Socioeconomic and Environmental Impacts of Landslides in the Western Hemisphere

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ABSTRACT: In spite of improvements in recognition, prediction, mitigative measures, and warning systems, economic losses and casualties due to landslides in the Western Hemisphere appear to be growing as a result of increasing development of landslide-prone areas due to population pressures. This paper notes outstanding examples of socioeconomic losses in the Americas.

Landslides impact the following elements of the natural environment: (1) the topography/morphology of both the subaerial and submarine surfaces of the Earth, (2) rivers, streams, forests, and grasslands, and (3) habitats of native fauna, both on the Earth's surface and in its streams and oceans. Environmental disturbances are results of general tendency toward degradation of the Earth's surface by gravitational mass wasting and erosion.

KEYWORDS: Landslide, environment, earthquake, debris flow, avalanche

1 INTRODUCTION

In most nations of the Western Hemisphere, landslides have caused major socioeconomic impacts on people, their homes and possessions, industrial establishments, and lifelines, such as highways, railways, and communications systems. Socioeconomic losses due to slope failures are great and apparently are growing as the built environment expands into unstable hillside areas under the pressures of expanding populations. Human activities disturb large volumes of earth materials in construction of buildings, transportation routes, dams and reservoirs, canals, and communications systems, and thus have been a major factor in increases in damages due to slope failures.

Landslides are responsible for considerably greater economic and casualty losses than is generally recognized; they represent a significant element of many major disasters in which the magnitude of their effects is overlooked by news media. For example, the tremendous destruction and loss of life caused by the 1970 Huascaran disaster in Peru, which killed some 20,000 people, is often referred to in publications that review disasters as an earthquake disaster, because the landslide was triggered by an earthquake; this is in spite of the fact that the actual damage, destruction, and casualties were directly caused by a huge, high-velocity debris avalanche.

Related to increases in population is the continuing high rate of deforestation due to logging, burning, and development, a factor that increases landslide activity on the world's slopes. In the early 1990's, the World Resources Institute estimated that the world's tropical forests were disappearing at a rate of 16-20 million ha/yr (Collier's Encyclopedia, 1997), an area roughly the size of Surinam. In the Amazon River Basin of Brazil, alone, approximately 2.9 million ha of forest was destroyed during the 1994-95 burning season (Facts on File News Services, 1998).

Government agencies and other policy-making bodies in the Western Hemisphere need to develop a better understanding of the socioeconomic significance of landslides. Such understanding will allow rational allocation of funds needed for landslide research, for avoidance, prevention, control, and warning, and for post-failure repair and reconstruction

Many papers have been written on the socioeconomic impacts of landslides on the *built* environment. However, relatively few authors have discussed the effects of landslides on the *natural* environment, i.e., on (1) the morphology of both subaerial and submarine surfaces of the Earth, (2) the natural forests and grasslands that cover much of the Earth's surface, (3) quality of streams and other bodies of water, and (4) the habitats of native fauna, both on the Earth's surface and in its streams and oceans (Schuster, in press). Morphologic effects are part of a general tendency toward degradation of the Earth's surface by mass wasting and erosion. The effects on vegetation and wildlife are generally negative, in some cases disastrous.

This paper discusses the socioeconomic and environmental impacts of landslides, with emphasis on the Western Hemisphere. We will use landslide terminology as presented by Varnes (1978) and Cruden and Varnes (1996). Basically the term *landslide* as used will include all types of gravity-caused mass movements, ranging from rock falls through slides, avalanches, and flows.

2 SOCIOECONOMIC IMPACTS OF LANDSLIDES

2.1 Economic Losses Caused by Landslides

In this discussion of landslide-caused economic losses, costs are presented in United States (U.S.) dollars for the years in which they were originally determined. In addition, the original values as inflated to U.S. dollars for the year 2000 follow in parentheses. The adjustments have been made on the basis of yearly cost-of-living indexes for the United States (United States Government Printing Office, 1975, 2000).

