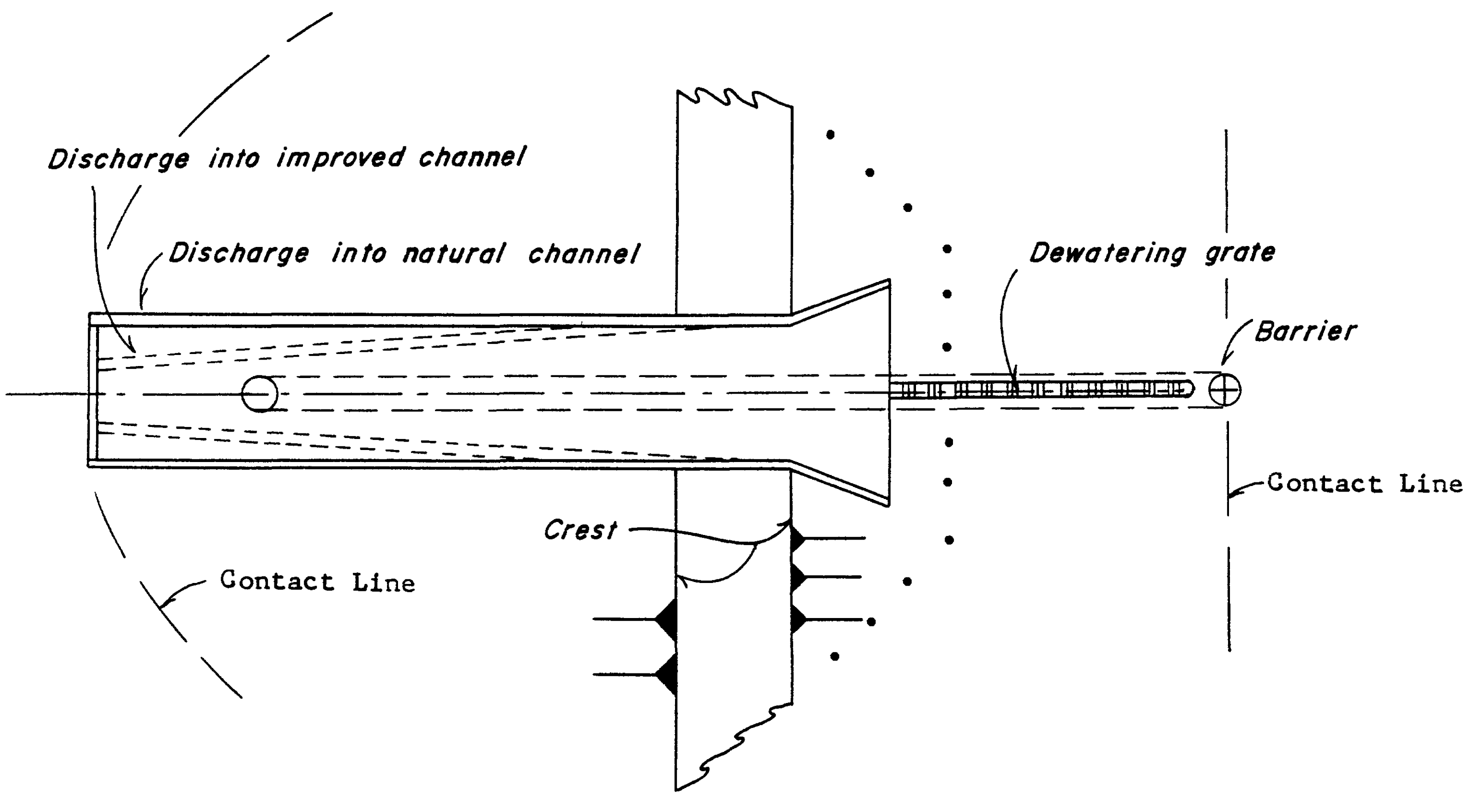
Figure 7. Graph showing potential for debris production



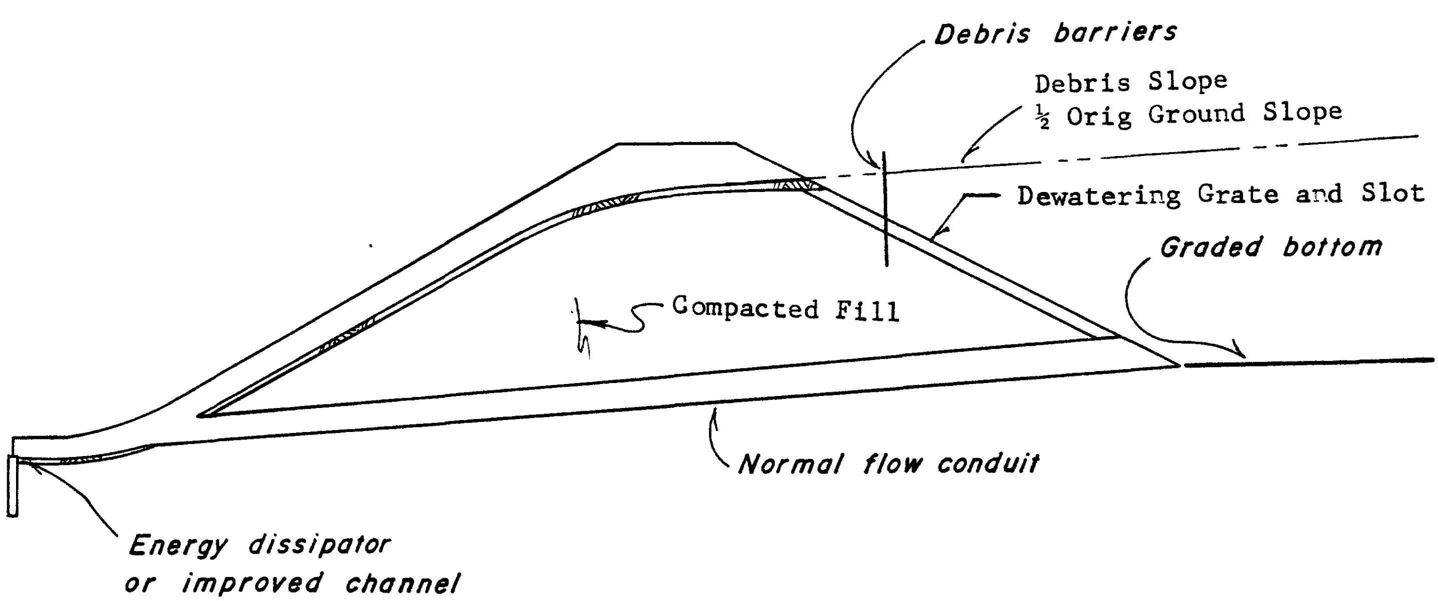
DEBRIS PRODUCTION RATES
NOTE
DEBRIS POTENTIAL AREA NOMENCLATURE
PRIOR
CURRENT
1) LOS ANGELES BASIN
a) CURVE A DPA-1
b) CURVE B DPA-2
c) CURVE C DPA-4
d) CURVE D DPA-6
e) CURVE E DPA-7
2) SANTA CLARA RIVER
a) CURVE I DPA-3
b) CURVE II DPA-5
c) CURVE III DPA-8
d) CURVE IV DPA-9
Pivot Point
Rudd Cyn., 1983
WASATCH FRONT CURVES
SEVERE FLOOD (Orig.)
SEVERE FLOOD (Adj.)
MODERATE FLOOD
LIGHT FLOOD
DEBRIS POTENTIAL IN 1000 CUBIC YARDS PER SQUARE MILE
DRAINAGE AREA IN SQUARE MILES
LACFCD hydrology manual

