GEOLOGICAL SURVEY CIRCULAR 689

Effects of the May 5–6, 1973, Storm in the Greater Denver Area, Colorado

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1973

United States Department of the Interior
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Geological Survey
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Free on application to the U.S. Geological Survey, National Center, Reston, Va. 22092

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ABSTRACT

Rain began falling on the Greater Denver area the evening of Saturday, May 5, 1973, and continued through most of Sunday, May 6. Below about 7,000 feet altitude, the precipitation was mostly rain; above that altitude, it was mostly snow. Although the rate of fall was moderate, at least 4 inches of rain or as much as 4 feet of snow accumulated in some places. Sustained precipitation falling at a moderate rate thoroughly saturated the ground and by midday Sunday sent most of the smaller streams into flood stage. The South Platte River and its major tributaries began to flood by late Sunday evening and early Monday morning.

Geologic and hydrologic processes activated by the May 5–6 storm caused extensive damage to lands and to manmade structures in the Greater Denver area. Damage was generally most intense in areas where man had modified the landscape — by channel constrictions, paving, stripping of vegetation and topsoil, and oversteepening of hillslopes. Roads, bridges, culverts, dams, canals, and the like were damaged or destroyed by erosion and sedimentation. Streambanks and structures along them were scoured. Thousands of acres of croplands, pasture, and developed urban lands were coated with mud and sand. Flooding was intensified by inadequate storm sewers, blocked drains, and obstructed drainage courses. Saturation of hillslopes along the Front Range caused rockfalls, landslides, and mudflows as far west as Berthoud Pass. Greater attention to geologic conditions in land-use planning, design, and construction would minimize storm damage in the future.

INTRODUCTION

The Greater Denver area has had a long history of intensive rainstorms and infrequent but destructive floods. Though people are prone to forget, memories were refreshed by the storm of May 5–6, 1973, and the events that followed.

The weather forecast for Sunday, May 6, called for cooler temperatures, considerable cloudiness, and a chance of showers. Few people, therefore, took much note of the onset of a light drizzle late Saturday evening of May 5, but by early Sunday morning, the magnitude of the area-wide storm was becoming apparent to all. By midday, many small streams were flooding over their banks, reservoirs were spilling, and canals were overflowing. The South Platte River and its major tributaries were rising ominously toward peak discharges late Sunday night and early Monday morning.

Although the rate of precipitation on Sunday was not heavy by meteorological criteria, the long duration of steady rain and the total amounts in some places were exceptional. Some backyard rain gages showed more than 4 inches of moisture. The 24-hour depth measurements at rainfall-runoff stations of the U.S. Geological Survey ranged from 2.03 inches in Northglenn to 4.38 inches in northeast Denver (Ducret and Hansen, 1973, table 2). In northeast Denver a 100-year record was set for sustained precipitation for a 24-hour period.

Above an altitude of about 7,000 feet, most of the precipitation fell as snow. Twenty inches of heavy wet snow fell over broad areas of the mountains, and as much as 42 inches was reported at Black Mountain, west of Conifer (The Denver Post, May 9, 1973). Precipitation in the form of snow retarded runoff in these areas and, therefore, diminished the peak of flood discharge. Conversely, infiltration of moisture into the ground was increased, and, consequently, so was the potential for landsliding. Had all the moisture in the mountains fallen as rain, runoff would have been more rapid, and flooding would have been more intense, but infiltration would have been less, and there would have been fewer landslides.

In terms of local runoff in the metropolitan area of Denver, especially with respect to the smaller tributaries of the South Platte River, the May 5–6 storm was fairly commonplace. Residents can expect similar occurrences at fairly frequent intervals. Peak-flow recurrence intervals ranged from only 3 years at some sites to 20 years or more at others (Ducret and Hansen, 1973, tables 3, 4). The flooding of the South Platte itself was essentially a 50-year event.

In terms of geologic effects, such as scour and especially mass wastage, the storm was unusual — probably because of the thorough saturation of the ground that resulted from the moderate rate of sustained precipitation. In nearly 25 years of residence in the area, the author has not seen its equal.

The rainfall and flooding that accompanied the storm had widespread geologic and hydrologic effects, brought about through erosion, sediment transport and deposition, and slope failure. By "geologic effects" are meant the quasi-permanent changes, however small, in the character or form of the rocks, soils, and physical geography that together make up the landscape. Many of these effects were of a small scale compared to the gross geologic setting of the area, but they provided dramatic evidence of the irresistibility of geologic processes, and they accounted for a substantial part of the damage to the works of man. Thus, the deposition of a few inches of sediment on a few acres of ground, or the erosion of a few cubic yards of river bank, might be of little obvious note in the geologic scheme of things but might damage or destroy cropland or a section of highway worth many thousands of dollars. Similarly, the undercutting of the footing of a single bridge pier might destroy the whole bridge and necessitate the expenditure of many thousands of dollars for replacement or repair. A small landslide might jeopardize the integrity of a structure worth a large sum of money. Geologic processes set into motion by the storm thus caused extensive damage to lands and engineering works throughout the Greater Denver area and the South Platte River flood plain. Damaged roads, bridges, dams, canals, and the like, were the chief losses in the public sector.

PURPOSE OF THE REPORT

Because of the rapid present and projected growth of Greater Denver, problems related to storm drainage are likely to increase in scale and frequency in the future. Natural processes, once set into motion, may be very difficult to control, but man can, with foreknowledge, prevent or avoid many direct encounters. He can sometimes circumvent the effects of a major storm, and he can take steps to minimize the causes and effects of inundation. The first step is to assess and attempt to understand the causes of past storm damage.

This report, therefore, presents a capsule summary of the principal effects of the storm of May 5–6, 1973, in the hope that a broader public understanding of the effects of a past storm will lead to a greater awareness of the potential effects of future storms and to more effective measures to forestall storm damages in the future.

PLACE NAMES

Dozens of local place names are variously mentioned in this report. Most of these names are plotted on the location map (fig. 1), but to so identify all of them on a map of this size is not feasible. Such features as roads and street intersections are readily located from city maps and directories published by private and public agencies, including the U.S. Geological Survey's topographic maps at a scale of 1:24,000 (1 inch to 2,000 feet), which are available at map-sales outlets. Oil-company road maps of Denver and vicinity are available at most gasoline service stations and are very useful references. One or more of these sources can be consulted to locate place names closely enough for most purposes.

ACKNOWLEDGMENTS

Much information in this report was provided by Geological Survey colleagues who investigated flood effects in various parts of the Greater Denver area immediately after the storm; included were Roger B. Colton, Eugene R. Hampton, Robert M. Lindvall, John O. Maberry, Edward E. McGregor, and Howard E. Simpson. Local newspaper accounts have been freely utilized, also. David J. Varnes kindly loaned the original drawing from his diagram showing the nomenclature of a landslide