2.1.1 Categories of Economic Losses Due to Landslides

2.1.1.1 Direct versus Indirect Losses

Landslide costs include both direct and indirect losses affecting private and public properties. Direct costs can be defined as the costs of replacement, rebuilding, repair, or maintenance resulting from direct landslide-caused damage or destruction to property or installations (Schuster and Fleming, 1986; Schuster, 1996). All other costs of landslides are indirect; examples are:

- Reduced real estate values in areas threatened by landslides.
- Loss of tax revenues on properties devalued as a result of landslides.
- Loss of industrial, agricultural, and forest productivity, and of tourist revenues, as a result of damage to land or facilities or interruption of transportation systems.
- Loss of human or domestic animal productivity because of death, injury, or psychological trauma.
- Costs of measures to prevent or mitigate potential landslide activity.

2.1.1.2 Private versus Public Costs

Landslide losses also can be divided into costs to private and public entities (Fleming and Taylor, 1980). Private costs are incurred mainly as damage to land and structures, either private property or corporate industrial facilities. A destructive landslide can result in financial ruin for property owners because landslide insurance or other means to offset damage costs usually are unavailable.

Public costs are those costs borne by government agencies, either national, regional, or local. The largest direct public costs resulting from landslides most often have been for repairing or relocating highways/roads and accessory structures, such as sidewalks and storm drains. Indirect public costs include losses of tax revenues, reduction of transmission capabilities of lifelines, reduction of productivity of government forests, impact on quality of sport fisheries, etc.

2.2 Landslide Casualties

In the 20^{th} century, the problem of deaths and injuries due to landslides was exacerbated by burgeoning populations in landslide-prone areas; undoubtedly, this trend will continue in the 21st century. In the only known evaluation of worldwide landslide deaths, Varnes (1981) estimated that during the period 1971-1974 nearly 600 people per year were killed worldwide by slope failures. About 90 percent of these deaths occurred within the Circum-Pacific region (i.e., in or on the margins of the Pacific Basin). The current authors estimate that at least half of these Circum-Pacific casualties (about 300 per year) would have been along the west coast of the American continents.

2.3 Socioeconomic Losses in North and Central America

2.3.1 Canada

Because of Canada's large area (it is the second largest nation in the world) and relatively small population, the economic significance of its landslide problem is extremely difficult to assess. For a number of reasons, the effects of slope movements on the Canadian economy have been significantly underestimated (Cruden et al.,1989); this is mainly because costs often have been tabulated only on the basis of direct costs of replacement of facilities. In addition, direct costs of small slope movements commonly are hidden in larger, routine budget items for maintenance and repairs. Undoubtedly, indirect costs for such items as traffic delays and disruption are a substantial part of the total costs of landslides to the Canadian economy.

Thus, although the costs of individual slides can be estimated, a total for Canada is difficult to establish. S.G. Evans (personal communication, 1989, Geological Survey of Canada, Ottawa) estimated that annual landslide costs for Canada are about $50 million ($70 million). However, in the same year, Cruden et al. (1989) estimated that total annual landslide costs for Canada may be as high as $1 billion ($1.4 billion) per year.

It has been estimated that approximately five people per year are killed by landslides in Canada (S.G. Evans, personal communication, 1987, Geological Survey of Canada, Ottawa). Most are killed by relatively small events, mostly rock falls. Cruden et al. (1989) noted that 365 landslide deaths have been recorded for the Cordillera of western Canada since 1855. Debris flows caused 20-30 percent of these deaths; 47 percent resulted from rock falls. For the St. Lawrence Lowlands in eastern Canada, estimated minima for landslide-related deaths for the past 100 years are: 100 in sensitive-clay slides, 100 in rock falls, and 10 in other landslide types. In the rest of Canada, flatter topography dictates that casualty numbers due to landslides will be lower than in regions of higher elevations and more rugged topography.

Although there have been some very large and catastrophic landslides in Canada, most have occurred in relatively unpopulated areas; thus, these failures have not resulted in major losses of life. However, there have been some notable exceptions. In 1903 a great rock slide killed about 70 people in the coal mining town of Frank, Alberta (McConnell and Brock, 1904). A more recent Canadian landslide disaster was the 1971 sensitive-clay flow failure that demolished part of the town of Saint-Jean-Vianney, Quebec, destroying 40 homes and killing 31 people (Tavenas et al., 1971).

2.3.2 United States

Landslides occur in all 50 of the United States and are widespread in the American island territories of Puerto Rico and the U.S. Virgin Islands. In the conterminous United States, the areas most seriously affected are the Pacific Coast, the Rocky Mountains, and the Appalachian Mountains.