FIGURE 7

Figure 8. Typical debris basin.

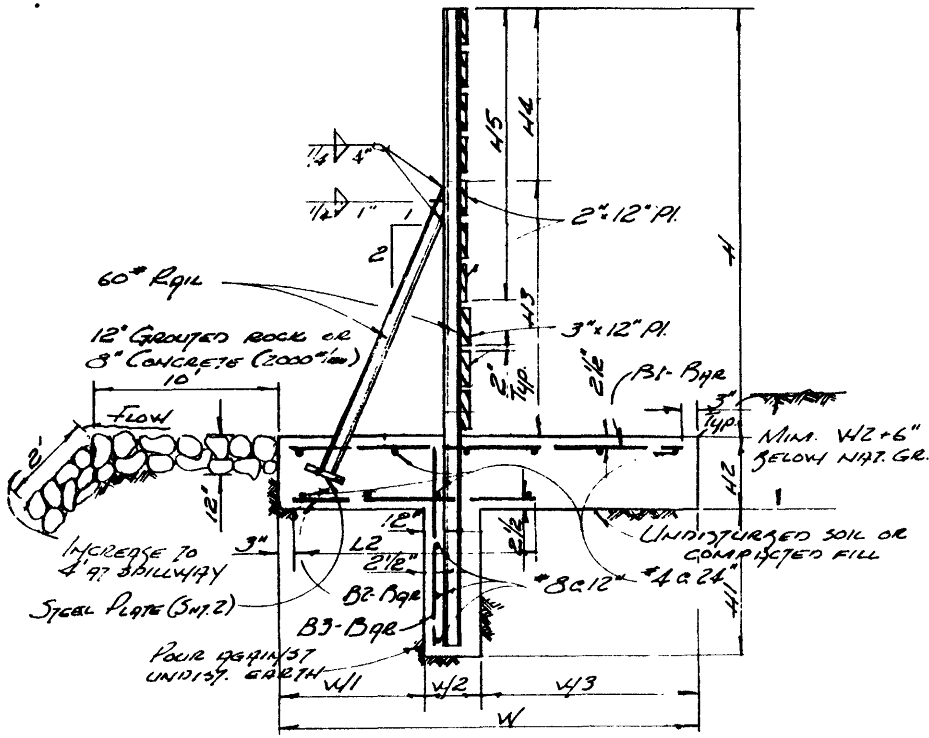


PLAN



SECTION

Figure 9. Rail-and-timber barrier.



TYPICAL SECTION

Wall Details		A	B	C	D	E
Wall Ht.	H	15'-2"	14'-0"	11'-8"	9'-4"	7'-0"
Rail Spc.	S	3'-0"	3'-6"	4'-6"	4'-6"	4'-6"
Key Depth	H1	7'-0"	6'-6"	5'-6"	5'-6"	4'-0"
Slab Thick.	H2	18"	18"	15"	15"	15"
Strut Loc.	H3	9'-3"	8'-5"	7'-3"	5'-9"	4'-4"
Strut Loc.	H4	5'-11"	5'-7"	4'-5"	3'-7"	2'-8"
⚠2 Loc. of 3"x12" O.F. #2	H5	11'-8"	8'-2"	3'-6"	3'-6"	3'-6"
Loc. of 3"x12" O.F. #3	H5	5'-10"	3'-6"	0'-0"	0'-0"	0'-0"
Slab Width	W	25'-0"	21'-6"	19'-0"	14'-3"	10'-6"
Toe Length	W1	6'-0"	5'-6"	4'-0"	3'-3"	2'-6"
Key Thick.	W2	2'-0"	2'-0"	2'-0"	2'-0"	2'-0"
Heel Length	W3	17'-0"	14'-0"	13'-0"	9'-0"	6'-0"
Bar B1	No	#8@6	#8@8	#8@9	#6@12	#4@12
Bar B1	L1	24'-6"	21'-0"	18'-6"	13'-9"	10'-3"
Bar B2	No	#8@12	#8@16	#8@18	#6@24	#4@12
Bar B2	L2	8'-3"	8'-0"	7'-9"	4'-6"	3'-0"
Bar B3	No	#6@6	#6@8	#6@9	#6@12	#4@18

SECTION DETAILS

BARRIER WALL DETAILS

⚠2 INDEX TO DRAWINGS

⚠2 GENERAL NOTES

1. CONSTRUCTION SHALL NOT BE STARTED UNTIL PROJECT ENGINEER HAS VERIFIED BARRIER LOCATION IN THE FIELD.
2. FOOTING SHALL NOT BE POURED UNTIL PROJECT ENGINEER AND/OR DISTRICT GEOLOGIST HAS EXAMINED FOOTING AND KEY EXCAVATION.
3. PLANKS ABOVE A HEIGHT OF H/2 SHALL NOT BE PLACED UNTIL FOOTING CONCRETE HAS CURED FOR 7 DAYS.
4. ON PROJECTS WHERE AN ACCESS ROAD TO THE BACK OF BARRIER IS NOT PROVIDED CONSTRUCT REMOVAL PANEL AS SHOWN ON SHEET NO. 10 UNLESS OTHERWISE INDICATED ON PROJECT DRAWINGS.