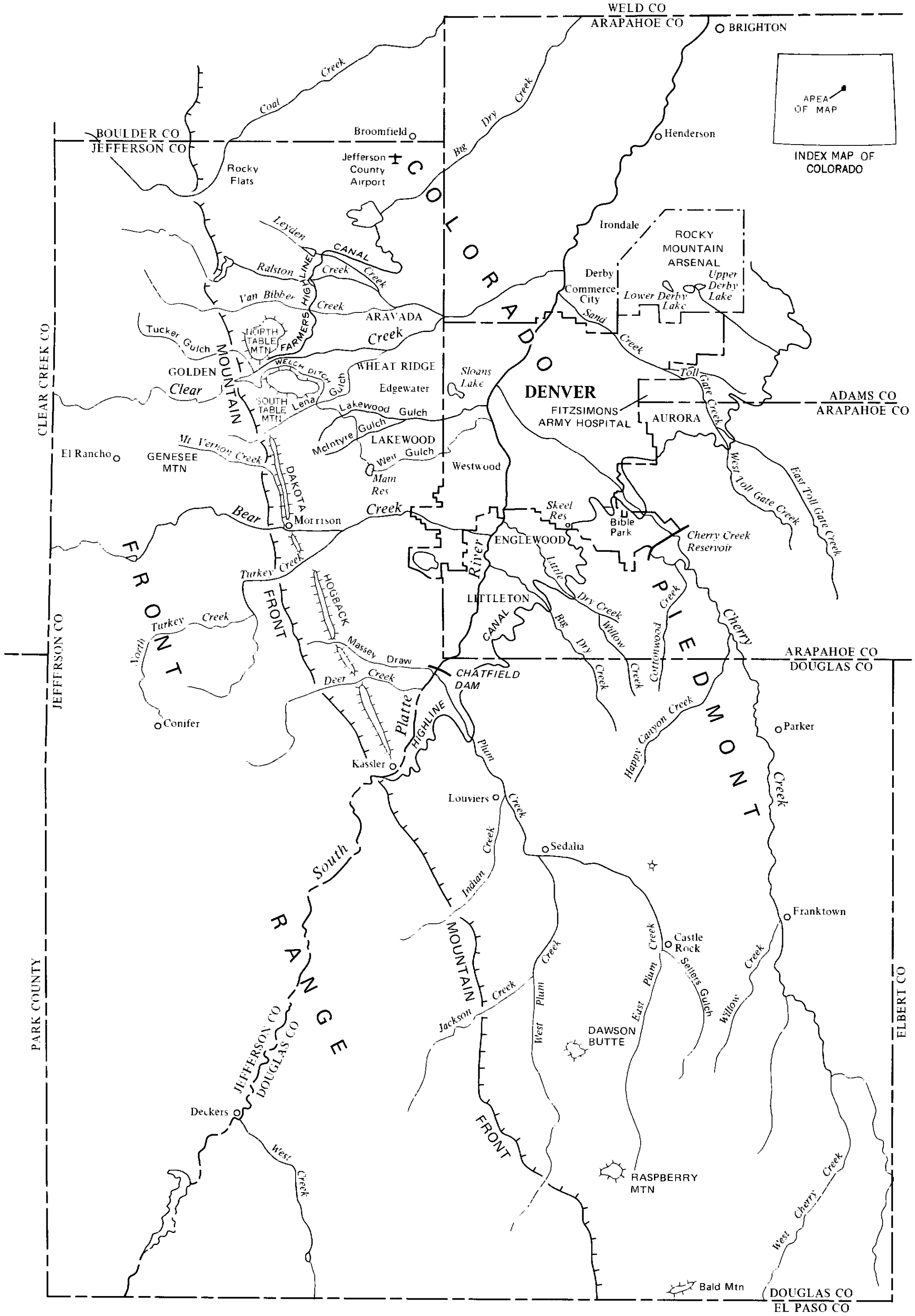

FIGURE 1. — Location map of the Greater Denver area.

(Varnes, 1958, pl. 1). The well-done sketches of rockfall, slump, debris slide, and earthflow were drawn by Natalie J. Miller of Menlo Park, Calif., and were first published by Tor H. Nilsen (1972). A companion report, dealing with the rainfall-runoff frequencies of the storm (Ducret and Hansen, 1973), has been published by the Urban Drainage and Flood Control District (Denver).

INUNDATION

A large part of the total storm damage was caused simply by inundation, with all its costly side effects. In the private sector, inundation was the chief cause of loss. Many homes, commercial buildings, warehouses, outbuildings, utilities, and railroad rolling stock and yards received damage. Side effects included the related spoilage of myriad household goods and other personal properties, waterlogging of croplands and pastures, the drowning of livestock, and the indirect loss of income of the flood victims. The list is endless.

Inundation resulted not only from overbank flooding of streams but also from the backup of water behind obstructions at bridges and culverts along tributaries that otherwise would not have gone out of their banks, or along artificial drainages that had not been intended to accommodate more than moderate volumes of storm runoff. Much flooding was aggravated by intensified drainage in urban areas where roofs, driveways, walks, streets, parking lots, and other impermeable surfaces contributed to high peak runoff.

The main stem of the South Platte River was out of its banks from Douglas County to the Nebraska State line, having crested in Denver late Sunday night, May 6, and early Monday morning, May 7. At peak discharge, its flood attained an approximate recurrence interval of 50 years at Littleton, 1.1×50 years at Denver below the mouth of Cherry Creek, and 1.4×50 years at Henderson (Ducret and Hansen, 1973, table 3). Flooding along the South Platte in the metropolitan area was heaviest in the vicinity of Chatfield Dam (under construction in 1973) and Centennial Racetrack in Littleton; in the vicinity of West Alameda Avenue and South Santa Fe Drive in the Westwood section of Denver, where Interstate 25 Highway was closed to traffic for several days; in the lower downtown area in the vicinity of the railroad yards; in Commerce City; in Henderson; and in Brighton.

Elsewhere in Greater Denver, urban flooding was heavy locally where tributaries went out of their banks or backed up behind obstructions (fig. 2). In particular, extensive areas in Englewood were inundated by Little Dry Creek, the peak discharge of which had an approximate recurrence interval of 20 years (Ducret and Hansen, 1973, table 4). Many places throughout Greater Denver were flooded by overflow from canals and ditches.

OVERWHELMING OF ARTIFICIAL DRAINAGE SYSTEMS

In many built-up areas artificial drainage systems were inadequate to accommodate the runoff, and water quickly rose to flood levels (fig. 3). Proportionately, the amount of runoff that reached trunk drainages in built-up areas was much larger than in nonbuilt-up areas of equal size, simply because runoff which otherwise would have infiltrated the ground drained off totally from impervious roofs, sidewalks, streets, gutters, and pavements. Drains designed to accommodate modest rainstorms were overwhelmed or blocked with debris, and as tributary drain systems merged, the problem was compounded. Many areas, such as much of Lakewood, simply lack adequate facilities to handle heavy storm runoff (The Lakewood Sentinel, May 10, 1973). Facilities that may have been adequate in the past, moreover, were suddenly unable to accommodate the surge of water from new subdivisions higher in the watershed. As growth continues, smaller and smaller storms are able to generate larger and larger discharge.

PROBLEMS WITH CANALS AND DITCHES

Many irrigation canals and ditches were quickly filled to the point of spillage and washout despite efforts to shut them off at the source. But the flow of a canal cannot be turned off like a water faucet just by closing a headgate that is, perhaps, miles away. Canals flow nearly along the contour of the ground, and they intercept storm runoff from many minor drainageways that normally carry no water. Highline Canal is a good example. It heads at the mouth of Platte Canyon and flows northeastward across the Greater Denver area to a point in Adams County east of the Rocky Mountain Ar-

FIGURE 2. — Flooding at East Jefferson Avenue and South Emerson Street in Englewood, caused by the overflow of Little Dry Creek. Denver Post photograph by John Prieto, May 6, 1973.

senal, intercepting many small drainages en route. Highline Canal was out of its banks in many places (fig. 4), especially in southeast Denver, where many basements were flooded. At Wellshire Municipal Golf Course it threatened Skeel Reservoir, which has no spillway and nearly overtopped its dam. Downstream at the Rocky Mountain Arsenal, overflow from the canal and the Montbello ditch breached Upper Derby dam, sent a surge of water into Lower Derby Lake, and threatened Irondale, 3 miles to the northwest. According to Quentin Hornback of the Denver Water Board (oral commun., relayed by Robert M. Lindvall) many small tributaries of the South Platte poured water into canals and ditches, such as Highline.

In Lakewood, much of the flood damage was caused by overflowing irrigation ditches. Spillage from Main Reservoir, taking excessive inflow from Welch ditch, flooded West Mississippi Avenue for 18 hours between South Kipling and South Garrison Streets (The Lakewood Sentinel, May 10, 1973). Normally, overflow of Main Reservoir is handled by Weir Gulch.

In Edgewater, sluggish drainage from an overflowing ditch backed up sewers in a four-block area near West 20th Avenue and Sheridan Boulevard, sent raw sewage into numerous basements, and caused the street to be closed for several hours. The problem has been recurrent. It was not caused exclusively by the storm, but it was aggravated by the storm. The Edgewater Volunteer Fire Department ultimately was forced to pump the water and sewage into nearby Sloans Lake in order to reopen street traffic (The Denver Post, May 9, 1973; The Lakewood Sentinel, May 10, 1973). Similar sewer backups were reported over wide areas of Greater Denver, the cause, for the most part, being the same: sanitary sewers were simply

FIGURE 3. — Flooding along Kennys Gulch at 21st and Ford Streets in Golden. Urban runoff and overflow of Welch ditch exceeded capacity of storm drains. Photograph by John R. Keith, May 6, 1973, at height of storm.

overwhelmed by the backup of water from overflowing ditches and storm sewers.