In perhaps the first national estimate of U.S. landslide costs, Smith (1958) reported that "the average annual costs of landslides in the U.S. runs to hundreds of millions of dollars," probably a realistic figure for that time. However, in the 43 years since Smith assembled his cost data, continued expansion of residential and industrial development into landslide-susceptible areas, as well as monetary inflation, have increased the costs of landslides.

On the basis of their analysis of landslide loss data for Southern California and extrapolation of these data to the rest of the nation, Krohn and Slosson (1976) estimated the annual costs of landslides to private dwellings in the U.S. to be about $400 million in 1971 dollars ($1.2 billion). This estimate did not include indirect costs or costs to public property, forest or agricultural lands, mines, or transportation or communications facilities. In 1985 the U.S. National Research Council (Committee on Ground Failure Hazards, 1985), using these estimates, rough approximations of indirect costs, and inflationary trends, evaluated annual landslide losses in the U. S. at about $1 billion to $2 billion ($1.6-$3.2 billion). Landslide deaths in the U.S. have been estimated at 25-50 people per year. Obviously these estimated annual losses are *averages*, which will be exceeded in some years, but will not be approached in others.

The most economically devastating landslides in the United States in recent decades have been those triggered by the 1964 Alaska earthquake, the 1980 rainfall-induced landslides in southern California, the 1982 landslides in the San Francisco Bay area, the 1983-84 El Niño-triggered landslides in the State of Utah, and the 1998 El Niño-related landslides in California.

Youd (1978) estimated that ground failure caused 60 percent of the $300 million ($1.6 billion) total damage from the 1964 Alaska earthquake. Five major landslides caused about $50 million ($260 million) in damage to housing, public and industrial buildings, and lifelines in Anchorage, Alaska's largest city