REVISIONS		
MK	DATE	DESCRIPTION
⚠1	11-81	Added Sh. 10 & added Note 4.
⚠2	10-82	Added General Notes, deleted Notes and revisions

DESIGNED BY R.J. Smith
CHECKED BY D.N. Short
DRAWN BY R.J. Smith

LOS ANGELES COUNTY FLOOD CONTROL DISTRICT

BARRIER - RAIL AND TIMBER

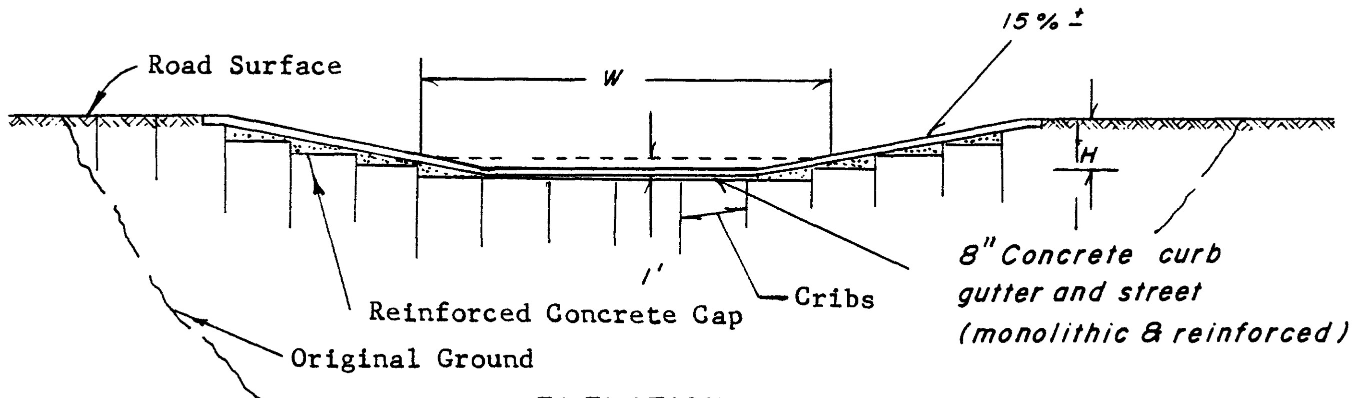
GENERAL NOTES AND ⚠2 BARRIER WALL DETAILS

RECOMMENDED BY
APPROVED BY
DEPUTY ENGR.

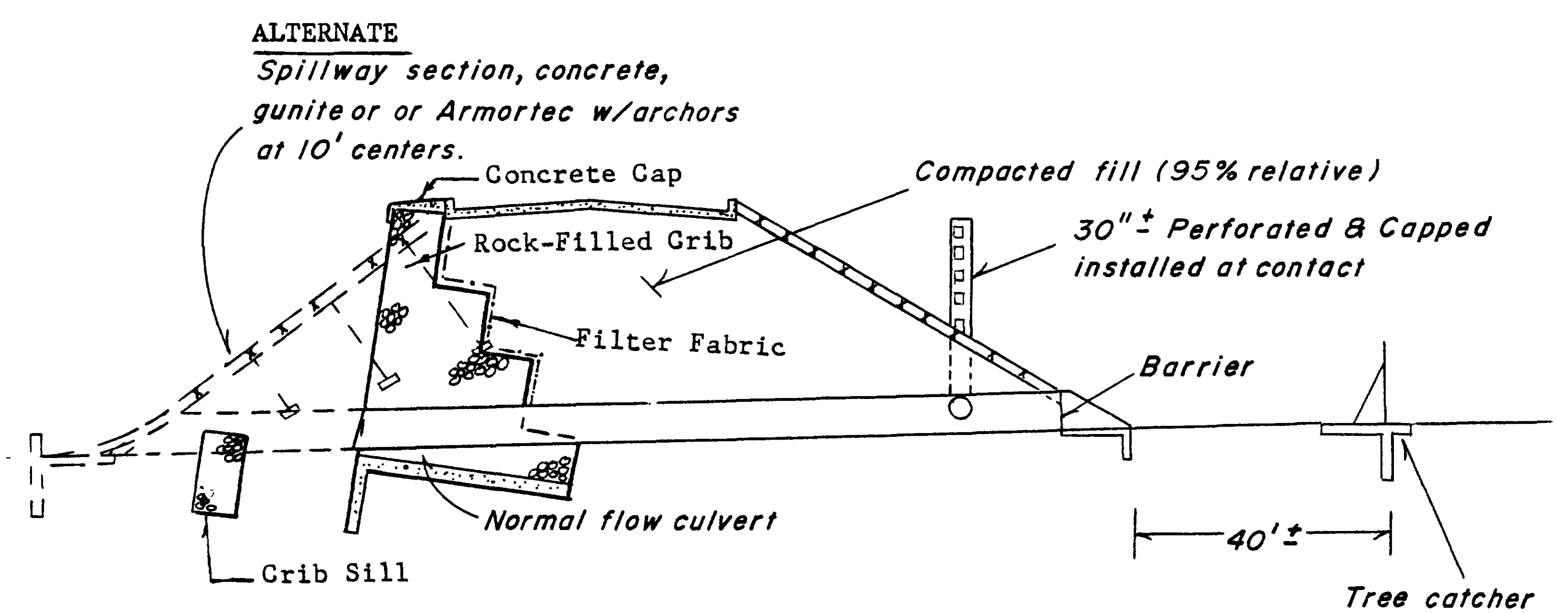
DATE OCT. '79 SCALE: A.S.
NO. 2-D OC B1.1
SHEET 1 OF 10 ⚠1

FIGURE 9

Figure 10. Depressed street basin.