Outside the urban area, according to Don Svedman, State Deputy Commissioner of Agriculture, farmers and ranchers sustained heavy flood losses, partly the result of overfilled washed-out irrigation ditches (The Denver Post, May 8, 1973).

GEOLOGIC EFFECTS OF THE STORM

The processes of erosion, transport, and redeposition of materials by the floodwaters, and the infiltration of moisture into the ground — either directly from precipitation or indirectly by lateral soaking from flooded stream courses — altered the landscape in many ways. Streambanks and structures along the banks were attacked by scour, and, in many places, were destroyed. Thousands of acres of flooded lands were coated with mud and sand. Saturated hillsides and streambanks gave way under the added weight of the moisture. Locally, rocks bounded down hillsides onto roads and highways.

For discussion purposes, the geologic effects of the storm are here grouped by process under the three main headings "Scour," "Sedimentation," and "Mass Wastage." Scour predominated over other processes in its effects on manmade structures and the resultant damage costs. Mass wastage—mainly landsliding—was widespread in hilly areas, but its economic consequences were much less than those of scour. Sedimentation was the least destructive of all in the Greater Denver area, although it did much damage to croplands downstream along the South Platte River.

SCOUR

The sediment-carrying capacity of a stream increases enormously in flood. As the volume of water rises, so does the velocity, and with increased velocity, the carrying capacity increases geometrically — the enlarged stream, flowing faster, scours its channel and quickly acquires a load of sediment. Conversely, the sediment carried in flood is quickly dropped when stream velocity is reduced.

Nearly all perennial streams in the area, and countless intermittent ones, scoured segments of their banks and beds. Scour was a major cause of damage along the South Platte itself, as well as along its tributaries. Scour was most noticeable in cutbanks at the outsides of bends, where the force of the current has the most

FIGURE 4. — Highline Canal out of its banks and flooding across Bible Park in southeast Denver, May 6, 1973. Photograph by L. Scott Tucker, executive director, Urban Drainage and Flood Control District (Denver).

kinetic energy, and along entrenched reaches, especially at places where channels had been constricted by artificial landfilling along the banks. According to Fred Watts, Deputy Director of Public Works for Denver, the South Platte "just ate away all of Platte River Drive between Yale and Mississippi" (quoted from the Rocky Mountain News, May 9, 1973). Along this reach the channel of the river had been greatly constricted by filled land. Three weeks after the storm, the South Platte was still running bankfull and was too high to permit close inspection of scour effects along its banks. The South Platte had, in fact, surged over its banks again on May 22 after having receded to a level below flood stage in Denver a week earlier.

In downtown Denver, the 15th Street Bridge across the South Platte River collapsed when its center-support pier was undercut by scour (fig. 5). Collapse of the bridge, moreover, severed eight telephone cables and disrupted telephone service between downtown Denver and northwest Denver, parts of Arvada, Broomfield, and Boulder. The four-lane bridge was less than 10 years old and had survived the 1965 flood and the heavy runoff of 1969. According to City Engineer Jack Bruce (The Denver Post, May 7, 1973), it was the bridge least expected to fail. When the center pier went out, the bridge collapsed inward, trapdoor like, from both abutments.

Although no other bridges failed within the city limits of Denver, bridges and culverts were among the chief casualties of the flood elsewhere, and their failures added greatly to the cost of the storm. Bridges and culverts are particularly vulnerable because they form channel constrictions which increase the velocity and the competence of the stream. Bridges and culverts, moreover, tend to increase the severity of flooding when dammed or blocked by trapped debris. Such blockages backed water into building basements and first-floor levels in many parts of the metropolitan area, blocked and

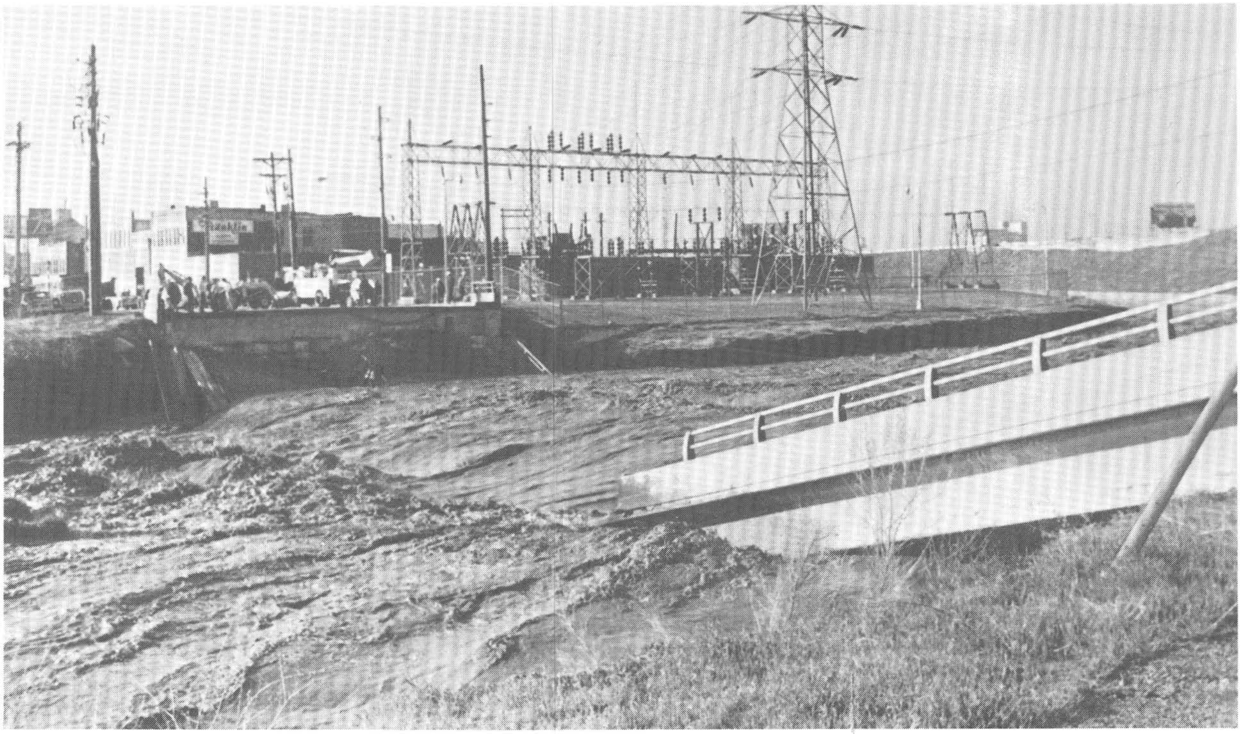

FIGURE 5. — View of 15th Street Bridge in downtown Denver, shortly after its collapse. Center-support pier was undercut by scour. Denver Post photograph by John Prieto, May 6, 1973.

backed up sewers in many places, and extinguished pilot lights and shorted out home furnaces. With these effects in mind, crews from the Denver Street, Highways, and Fire Departments worked throughout the hours of peak flooding to keep bridges across the South Platte free of floating debris (The Denver Post, May 7, 1973). Their actions probably saved many bridges from damage or destruction and diminished the severity of flooding along the banks.

West of the city, scour was severe on such tributary streams as Coal Creek, Ralston Creek, Big Dry Creek, Leyden Creek, Van Bibber Creek, Lena Gulch, McIntyre Gulch, Weir Gulch, Mount Vernon Creek, Bear Creek, Turkey Creek, North Turkey Creek, Deer Creek, and Massey Draw (figs. 6, 7). Much of the damage caused by these streams resulted from scour, undermining, blockage of culverts, and consequent inundation. Massey Draw did extensive damage at Chatfield Dam, on the Jefferson County side, when it broke out of an artificial channel and badly scoured engineered slopes and embankments (Edward E. McGregor, written commun., 1973). Damage at Chatfield Dam totaled many thousands of dollars.

Roads, embankments, and bridges in the mountains were badly damaged by scour, primarily by overtopping and undercutting at places where channels were constricted by road embankments. Scour of this sort along Turkey Creek, North Turkey Creek, and Deer Creek caused the largest losses in Jefferson County.