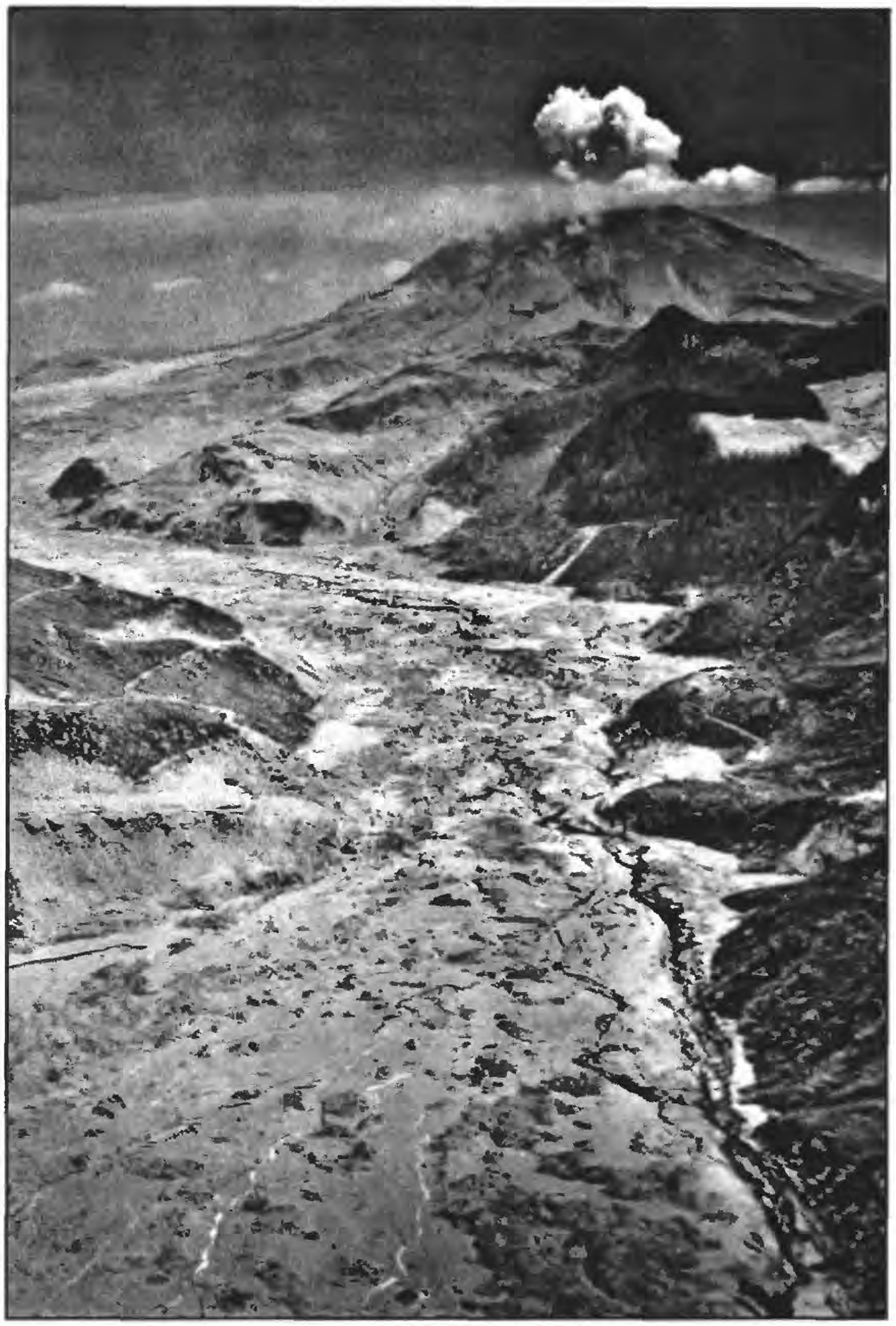

Figure 1. Mount St. Helens debris avalanche in valley of North Fork Toutle river, State of Washington, U.S.A.: view east from terminus of avalanche toward devastated cone of the volcano. (May 1980 photo by R.M. Krimmel, U.S. Geological Survey)

Landslide-causing storms (many of which are now thought to have been related to El Niño Southern Oscillation) have plagued California for the past 50 years. Exceptional landslide activity occurred in 1951-52, 1956, 1957-58, 1961-62, 1968-69, 1977-78, 1979-80, 1982, 1995, and 1997-98. As an example, total losses in the six southern counties of California due to landslides caused by heavy winter rainfall in 1979-80 were estimated at $500 million ($1.1 billion) (Slosson and Krohn, 1982).

The May 1980 eruption of Mount St. Helens, a volcano in the State of Washington, caused the world's largest historic landslide, a 2.8-km^3 rock slide–debris avalanche (Fig. 1) that traveled about 22 km westward (Voight et al., 1983), destroying nine highway bridges, many kilometers of highways, roads, and railroads, and numerous private and public buildings (Schuster, 1983). The debris avalanche also formed several new lakes by damming the North Fork Toutle River and its tributaries. These lakes posed downstream hazards because of the possible failure of their natural dams, which could have resulted in catastrophic downstream flooding. The largest landslide-dammed lake is 260-million-m^3 Spirit Lake, which was prevented from overtopping its natural dam by construction of a 2.9-km-long bedrock outlet tunnel that was completed in 1985 at a cost of $29 million ($44 million) (Sager and Budai, 1989).

Interestingly, although the Mount St. Helens debris avalanche moved down-valley at high velocity, it killed only 5-10 people (Schuster, 1983). The low casualty rate was a direct result of the evacuation of residents and tourists in anticipation of a possible eruption of the volcano.

An intense storm in January 1982 in the San Francisco Bay area triggered 18,000 debris flows and landslides. About 6,500 homes and 1,000 businesses were damaged or destroyed. Creasey (1988) documented that the total direct costs of these landslides were in excess of $66 million ($121 million). As a result of these damages, 930 lawsuits and claims in excess $298 million ($544 million) were filed against city and county agencies in the San Francisco Bay region (Smith, 1982), an amount considerably exceeding the total property losses.

Abnormally high precipitation in 1982-84 related to a strong El Niño Southern Oscillation caused thousands of landslides in mountain areas of the western United States. Anderson et al. (1984) estimated that total direct costs of landslides in the State of Utah in spring 1983 exceeded $250 million ($430 million). The April 1983 Thistle debris slide (Fig. 2), probably the world's most expensive individual

Figure 2. The 1983 Thistle landslide, central Utah, U.S.A. Thistle Lake, which resulted from damming of the Spanish Fork River, was later drained as a precautionary measure. This view, taken about 6 months after the slide occurred, shows the realignment of the Denver and Rio Grande Western Railroad lines in the lower center and the large cut for rerouting U.S. Highway 6/50 on the extreme left side of the photo.