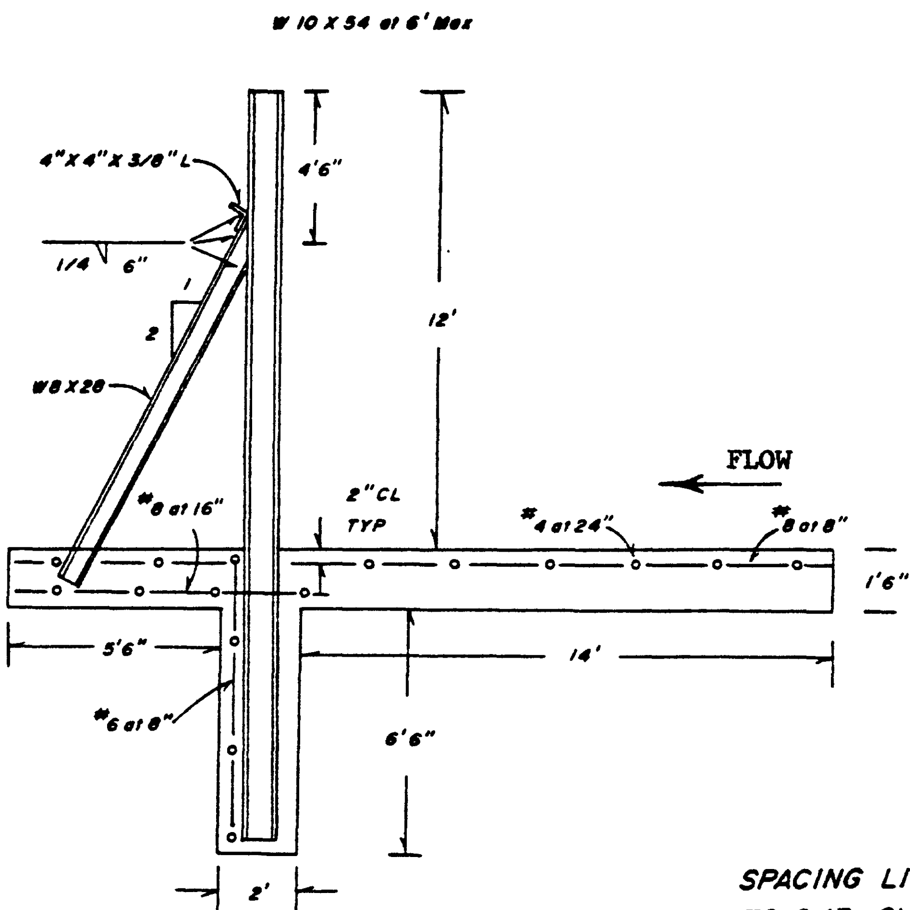
ELEVATION



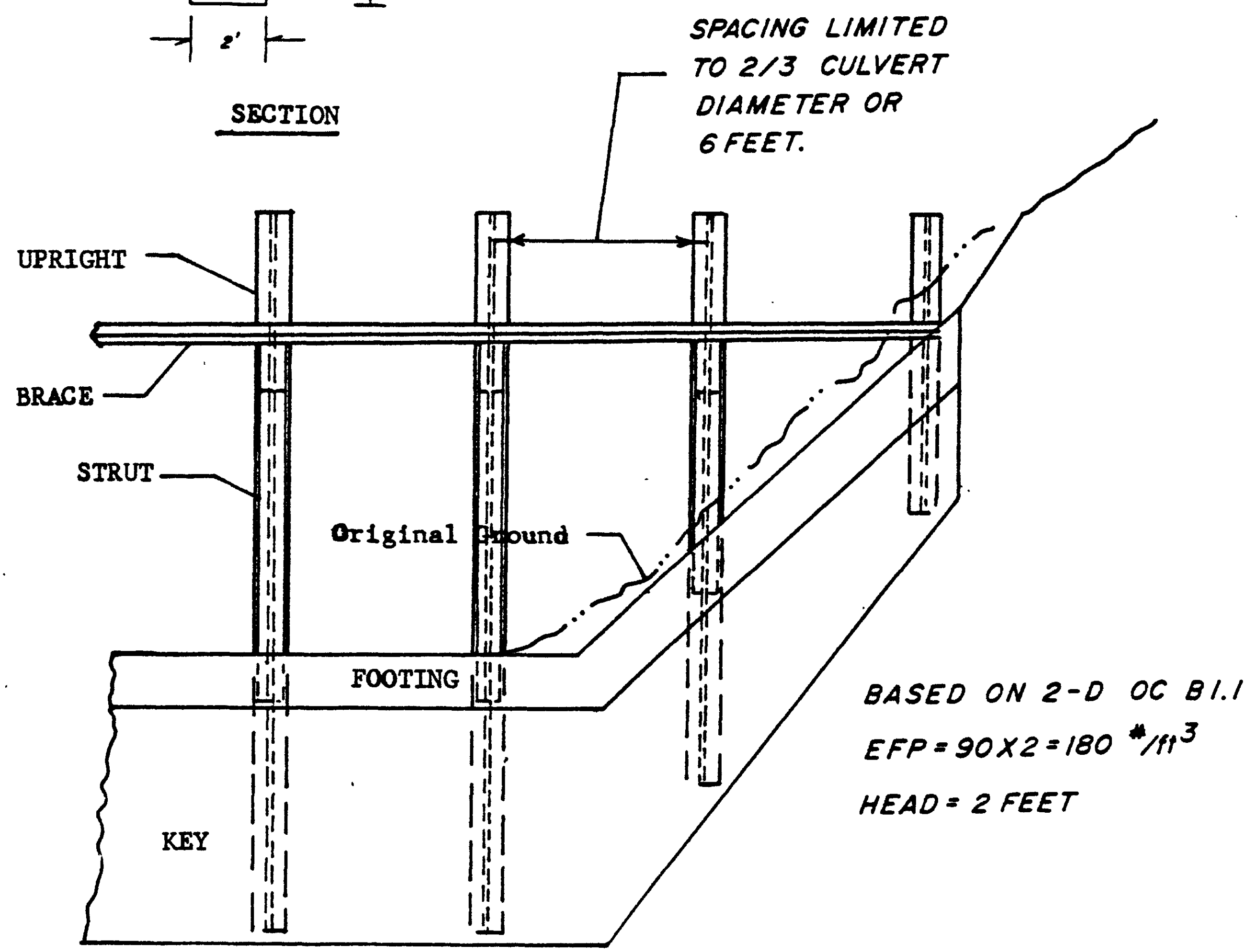
SECTION

NOTE: Soil cement fill is Recommended for alternate without a concrete spillway.

Figure 11. Tree catcher.