To the south, in Douglas County, scour damage was extensive at West Creek, West Plum Creek, Happy Canyon Creek, Sellers Gulch south of Castle Rock, Cherry Creek, West Cherry Creek, Willow Creek at State Highway 470, Indian Creek, and several other small gulches (John O. Maberry, written commun., 1973). Specifically, the following scour effects were noted by Maberry:

West Creek damaged and closed State Highway 67 between Deckers and Woodland Park to the south; two small reservoirs failed in sequence, the upstream one first, by overtopping, thereby swamping the lower dam and creating a "wall" of water that destroyed much of the highway and several mountain homes (fig. 8).

West Plum Creek washed out bridges at Sedalia and at Jackson Creek Road. It washed out culverts, dips, and weirs for irrigation ditches,

FIGURE 6. — Severe bank scour by Bear Creek at West Dartmouth Avenue and South Newland Street, May 9, 1973. Denver Post photograph by Bill Wunsch.

scoured its banks laterally in many places and, in overtopping its banks, caused sheet flooding that silted cultivated fields.

Plum Creek itself scoured and destroyed bridge abutments at Titan Road (east from the Martin Marietta Corp., toward Louviers), at Sedalia, on Douglas County Road 20 west of Sedalia, and at Louviers. Near Titan Road about 13 acres of land was badly eroded (E. E. McGregor, written commun., 1973). Many ranches along Plum Creek were isolated when access roads were severed by scour (The Parker Press, May 10, 1973). Scour undercut and collapsed the center span of a railroad bridge at the Du Pont Company plant in Louviers. Happy Canyon Creek and its tributaries damaged culverts and caused rockfalls in the Dawson Formation.

Abutments of the West Cherry Creek bridge above Franktown, according to Maberry, were destroyed by scour. The east abutment of the main stem Cherry Creek bridge on West Parker Road (Douglas County Road 8) was badly scoured. Cherry Creek washed out the bridge on the Parker–Castle Rock shortcut road and deposited sediment over about 50–100 acres of sod farms on its flood plain. It eroded its banks slightly at Havana Street, about half a mile downstream from Cherry Creek Dam.

County Line Road (Colorado Highway 470) was closed between South University Boulevard and Interstate 25 when Willow Creek washed out twin 2-foot-diameter culverts and about 50 feet of roadway. Maberry noted that countless unnamed tributaries, normally dry washes, and shallow drains did some damage by scouring and rill erosion, even on nearly flat ground. He also noted that much of the stream scour in Douglas County coincided with the outsides of

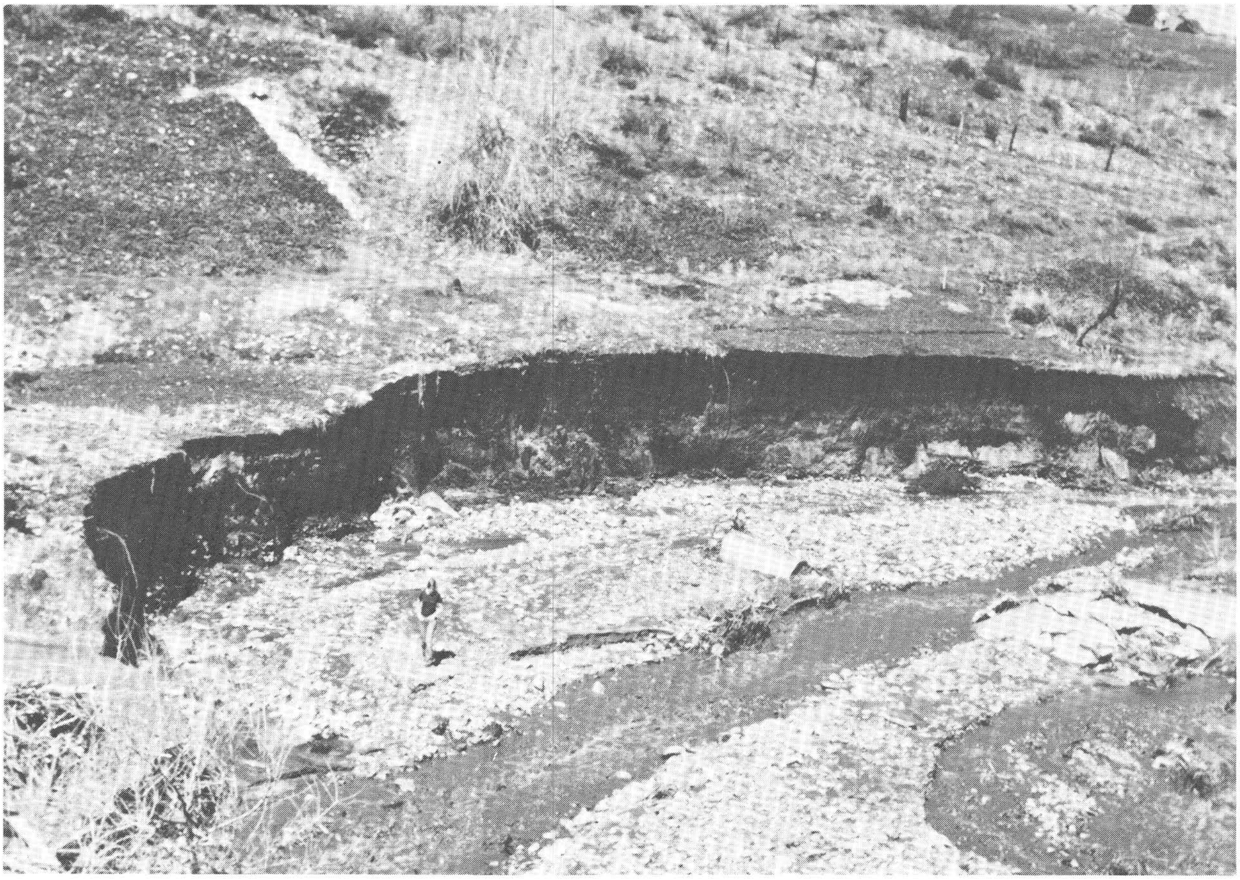

FIGURE 7. — Severe scour by Mount Vernon Creek east of Red Rocks Park. Area where figure is standing to left of center was a vegetable garden before the storm. Photograph by Eugene R. Hampton, May 7, 1973.

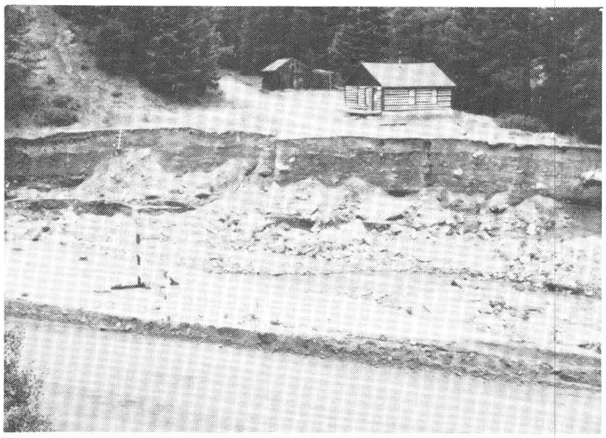

FIGURE 8.—Severe scour by West Creek between Deckers and Woodland Park. State Highway 67 and many mountain cabins were damaged or destroyed. Before the flood, road beside cabin in background joined Highway 67 in foreground. Photograph June 1973 by Brent N. Petrie, consultant on land and water resources.

bends. Scour in such places was prevalent throughout the metropolitan area.

Tributaries on the east side of Greater Denver in Adams and Arapahoe Counties did relatively little scouring; Cherry Creek below the dam was largely restrained. Toll Gate Creek parallel to Interstate 225 eroded its banks slightly between East 6th Avenue and Fitzsimons Army Hospital, a distance of about 12 blocks. Sand Creek, historically troublesome, scoured its banks and channel considerably and transported and deposited large quantities of sediment. At Brighton Boulevard it scoured the abutments of a bridge but without structurally damaging the bridge itself (Robert M. Lindvall, written commun., 1973). Scour in the form of sheet wash and minor gullying was widespread in denuded areas undergoing construction.