Figure 3. The October 1985 Mameyes, Puerto Rico, rock slide, which killed at least 129 people. (Photo by R.W. Jibson, U.S. Geological Survey)

landslide, and the lake it formed by damming the Spanish Fork River severed three major transportation arteries: U.S. Highways 6/50 and 89, and the main transcontinental line of the Denver and Rio Grande Western Railroad (D&RGW). The D&RGW spent about $40 million ($69 million) to reestablish its line outside the devastated area, mostly to construct a twin-bore tunnel about 900 m long that bypassed the landslide and lake (Malone, 1983).

An economic analysis by the University of Utah (1984) evaluated both direct and indirect costs of the Thistle landslide. Direct costs totaled $200 million ($344 million). In addition, numerous indirect costs were reported; most of these involved temporary or permanent closure of highways and railroads to the detriment of local coal, uranium, and petroleum industries, several types of businesses, and tourism. Perhaps the largest single loss due to the Thistle slide was $81 million ($139 million) in revenue lost by the D&RGW during 1983. These indirect losses from the Thistle landslide disaster may exceed the direct costs. Thus, total costs (direct and indirect) of this slide were probably on the order of $400 million ($688 million). Although there were no casualties as a result of the Thistle slide, it ranks as the most economically costly individual landslide in North America, and probably in the world.

In terms of loss of life, by far the most disastrous landslides to occur within the U.S. and its territories have been caused by hurricanes/tropical storms in the Western Atlantic Ocean. In 1969, one of the worst natural disasters to hit the United States in the 20th century was caused by debris flows and associated flooding in central Virginia resulting from Hurricane Camille. Although no exact number can be ascertained, most of the 150 who died as a result of Hurricane Camille are thought to have been victims of debris flows triggered by heavy rains associated with the hurricane (Williams and Guy, 1973).

Another Atlantic storm-caused landslide disaster occurred in October 1985 on the Caribbean island commonwealth of Puerto Rico when heavy rain from Tropical Storm Isabel caused a major rock slide (Fig. 3) that obliterated much of the Mameyes district of the city of Ponce on the south coast of the island. The slide killed at least 129 people and destroyed about 120 houses (Jibson, 1992). The death toll at Mameyes is the greatest in North American history from a single landslide.

Severe winter storms in January and March 1995 brought above-normal rainfall that triggered damaging debris flows, deep-seated landslides, and flooding to Los Angeles and Ventura Counties, southern California (Harp et al., 1999). Several deep-seated landslides were triggered by the storms, the most notable of which was the La Conchita landslide (Fig. 4), which, in combination with a local debris flow, destroyed or badly damaged 11-12 homes in the small town of La Conchita, about 20 km west of Ventura (O'Tousa, 1995). There also was widespread debris-flow and flood damage to homes, commercial buildings, and roads and highways in areas along the Malibu coast that had been devastated by wildfire 2 years before (Harp et al., 1999).

Figure 4. The 1995 La conchita landslide, southern California, U.S.A.

In the late winter and early spring of 1998, heavy rainfall associated with a strong El Niño again caused major landslide activity and resulting damage to housing (Fig. 5) and lifelines in the 10-county San Francisco Bay, California, region. Direct costs of landslide damage in the region totaled approximately $156 million ($163 million) (Godt and Savage, 1999).

In addition to costs of damage to roadways, tracks, bridges, and other structures and equipment, transportation systems in the U.S. sustain continuing reconstruction and maintenance costs due to landslides (Fig. 6). Based on a survey of state transportation departments, Walkinshaw (1992) found that the total annual direct costs of maintenance and repairs to U.S. highways from 1985-1990 averaged nearly $106 million ($142 million). One deficiency of the Walkinshaw survey was that the state and federal highways for which the survey was conducted represent only about 20 percent of the more than 6 million km in the entire U.S. highway and road system. However, this 20 percent probably is subject to the

Figure 5. Home destroyed by the April 1998 El Niño-triggered Anzar Road landslide, San Benito, California, U.S.A. (Schuster, et al., 1998).