SECTION

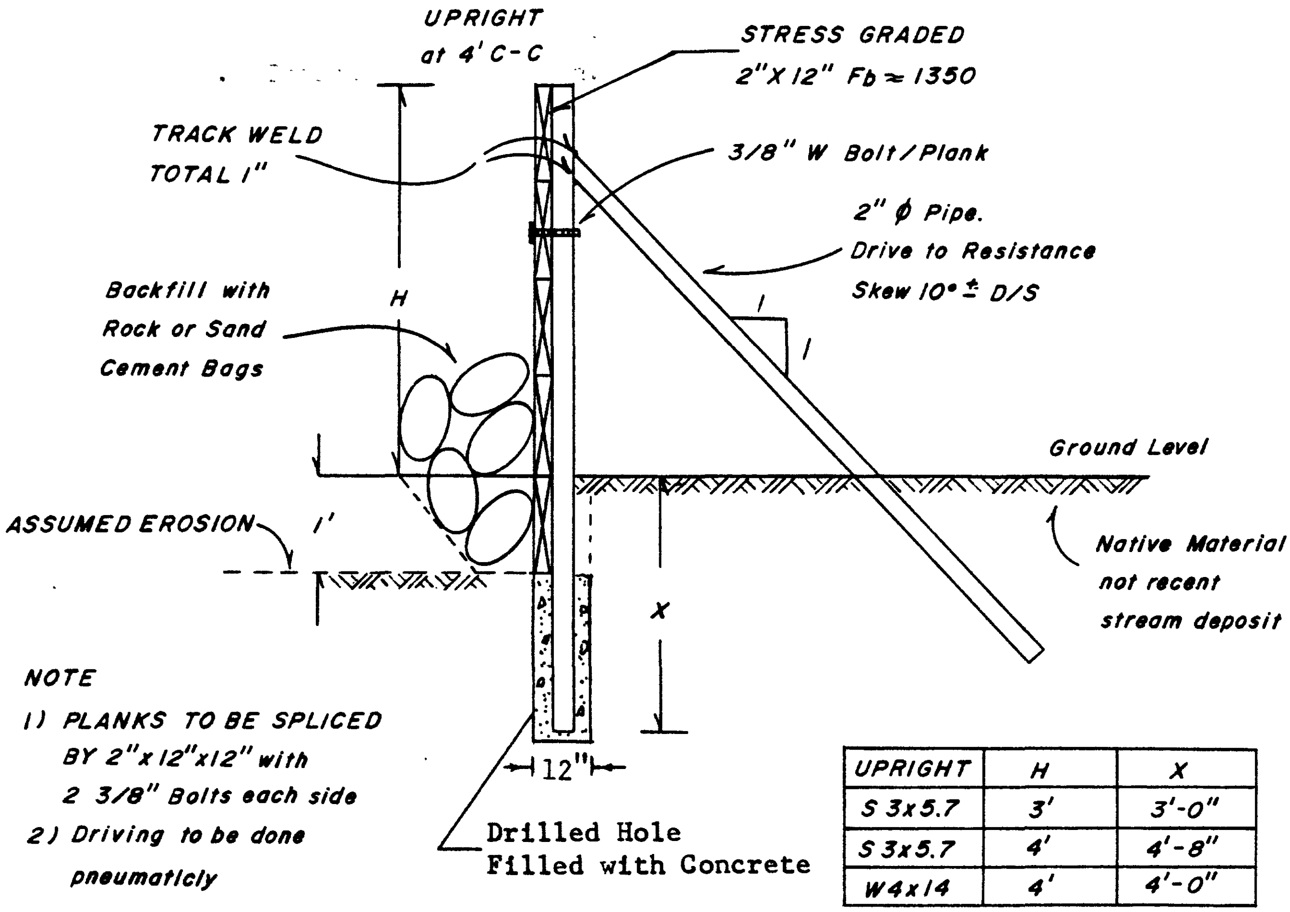


TREE CATCHER

PARTIAL ELEVATION

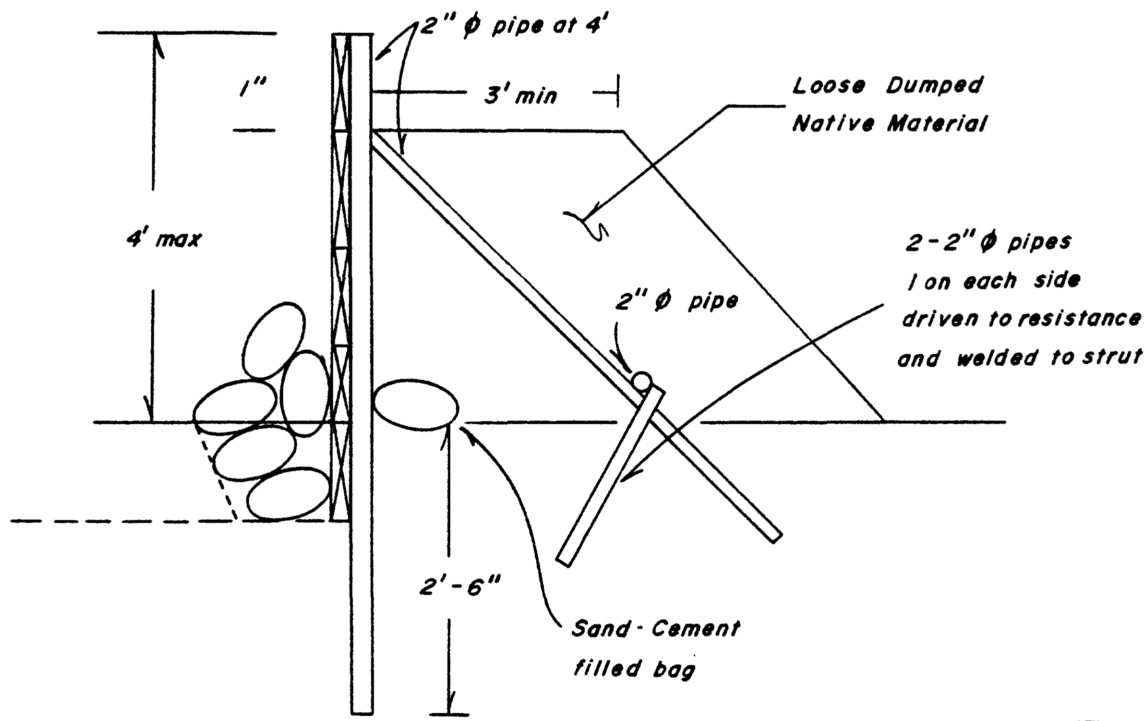
FIGURE 11

Figure 12. Temporary rail-and-timber revetments.