SEDIMENTATION

At flood stage, nearly all drainage through the Greater Denver area was overloaded with sedi-

FIGURE 9. — South Platte River just west of Brighton, May 6, 1973. Silt and mud damaged hundreds of acres of cropland and pasture. Aerial view is northeast toward East 160th Avenue in middle distance. Denver Post photograph by Barry Staver.

ment, and deposition occurred where and when flow velocity was slowed. Sedimentation was subordinate to other flood effects in Greater Denver in terms of damage to property, but it caused local hardship to many people. Overbank flooding was the chief cause of sedimentation along most major streams, even while they were still scouring their channels. Scores of acres of flooded ground along the South Platte, including much cropland, received sediment from overbank flooding. North of Commerce City the South Platte River was out of its banks in a strip of land one-half to nearly 1 mile across (fig. 9). At Chatfield Dam, 60 acres was inundated. These areas were coated with mud when the water disappeared. Downstream, at Platteville, about 30 miles north of Denver, the mud reportedly was 3 feet deep and caused severe damage to pastures and cropland.

Sheet flooding resulted when temporary rivulets spread out fanlike at the mouths of small ravines or gullies. Much sediment was deposited on roads and streets. Some of these deposits graded into mudflows.

Many tributaries without well-defined flood plains deposited large quantities of sediment when they were ponded by obstructed bridges or culverts. Obviously, these problems would not have arisen had the channels remained clear (fig. 10).

MASS WASTAGE

"Mass wastage" is a general term for the processes by which rock or earth material is transported en masse downslope. It includes landsliding (fig. 11) but excludes sediment transport by streams. Gravity is the chief transporting agent.

Many small landslides, perhaps hundreds of them, were triggered in the western hilly part of the Greater Denver area by the storm of May 5–6. The moderate but steady precipitation saturated slide-prone areas, led to renewed

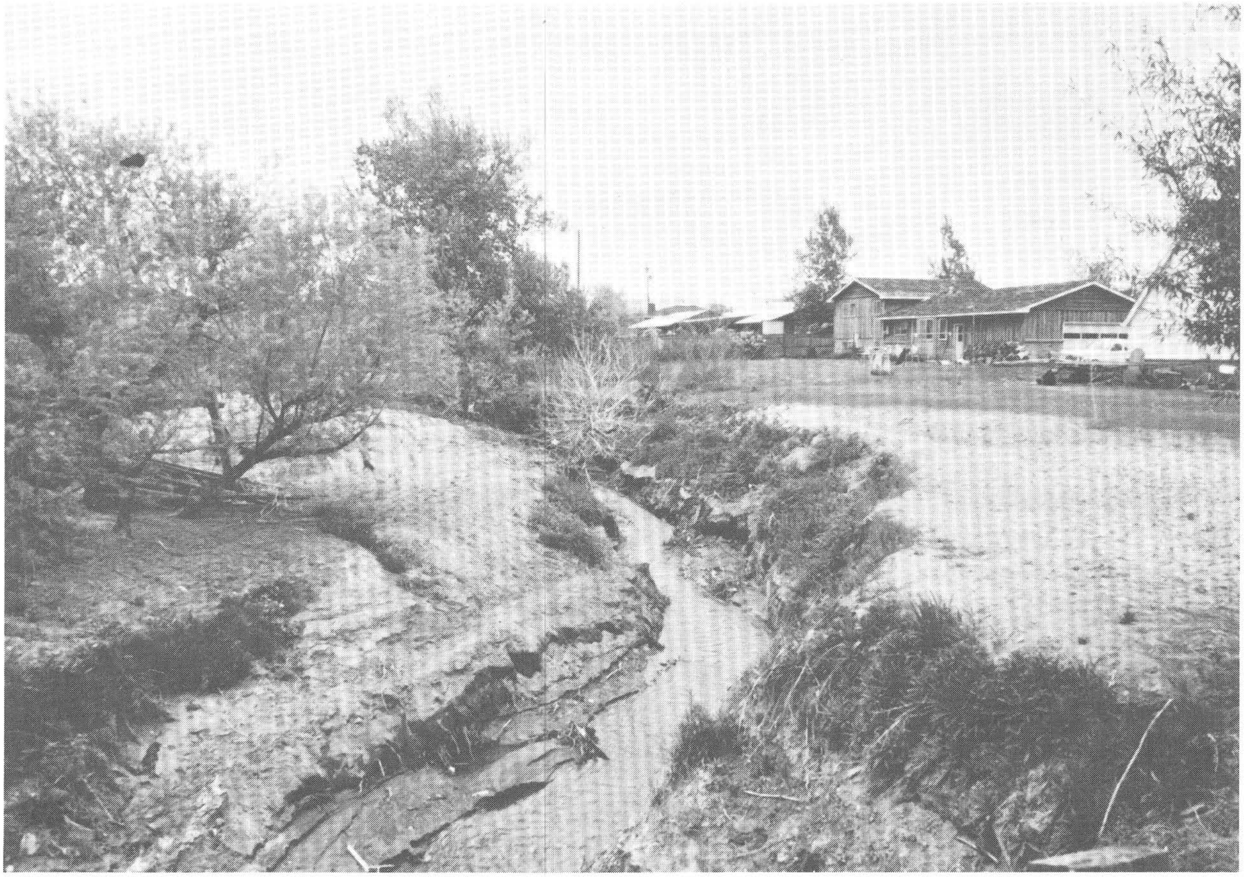

FIGURE 10. — Overbank sediments deposited along McIntyre Gulch at Holland Street in Lakewood, when culvert under street, behind observer, was unable to accommodate flood crest. Similar blockages caused flooding and sedimentation in many other places in Greater Denver area.

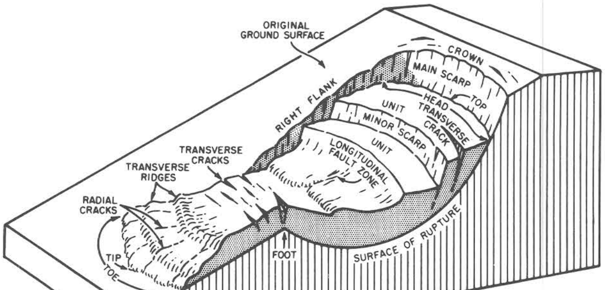

FIGURE 11. — Form and nomenclature of a landslide (Varnes, 1958, pl. 1).

movement of many old landslides, and caused new landslides where none had existed previously.

The landslides that ensued included slumps, earthflows, mudflows, debris slides and debris flows, and rockfalls (in the nomenclature of Varnes, 1968, pl. 1). Transitional forms were abundant, and the distinction between types was often arbitrary — the difference between a simple flood of muddy water and a true mudflow, for example, is largely a matter of the proportion of water to sediment. In most classifications, the so-called "mudslides" reported by the news media are highly fluid mudflows or debris flows. The term "flow" is more appropriate than the term "slide" because the mode of movement is essentially flowage rather than sliding. Similarly, mudflows grade into earthflows, and earthflows grade into slumps.

Landslides occurred when the frictional forces that tend to hold a slope in place were exceeded by the gravitational forces that tend to cause it to move or fail. These forces can be expressed as a safety factor, *s*, which, in the simplest terms, is the total shear resistance, *r*, of the slope divided by the total shear force exerted, f. Thus, $s=r/f$, and failure occurred when the ratio fell below 1.0 — that is, when shear force exceeded shear resistance. Moisture, which reduces r, was (and is) the chief cause of failure, although many other factors generally contributed to the failure. The addition of moisture to marginally stable slopes on May 5–6 reduced the safety factor to 1.0 or less by (1) weakening the cementing bonds between soil and rock particles and, hence, reducing the internal shear resistance of the slopes, (2) adding weight to the potential slide mass, and (3) increasing the pore-water pressure in the interstices of the rock or soil. The effect of increased pore-water pressure was to "float" or suspend soil or rock grains relative to one another, thereby drastically reducing the shear strength of the mass and precipitating failure.

Still another effect of adding moisture to the ground on May 5–6 was related to the behavior of soils that contain plastic clays having high swell-shrink ratios. Such clays, often called "bentonite," are common soil constituents in many parts of Greater Denver. They contain large proportions of certain clay minerals, such as montmorillonite, which have the property of greatly increasing their volume by the adsorption of water, or of shrinking with the loss of water. The adsorption of water not only changes the volume of the soil but, at the same time, adds weight and reduces shear strength which reduce the safety factor and lead to slope failure.