Figure 6. A minor landslide caused the April 1985 derailment of the ***California Zephyr*** *passenger train in Fraser Canyon, Central Colorado, U.S.A.*

major portion of highway landslide costs because it has been constructed to higher standards than the rest of the system (i.e., larger cuts and fills were used). Another deficiency of the survey data is that many state transportation departments do not maintain satisfactory records of their highway landslide maintenance costs. California distinguished itself by reporting the highest annual cost for landslide maintenance of all the states – more than $15 million ($20 million) per year, even during 5 years of below-average precipitation from 1985-90.

An interesting comparison of the magnitude of indirect costs of landslides to direct costs (actual repair) for a transportation system was provided by the 1983 landslide closure of heavily traveled U.S. Highway 50 in California, which prevented tourist access to popular Lake Tahoe. Costs of highway repairs totaled $3.6 million ($6.2 million), but the estimated loss of tourist revenues was $70 million ($120 million) (San Francisco Chronicle, 1983), nearly 20 times as much as direct expenditures for repair.

In 1997, a slide again closed U.S. Highway 50 near the site of the 1983 event. Before the highway could be reopened, 270,000 m^3 of landslide material (35,000 truck loads) had to be removed over a 4-week period at a cost of $4.5 million ($4.7 million). Indirect economic losses due to the highway closure were estimated at more than $1 million per day, for a total indirect cost of about six times the direct cost of repairs (California Department of Transportation, 1997).

2.3.3 Mexico

Records of landslides in Mexico are sparse. However, based on research by Scott et al. (in press) we have learned of a 1920 M~6.5-7.0 earthquake that caused major debris-flow activity in rugged highlands 30 km northeast of Orizaba Peak in southern Mexico. Debris flows 40-65 m deep destroyed the town of Barranca Grande in the valley of the Río Huitzilapan 15 km downstream from the epicenter. Some 600 bodies were recovered downstream.

2,3,4 Guatemala

Although Guatemala has been subject to many landslides caused by both heavy rainfall and earthquakes, damages from most of these events have not been well documented. The major exception has been the effects of landslides triggered by the 1976 M7.5 Guatemala earthquake. This quake generated more than 10,000 landslides throughout an area of approximately 16,000 km^2, causing hundreds of fatalities as well as extensive property damage (Fig. 7) (Harp et al, 1981). Landslides disrupted major highways and the national railroad system. The railroad between Guatemala City (the capital) and Puerto Barrios (the Caribbean port city) was blocked in more than 30 places. The most extensive property damage and loss of life from landsliding due to the earthquake was in Guatemala City. Although there were no exact figures, a conservative estimate was that 500 dwellings were damaged and there were at least 200 deaths.

In October 1998, Hurricane Mitch, one of the most devastating storms to ever hit Central America and the Caribbean area, caused major flooding and innumerable landslides in Belize, Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua. Although Honduras suffered the greatest landslide devastation from Hurricane Mitch, Guatemala was also hit hard, particularly in the Sierra de las Minas.

2.3.5 Honduras

As noted by King (1989): "Landslides are a recognized, but little studied phenomenon in Honduras….." Most landslides in this Central American country are triggered by heavy rainfall, most commonly associated with hurricanes. As noted above, Honduras was the hardest hit of Central American nations in the path of 1998 Hurricane Mitch. Harp (2001) has reported that intense rainfall from Hurricane Mitch exceeded 900 mm in places in Honduras, and triggered more than 500,000 land-

Figure 7. Damage caused by a landslide triggered by the February 1976 Guatemala earthquake. (Photo by E.L. Harp, U.S. Geological Survey)

slides throughout the nation. These landslides damaged an estimated 70 percent of the Honduran road network and killed about 1,000 people.

Debris flows accounted for more than 95 percent of the Hurricane Mitch landslides in Honduras (Harp, 2001). Although landslides other than debris flows were few, several deep-seated landslides in the city of Teguçigalpa severely impacted people and property. The "El Berrinche" rotational slump–earth flow (volume: ~6 million m^3) destroyed the entire neighborhood of Colonia Soto near the center of the city (Fig. 8). This landslide also dammed the Rio Choluteca, impounding a temporary urban lake that immediately posed a major health problem.