UPRIGHT	H	X
S 3x5.7	3'	3'-0"
S 3x5.7	4'	4'-8"
W4x14	4'	4'-0"

A FREE-STANDING

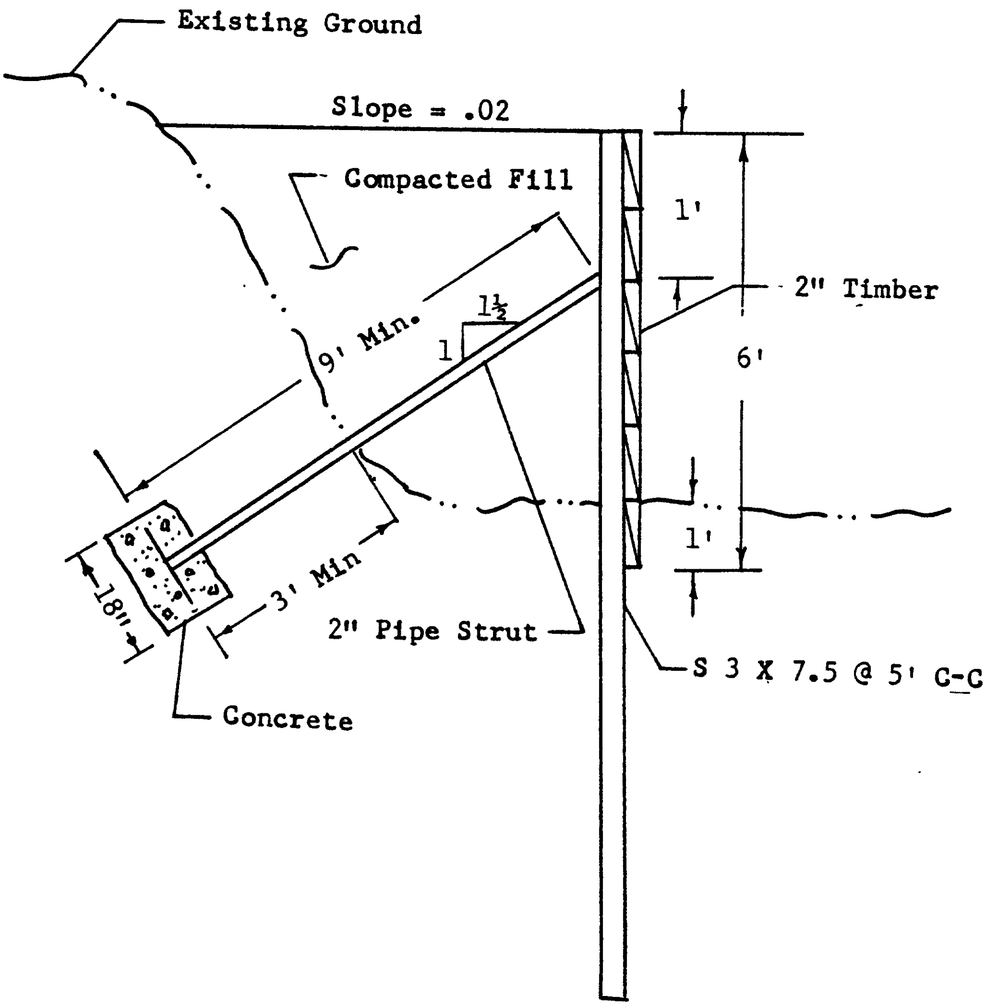


TEMPORARY RAIL AND
TIMBER REVETMENTS

Details not shown are same as above

FIGURE 12 A & B

B BACKFILLED



C RETAINING

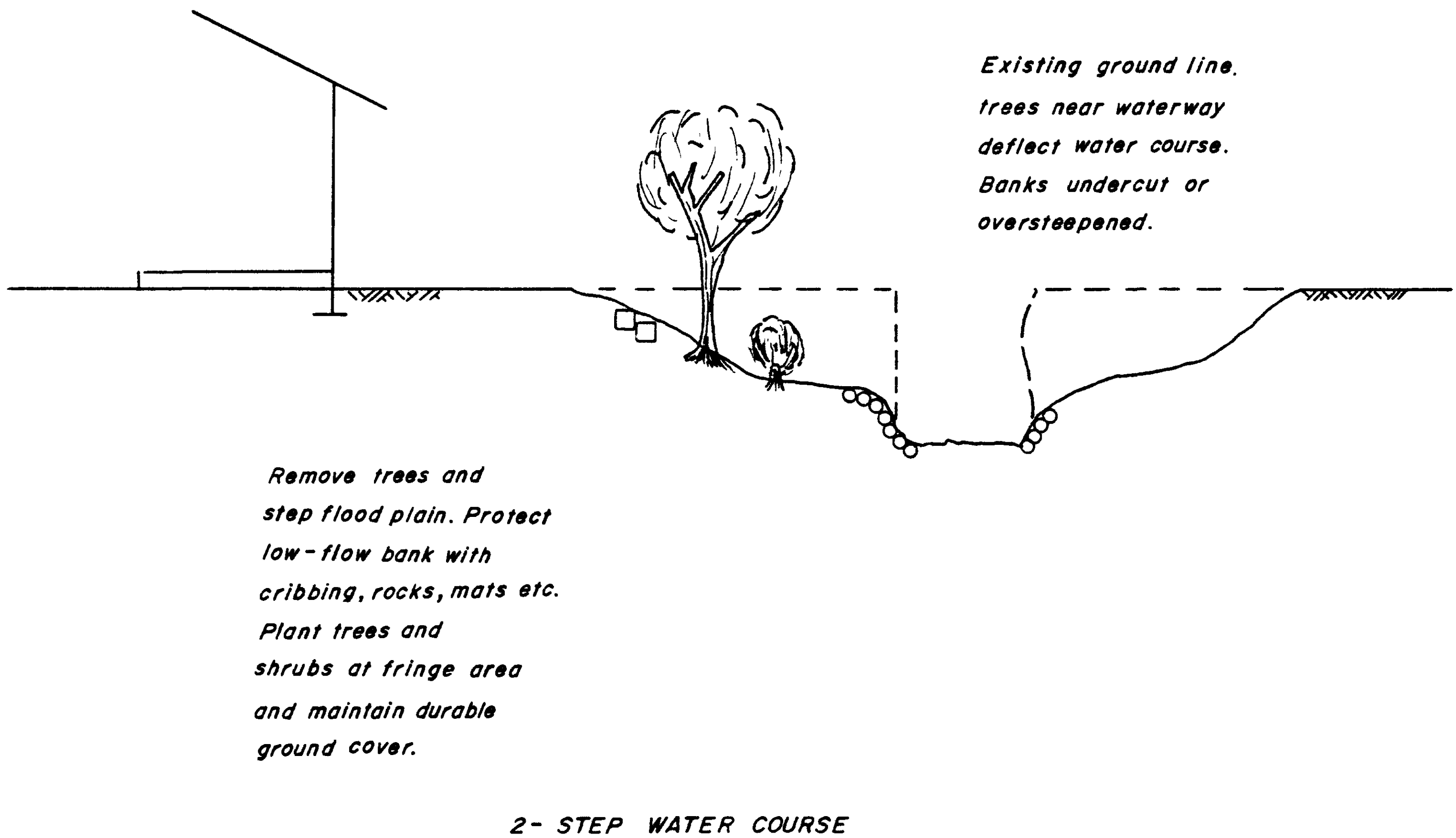
NOTE:

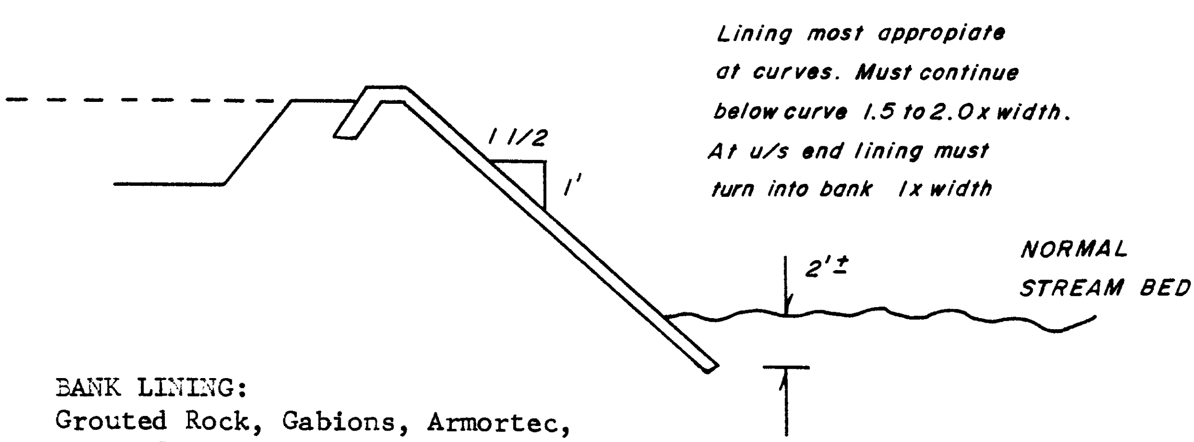
1. Timber shall be Douglas Fir No. 1, rough sized and creosoted.
2. A 3/8 inch U bolt shall be installed for each plank.
3. Backfill shall be granular and free-draining.

TEMPORARY RAIL AND
TIMBER REVETMENTS

FIGURE 12 C

Figure 13. Watercourse improvements.



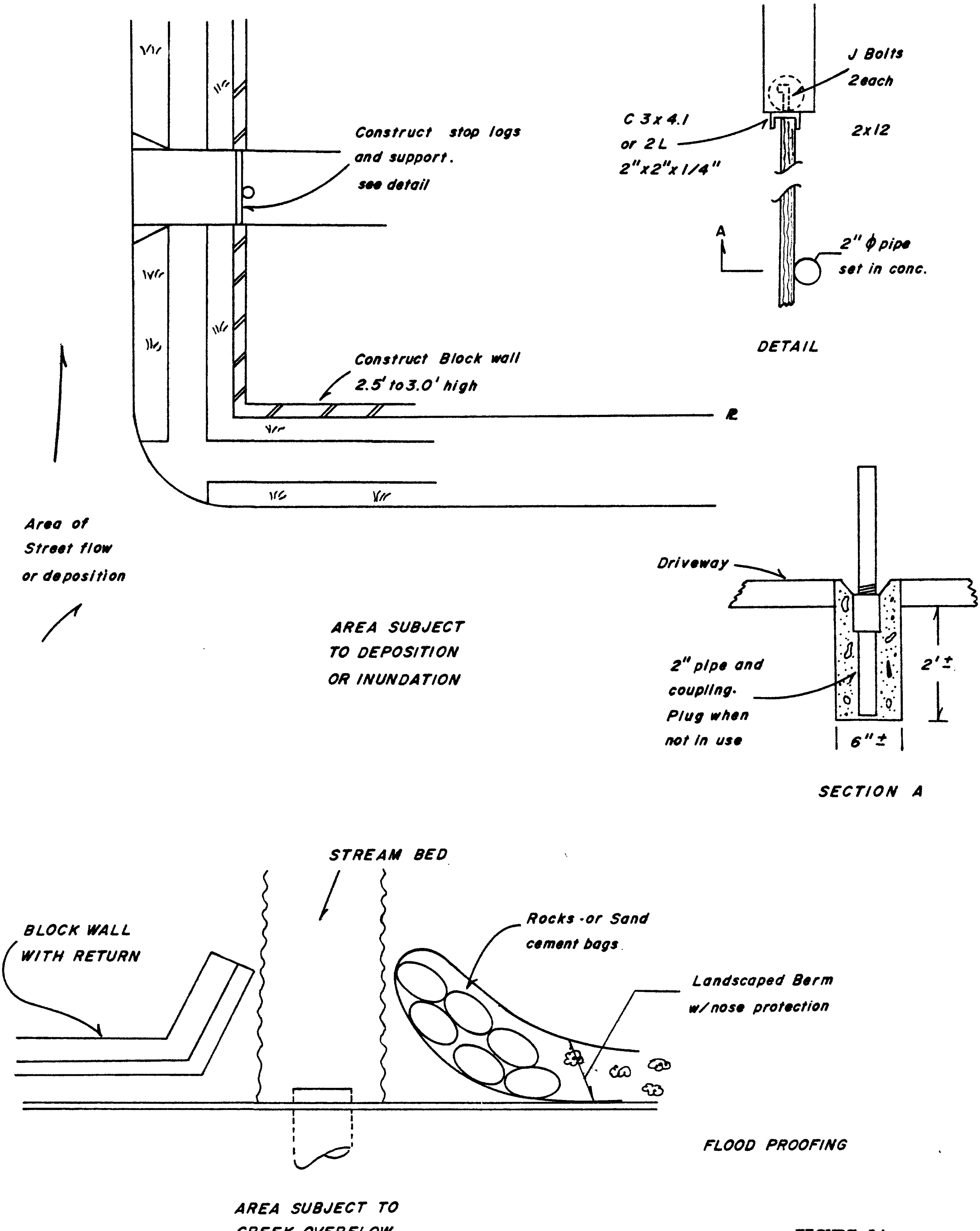


BANK LINING:
Grouted Rock, Gabions, Armortec,
Grass Crete, Fabriform, Cribbing,
Sand-Cement Bags etc.

LEVEE

WATER COURSE

Figure 14. Flood-proofing measures.