SLUMPS AND EARTHFLOWS

Slumps and earthflows were among the more prevalent kinds of landslides (fig. 12). Many existed in the western part of Greater Denver before the May 5–6 storm, many of these were further activated by the storm, and many new ones appeared during or after the storm. In the Greater Denver area sloping ground that is underlain by the Lykins, Morrison, Benton, Pierre, Laramie, or Denver Formation is more prone to landsliding than is other ground, because of the high proportion of plastic clay in these formations. Landslides occurred, however, even on the Precambrian terrane back in the mountains.

A slump moves as a coherent block by displacement along a curved shear surface. The block rotates and slides about a horizontal axis on its center of gravity. Motion is arrested when the rebalancing of weight or an increase in friction returns the safety factor to more than 1.0. Because of their rotational habit, slumps tilt backward at their heads and bulge outward at their toes, and even slight movement is disruptive to a superincumbent structure. Most slumps in the Greater Denver area were com-

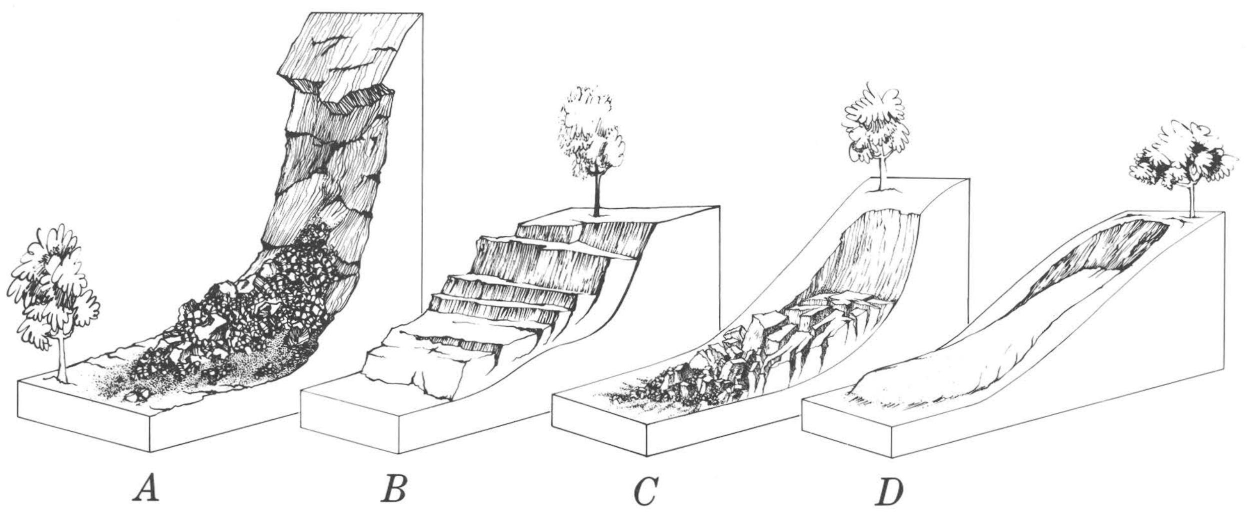

FIGURE 12. — Landslide types common in the western part of the Greater Denver area. From left to right: *A*, *Rockfall* moves mostly by free fall, bounding, and rolling; *B*, *slump* by rotational slippage on concave-upward shear surfaces; *C*, *debris slide* by complex internal adjustments of highly deformed, sheared slide mass; *D*, *earthflow* by displacements and velocities similar to those of viscous fluids (Varnes, 1958, pl. 1). Illustrations by Natalie J. Miller, from Nilsen (1972).

FIGURE 13. — Debris-mudflow blocking Hogback Road about 1 mile north of Morrison on west side of Dakota hogback. Photograph by Eugene R. Hampton, May 7, 1973.

pound in that they failed along multiple slip surfaces. Many of them, moreover, passed downslope into earthflows where the material tended to break up and disintegrate from wetting and flowage. This is the material that moved out onto the highways during the storm.

Many small slumps and earthflows appeared along the outcrop of the Morrison Formation on the west side of the Dakota hogback, particularly at roadcuts where the natural slope had been oversteepened. Most of these small landslides were very wet and soupy, and they passed downslope into debris-mudflows (fig. 13). In some places removal of material from the roadways during cleanup operations only caused more material to flow into place. Arresting of motion in such places is possible only when the entire mass is removed or when the material finally dries out enough for flowage to stop.

The flanks of both North and South Table Mountain have had a long history of landsliding (Van Horn, 1954, 1972; Gardner and others, 1971; Simpson, 1973). West 32d Avenue was closed temporarily when many new slumps appeared on the north flank of South Table Mountain after the May 5–6 rains. Some older slumps were reactivated or accelerated, including the large landslide just south of Rolling Hills Country Club. Two long-active landslides above Clear Creek, one at West 32d Avenue and one at West 44th Avenue (old Colorado Highway 58) were both in motion before the rains started (fig. 14). Their prior activity had been promoted by the prolonged wet weather earlier in the season. Both showed evidence of increased movement after the May 5–6 storm.

Because of the heavy moisture take-up by the Highway 58 slide, the damage potential of continued movement had been very large, involving an imminent threat to new Colorado Highway

FIGURE 14. — Landslide in Denver Formation on old Colorado Highway 58, one-half mile east of Golden at foot of North Table Mountain. This slide has been intermittently active for many years and has been a continuing problem for highway and railroad maintenance people. Present activity was aggravated by the May 5–6 rains.

58, continuing damage to West 44th Avenue, continuing damage to the Colorado and Southern Railroad tracks, potential disruption of the Farmers Highline Canal, and a serious threat to the Coors Co. sewage-disposal plant. The Colorado Highway Department, therefore, has taken steps to rectify the conditions that led to slide movements in the past.

Many small slumps, earthflows, and mudflows appeared in backfilled areas along Interstate 70 in the mountains (fig. 15). Most of these were superficial failures involving only topsoil or dressing on sloping rock cuts. Mudflows appeared mostly on steep slopes where grass seeded the previous summer and fall had not yet established a protective turf. Even a good cover of turf, however, will not prevent slumping — in contrast with mudflowage — if the subsoil is saturated. The effects of the above

FIGURE 15. — Small debris slide on eastbound exit ramp of Interstate 70 at Genessee Mountain. Material is loam slope dressing and colluvium.

failures to date have not been hazardous, but they will present continuing maintenance problems unless arrested, and they could, perhaps, lead to some blockage of traffic lanes.

Northwest of Arvada, old slumps and earthflows are abundant around the edges of Rocky Flats. The Laramie Formation and the Pierre Shale are host rocks for most of these slides. A few of these were reactivated by the May 5–6 rains, and many new ones appeared for the first time (fig. 16). Most of these slides are along roadcuts, where marginally stable slopes had been oversteepened by highway excavations. Other small slides were triggered near the bottoms of gullies where bank scour set off slumps or earthfalls. A detailed survey probably would disclose scores of small failures of this sort.

East of Rocky Flats, two small landslides partly blocked the southbound lane of Colorado Highway 121, about three-fourths mile and 1 mile south of the Broomfield interchange (fig. 17). This area is underlain by highly expansive soil, if the bumps and waviness in the pavement are any indication. The southern slide had begun to fail several weeks before the May 5–6 storm when cracking and minor bulging first appeared, but the major movement was triggered by the May 5–6 rain. Movement was continuing in both slides at a diminished rate during the last week of May.

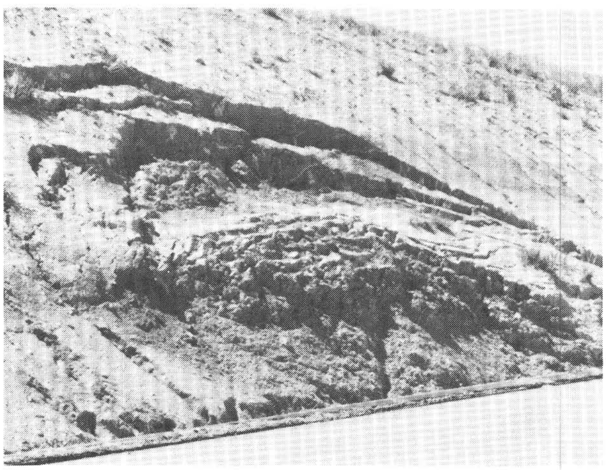

FIGURE 16. — Small slump in Laramie Formation on Boulder County road 2 miles west of Jefferson County Airport. Oversteepened slope and heavy rains triggered failure. Crown of slide is about 20 feet above roadway. Photographed on May 8, 1973.