2.3.6 El Salvador

Although El Salvador, the smallest of the Central American nations, has often been impacted by landslides caused by both heavy rainfall and earthquakes, documentation of socioeconomic losses from these events is limited mainly to those triggered by earthquakes. Rymer and White (1989) noted that for the previous 130 years, 10 major earthquakes had hit El Salvador; each event triggered as many as hundreds to thousands of landslides.

Rymer (1987) and Rymer and White (1989) have described landslide activity and effects from the 1986 M5.4 El Salvador earthquake, which triggered hundreds of landslides extending over an area of at least 200 km^2. The extent of property damage and loss of life in the San Salvador (capital city) area as a direct result of this landslide activity is not precisely known, but a conservative estimate would be

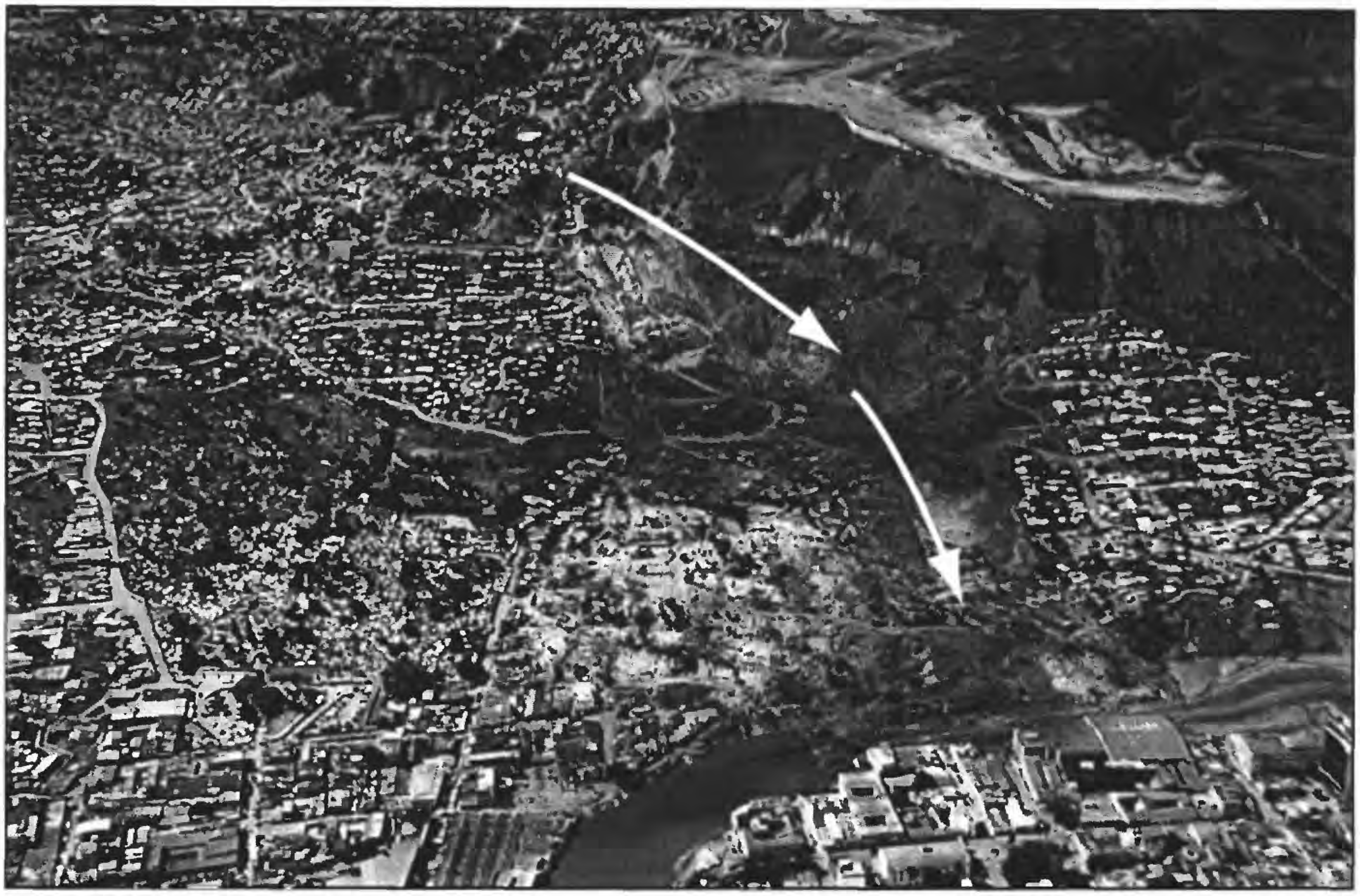

Figure 8. The El Berrinche landslide, Teguçigalpa, Honduras, which was caused by 1998 Hurricane Mitch. This 6-million-m^3 rotational slump-earth flow destroyed the entirety of the district of Colonia Soto near the center of the city, and temporarily dammed Río Choluteca, creating a lagoon that posed a health problem for the city (Harp, 2001). Arrows show path of landslide debris that dammed the river. (Photo by E.L. Harp, U.S. Geological Survey)

approximately 100 homes destroyed and 200 people killed. [In comparison, damage from the earthquake itself ranged to thousands of homes destroyed and about 1,500 deaths.]

In January 2001, El Salvador was again hit by a major earthquake (M7.6), which triggered many landslides that severely impacted the small nation, causing approximately $1 billion in damages and a large number of casualties. Especially hard hit was Las Colinas, a neighborhood of Santa Tecla, a suburb of the capital, San Salvador. Much of the neighborhood was buried by a landslide with a volume estimated at 300,000-500,000 m^3 (Fig. 9). Hundreds (or possibly thousands) of homes were destroyed, and as many as 1,000 people were killed in this one event. National police counted 4962 homes destroyed, 16,148 homes damaged, and 87 churches damaged by the earthquake (Aleman, 2001); most of this damage apparently was done by landslides. In addition, slides blocked several main highways, including the Pan-American Highway (Fig. 10).

2.3.7 Nicaragua