FLOOD PROOFING

FIGURE 14

Table 1 - Evaluation of Potential for Debris Flow and Debris Flood From Canyons

Drainage (South to North)	Historic & Prehistoric Documentation of Debris Flows and Debris floods reaching canyon mouth	Volume (m^3) of Largest Single Debris Flow 1983	Largest Estimated Volume (m^3) of Single Partly-Detached Landslide	Average Main-Channel Gradient	Evaluation of Potential: Debris Flow	Evaluation of Potential: Debris Flood
City Creek	1854[5], 1864[5], 1874[5], 1879[5]	Minimal	---	-	B	b
Mill Creek	alluvial fan[1]	Minimal	---	-	D	b
Kenney Creek	historic, multiple prehistoric[2]	Minimal	---	-	B	b
Holbrook Canyon	None	22,000±4,000	42,000±5,000	.120	A	a
Stone Creek/ Ward Canyon	prehistoric[3], 1983[3]	15,500±1,500	2,000±500	.126	B	a
Centerville Canyon	alluvial fan[1]	2,000±200	---	.140	D	b
Parrish Canyon	1930[5], 1930[5]	1,000±200	50,000±10,000	.177	A	a
Barnard Canyon	1930[5]	6,400±1,000	10,000±2,000	.195	C	a
Ricks Creek/ Ford Canyon	1901[5], 1923[5], 1929[3], 1930[5], 1934[5]	1,040±200	4,000±500	.203	B	a
Davis Creek	1878[5], 1901[5], 1903[5], 1923[5], 1929[3], 1930[5]	Minimal	---	.305	B	b
Steed Canyon	prehistoric[3], 1901[5] 1923[5], 1930[5]	10,000±2,000	25,000±5,000	.341	A	a
Rudd Canyon	prehistoric[3], 1983[3,7]	64,000[7]	70,000-100,000	.314	A	a

Farmington Canyon	1878[5], 1923[5], 1926[5], 1936, 1947[4]	17,000±3,000	40,000±5,000	.127	A	a
Shepard Creek	alluvial fan[1]	5,000±1,000	2,000±200	.175	D	a
Baer Creek	prehistoric[3], 1912[4], 1923[4], 1927[4], 1945[4], 1947[4]	2,400±400	20,000±5,000	.166	A	a
Holmes Creek/ Webb Canyon	alluvial fan[1], 1917[5]	Minimal	---	.209	C	b
S. Fork Kays Creek	1912[4], 1923[2], 1927[2], 1930[4], 1945[2], 1947[2]	Minimal	---	.203	B	b
M. Fork Kays Creek	prehistoric[1], 1947[2]	Minimal	---	-	C	b
Waterfall Canyon	1923[4]	Minimal	---	-	C	b
Ogden Canyon	1888[5], 1923[4,5], 1980[6]	Minimal	---	-	C	c
Coldwater Canyon	prehistoric[1], 1983[3,8]	12,000±2,000	---	.205	B	b
Willard Canyon	prehistoric[1], 1912[5], 1923[4], 1936[5]	8,000± 1,000	10,000±2,000	.195	A	a
Facer Canyon	multiple prehistoric[3], alluvial fan[1]	3,000±500	30,000±5,000	.307	A	a
Threemile Creek/ Perry Canyon	1923[4,5], alluvial fan[1]	Minimal	---	-	C	b

Sources of information:

[1]Miller (1980)
[2]Winkelaar, U.S. Forest Service, (oral commun., 1983)
[3]determined during this study
[4]Croft (1981)
[5]Woolley (1946)
[6]Thom Heller, U.S. Forest Service (oral commun., 1983) - both 1923 and 1980 events reported in tributaries to Ogden Canyon
[7]Kaliser, Utah Geologic and Mineral Survey (oral commun., 1983)
[8]Pierson, U.S. Geological Survey (oral commun., 1983)

Notes:

1) Average gradient of main stream channel was estimated from elevation difference between confluence of tributaries in headwater region and canyon mouth, divided by main channel length.
2) Volume of debris in channel could be larger than estimated if several partly-detached landslides mobilized and entered main channel simultaneously or if substantial volume of material were incorporated from channel.
3) Volumes of partly-detached landslides, estimated from aerial photos taken from helicopter and calibrated by comparison with more closely measured volumes of debris flows on Rudd, Ricks and Ward drainages.
4) Historic and prehistoric debris-flow events are underscored. Determination of whether a pre-1983 event was a debris flow or debris flood was based in part on the authors interpretation of the original citation.
5) The term "minimal" used in column 3 signifies that no landslides were observed during the spring of 1983 or that those observed were extremely small.
6) The symbol "---" in column 4 signifies that during our reconnaissance we did not observe partly-detached landslides. Such landslides may have been obscured by foliage by the time of our observation.

Plate 1 -
Map Showing Relative Potential for Both Debris Flows and Debris Floods to Reach Canyon Mouths

This map depicts the relative potential for debris-flow and debris-flood events to reach canyon mouths. Because the damage likely from these different processes may be different in type and areal extent, this map does not represent a risk evaluation.

Relative Potential for Debris Flow[1]	Debris-flow Criteria	Relative Potential for Debris Flood[2]	Debris-flood Criteria
Very high[3]	A, Canyons with existing partly-detached landslide of volume sufficient for debris flow to reach canyon mouth. This very high potential applies at least through the summer cloud-burst season and through the following winter and spring thaw.	Very high	a, Canyons with existing partly-detached landslides that could become mobilized as debris flows and subsequently diluted into debr floods. This very high potential applies at least through the summe cloud-burst season and through the following winter and spring thaw.
High	B, Evidence of more than one past debris flow reaching canyon mouth, indicating a recurrent long-term potential for debris flow.	High	b, At least one historic (including 1983) debris-flow or debris-flood scar or path regardless of volume or Evidence of past debris-flow or debris-flood at canyon mouth (fans mapped by Miller, 1980). This evidence suggests recurrent long-term potential for debris flood.
Moderate	C, Evidence of only one past debris flow reaching canyon mouth or Historic (including 1983) debris-flow scar or path suggesting volume sufficient for debris flow to reach canyon mouth.	Low	c, No old debris-flow scars or eviden of past debris floods.
Low	D, No evidence for past debris flows reaching canyon mouth.		

Symbols

○ Small range-front canyon having rating of moderate or higher; rating shown by letter designation

□ Approximate location of largest partly-detached landslide in each canyon.

[1] In debris flow, a combination of water, soil and rock form a muddy slurry, considerably more viscous than flowing water, that commonly moves downcanyon as a pulse

[2] In debris flood, soil and rock materials are transported by fast-moving flood waters.

[3] The assessment of very high potential for debris flow is based on the single largest volume of a partly-detached landslide within a canyon drainage, although in some cases more than one such landslide exists. The worst scenario could occur in the event that several of these partly detached landslides failed simultaneously and merged into a single debris flow within the canyon channel. The likelihood of such a scenario is judged to be very low, and therefore it was not factored into our assessment of potential for debris flows reaching the canyon mouth.