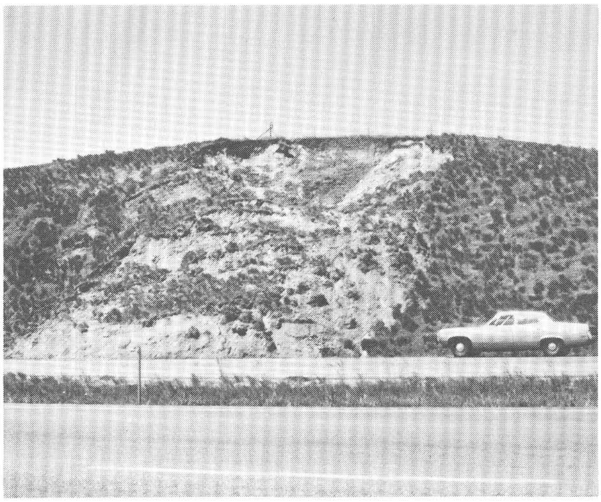

FIGURE 17. — Slump-earthflow on Colorado Highway 121 about three-fourths mile south of Broomfield interchange. Toe of landslide partly blocked southbound lane but was promptly cut back by Highway Department. Photographed on May 8, 1973.

MUDFLOWS

Small mudflows ran down both sides of the Dakota hogback west of Denver, especially between Interstate 70 and Morrison. They were abundant also on steep slopes in the foothills of Jefferson County — myriads of them scarred the new cuts of Interstate 70.

In Platte Canyon at the Denver Water Board's intake structure 3 miles above the Kassler Filter Plant, a mudflow engulfed the caretaker's house, which had stood undamaged for about 60 years (Quentin Hornback, oral commun., 1973, relayed by Robert M. Lindvall).

Debris-mudflows ran down several of the steep-sided buttes in the Plum Creek drainage in Douglas County (John O. Maberry, written commun., 1973). Some of these were accompanied by rockfalls.

In summary, small mudflows were common consequences of the storm in hilly or mountainous parts of the metropolitan area wherever sparsely vegetated hillslopes were underlain by shaly, clayey, or silty subsoils. Mudflows originated chiefly in the Morrison, Benton, Pierre, Denver, and Dawson Formations and in clayey or silty colluvium. They caused considerable inconvenience and some hazard where they flowed onto highways, but, in terms of total storm effects, their damage was minor.

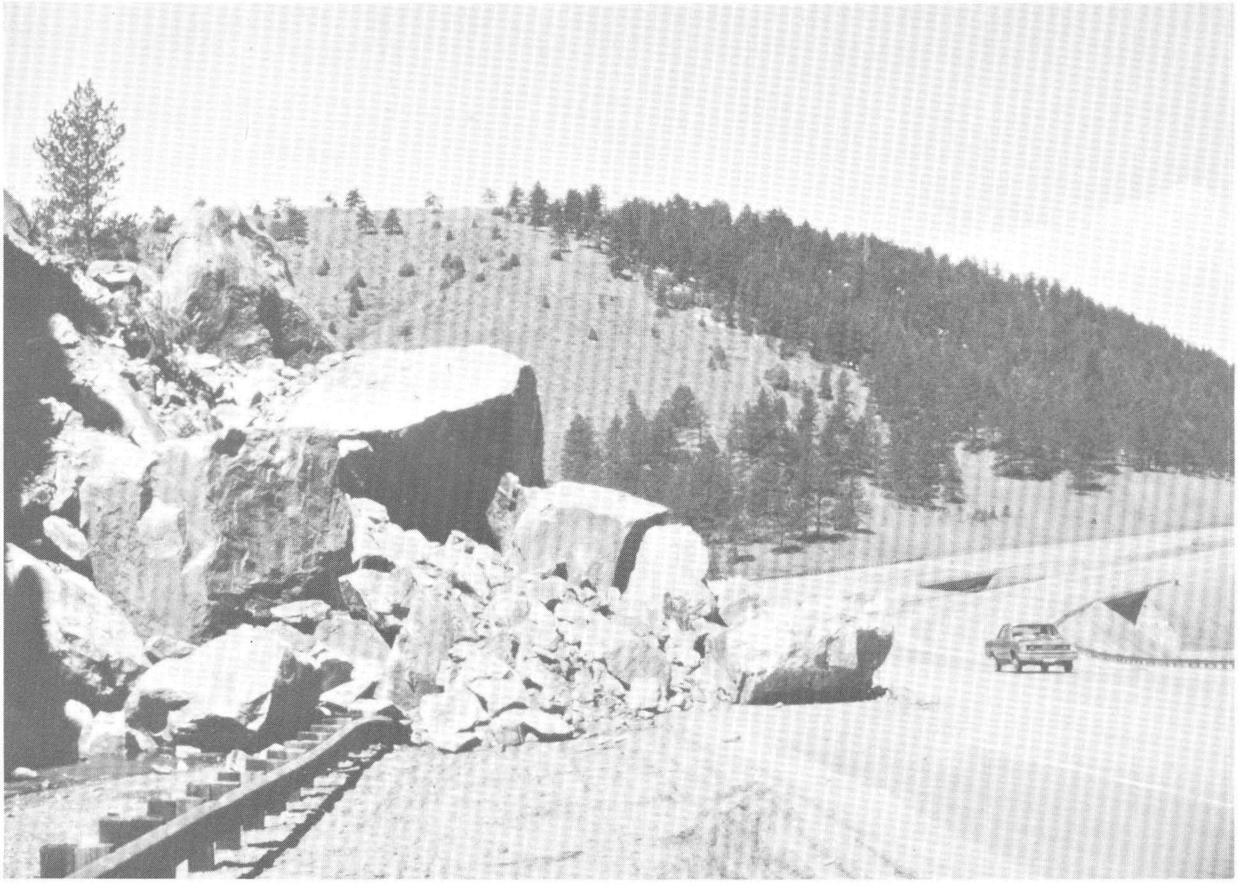

FIGURE 18. — Rockfall on eastbound lane of Interstate 70, 2 miles west of Bergen Park interchange (El Rancho). Failure was along joints (fractures) and foliation planes (layering) in Precambrian gneiss. Rockfall obstructed all of eastbound lane and median and part of westbound lane before cleanup began. Estimated weight of largest boulders exceeded 200 tons. Photographed on May 8, 1973.

ROCKFALLS

Rockfalls were triggered by the storm on the steeper hillsides and canyon walls west of Denver when rainwater and snowmelt percolating into cracks loosened rock fragments and sent them plummeting down the slopes. Loose mantle rock behaved similarly. Rockfalls were abundant in the canyons as far west as Berthoud Pass along U.S. Highways 6, 40, and 285, Interstate 70, and Colorado Highway 74. Most of these were quickly removed by highway maintenance crews.

By far the largest single rockfall collapsed onto Interstate 70 about 2 miles west of Bergen Park interchange, near El Rancho (fig. 18), completely blocking the eastbound lane. Some rock bounded across the median and into the westbound lane. Failure along steeply dipping foliation planes (layering) and joints (fractures) involved thousands of tons of rock, including giant boulders weighing hundreds of tons each that required drilling and blasting before they could be removed. The hillside above the fall was left in a precarious state, also, and much loose rock had to be drilled and blasted before cleanup work could start on the rockfall itself.

South of the metropolitan area in suburban Douglas County, rockfalls collapsed down the flanks of several steep-sided buttes south and west of Plum Creek, particularly Dawson Butte, Raspberry Mountain, and Bald Mountain (John O. Maberry, written commun., 1973). Rockfalls at these places resulted when failure of the soft claystones and sandstones in the Dawson Formation removed support from the overlying caprock.

TOWARD COPING WITH FUTURE STORMS

Greater Denver's history of intense rainstorms and destructive flooding extends back into pioneer days and even into Indian legend. (See Follansbee and Sawyer, 1948, for an excellent general reference, and Matthai, 1969.) Floods undoubtedly will occur in the future just as they have in the past. In fact, the South Platte was out of its banks again on May 24, 1973, and flash-flooding tributaries on June 12, 1973, took three lives. As urbanization spreads over the Colorado Piedmont, the frequency and intensity of urban flooding are likely to increase.

Measures can be taken, nevertheless, to forestall problems, and the initial cost of prevention in the areas of new construction can be more than recovered in the long-term savings from minimized storm damage. In older areas, where the problem is more complex, rectification is more difficult and much more costly.

Geologic processes triggered by the May 5–6 storm were intensified in places where the natural regimen had been altered by man. Inasmuch as such alterations are inevitable in any rapidly growing urban area, careful planning to ensure compatability with natural processes is essential if destructive side effects of heavy storms are to be minimized.

Some common land-development practices in the Greater Denver area that tended to accelerate geologic processes and aggravate the intensity of storm effects were (1) channeling drainage into concentrated systems that are incapable of accommodating peak storm runoffs, (2) inhibiting infiltration of moisture by reducing permeability and speeding runoff, (3) blocking or constricting natural drainages by dikes, bridges, culverts, and landfills, and (4) oversteepening natural slopes by undercutting or by filling at angles steeper than those that commonly persist in nature, particularly along rights-of-way for highways but also in housing developments in hilly areas. The effects of some of these practices seem to be self-evident, and to recapitulate them may be to restate obvious generalities, but there is some value in viewing diverse land-development practices in a perspective that relates one consequence to another. All these practices tend to compound the overall effects of a storm by reinforcing one another at the critical time of maximum storm intensity. Channeling drainage into systems that are unable to accommodate peak runoffs, for example, is a common consequence of inhibited infiltration, which, in turn, often results from the multitudinous land modifications associated with urbanization.

Another lesson that should now be clear is that gully bypasses, such as flumes, conduits, or siphons, are needed to prevent unwanted storm drainage from entering and overwhelming canals and ditches.

Inhibited infiltration, particularly because of impervious surfaces, such as roofs, driveways, sidewalks, streets and especially parking lots, increased storm runoff enormously. Artificial retention systems can be designed, on the other hand, to reduce runoff rates to acceptable levels. Large flat-topped roofs can be designed to provide temporary storage for slow release or evaporation. Downspouts from houses and commercial buildings can be directed onto lawns or other pervious areas where infiltration is possible and desirable. In some places, runoff can be recharged directly to the ground water by means of French drains, dry wells, or similar infiltration systems. Infiltration obviously should be avoided in potentially unstable slope areas where landsliding might be initiated or in areas where moisture might gain access to high swell-shrink clays beneath footings or poured slabs. In some places ponds can be designed to catch and hold excess runoff. When suitably landscaped, such ponds are assets that increase the value of adjoining real estate.

Heavy earthmoving equipment has made possible the economic development of large tracts of land. Such construction practices in the Greater Denver area, however, commonly denude large acreages of land for extended periods of time prior to construction and, during heavy rainstorms, greatly increase the vulnerability of the land to sheet wash, gullying, scour, mudflowage, and sedimentation (fig. 19). These costly storm effects can be reduced if, following the lead of the highway builders, provisions are made for rapid, even temporary, revegetation with fast-growing grasses and herbs to reestablish protective ground covers, reduce erosion, and retard runoff. Better yet, careful analysis of the landscape at the planning stage can often minimize the initial alteration of the natural land surface

FIGURE 19. — Gullying on a steep hillside previously denuded of vegetation and topsoil.

and prevent unforeseen geologic complications.

Blockage of natural drainageways was one of the principal causes of flood damage in the Greater Denver area. Many bridges and culverts were simply unable to accommodate the increased runoff; many were blocked with trash or sediment. In the urban environment, natural drainageways that seem unsuitable for one purpose or undesirable from one point of view may enhance the value of an area for something else. Most natural landscape features have the potential for being either liabilities or assets. During a major storm, an urbanized or industrialized flood plain is likely to be a liability, not only because of direct flood damage to facilities on the flood plain but also because of the obstructions that such facilities present to the free passage of the water. Such facilities, in other words, can actually intensify the effects of flooding. But a flood plain that is dedicated as parkland, open space, or wildlife habitat in an otherwise crowded city is nearly immune to flood damage and is likely to become a community asset that increases in value with time. Overland Park on the South Platte flood plain is a good example. The numerous ravines and gullies that drain the Greater Denver area ought to be natural assets that enhance the quality of urban living, but many of them are financial liabilities to the community and some, regrettably, are festering eyesores. Protecting natural drainageways should be a prime consideration of long-range planning. Existing structures that tend to obstruct drainage might well be phased out of use. Unobstructed drainageways not only afford insurance against storm damage from high runoff but they provide some of the open space that is fast disappearing from the urban scene.

Damaging floods are not restricted to streams that have broad flood plains. Indeed, an urban drainageway need not have any flood plain at all to generate a damaging flood. Even a small, normally dry watercourse is capable of inflicting damage, especially if its path is obstructed by manmade structures. One must remember that a ravine is the product of erosion by running water, that streams erode most effectively during occasional flood stages which greatly exceed normal flow, and that the lack of appreciable runoff in an innocuous-looking ravine does not imply that great volumes of water may not occupy the watercourse during a heavy storm.

Oversteepened slopes contribute greatly to storm damage. By far, the majority of slope failures that we observed immediately after the May 5–6 storm — slumps, earthflows, mudflows, and rockfalls — were consequences of manmade alterations. They occurred where slopes had been oversteepened, either by cutting or by filling, beyond the bearing capacity of the material in the slopes. If similar failures are to be prevented in the future, careful stability analyses must precede slope modifications. Expert professional judgment is needed to evaluate such slope problems in hilly parts of Greater Denver before construction work is started. Sound engineering practices must go hand in hand with cutting or filling operations in hillside situations.

Loose fills dumped into gullies or onto hillsides at the angle of repose of dry material are foredoomed to eventual failure; mute testimony was provided by some such failures after the May 5–6 storm. As a word of caution, slope modifications should be held to a minimum in geologic settings where the risk of slope failure is high. In general, the risk is highest in areas where bedrock or overburden contains a high percentage of plastic shale or clay, especially clay having high swell-shrink properties, and areas where appreciable moisture is likely to enter the ground either naturally or artificially.

Much hilly terrain in the western part of the Greater Denver area has a high risk potential for slope failure if modified by cutting or filling. Much of this terrain, however, also has natural attributes that would be highly desirable in scenic easements, green belts, or natural parks and that can contribute, therefore, to an increased quality of living in the area. With foresight and planning, potential liabilities to the community can become genuine assets.

REFERENCES CITED

Ducret, G. L., Jr., and Hansen, W. R., 1973, Storm of May 5–6, 1973, in the Denver Metro Area — Frequency and Effect: Urban Drainage and Flood Control District, Denver, Colo., 40 p., 6 figs., 5 tables.

Follansbee, Robert, and Sawyer, L. R., 1948, Floods in Colorado: U.S. Geol. Survey Water-Supply Paper 997, 151 p.

Gardner, M. E., Simpson, H. E., and Hart, S. S., 1971, Preliminary engineering geologic map of the Golden quadrangle, Jefferson County, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF–308.

Matthai, H. F., 1969, Floods of June 1965 in South Platte River basin, Colorado: U.S. Geol. Survey Water-Supply Paper 1950–B, p. B1–B64.

Nilsen, T. H., 1972, Preliminary photointerpretation map of landslide and other surficial deposits of the Mt. Hamilton quadrangle and parts of the Mt. Boardman and San Jose quadrangles, Alameda and Santa Clara Counties, California: U.S. Geol. Survey Misc. Field Studies Map MF–339.

Simpson, H. E., 1973, Map showing landslides in the Golden quadrangle, Jefferson County, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I–761B.

Van Horn, Richard, 1954, Landslides near Golden, Colorado: Engineers Bull., v. 38, no. 12, p. 6–15.

________1972, Surficial and bedrock geologic map of the Golden quadrangle, Jefferson County, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I–761A.

Varnes, D. J., 1958, Landslide types and processes, *in* Eckel, E. B., ed., Landslides and engineering practice: Natl. Acad. Sci.–Natl. Research Council Pub. 544, Highway Research Board Spec. Rept. 29, p. 20–47.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1973 O—543–579/56