As is the case for other Central American countries, Nicaragua has been severely impacted historically by landslides caused by heavy rains, earthquakes, and/or volcanic activity. However, these events generally have been only poorly documented. A major exception was the October 1998 flank collapse of Casita Volcano that led to a debris avalanche–debris flow (lahar) that completely demolished the "new" towns of El Porvenir and Rolando Rodriguez on the lower slopes of the mountain (Fig. 11), killing as many as 2,500 residents (Scott, 2000; Scott et al., in preparation). In addition to obliterating El

Porvenir and Rolando Rodriguez, the debris flow, which extended over a distance of about 10 km with a total area of about 10 km^2, destroyed many other smaller hamlets, isolated residences, and farms, and disrupted the Pan-American Highway at several locations, especially at bridges. The towns of El Porvenir and Rolando Rodriguez had been established only a few decades earlier in this area of great geologic risk. The "trigger" for the disaster was very heavy rainfall from Hurricane Mitch. During the last 4 days of October, rainfall in the area totaled 1,420 mm (Sheridan et al., 1999).

Other devastating debris flows originating on volcanoes in Nicaragua have been recorded from about AD1670 (Mombacho Volcano: ~400 fatalities), 1950 (Cosegüina Volcano: ~1,000 deaths), 1960 (El Chonco Volcano: 60-65 killed), and 1996 (Maderas Volcano: seven deaths) (Scott et al., in preparation).

2.3.8 Costa Rica

Landslides triggered by earthquakes and/or rainfall are a major cause of social and economic loss for the population of Costa Rica; these events have now become so commonplace that people consider them part of their daily lives (Mora, 1989). As the population expands into hillside areas, slopes are becoming more and more disturbed, and the frequency of landslide activity is increasing.

The Costa Rican landslides of greatest impact economically have been associated with the 1973 Tilarán and 1983 Pérez Zeledón-Division earthquakes and the 1986 Sabalito and 1987 Pejibaye-El Humo storms (Mora, 1989). The Pérez-Zeledón-Division earthquake caused many landslides over an area of 175 km^2. Many agricultural and grazing areas and about 18 km of the Pan-American Highway were destroyed.

The Pejibaye-El Humo storm produced more than 270 mm of rain in 4 hrs (Mora, 1989). At least 25 $km^2$of land experienced landsliding, avalanching, and flooding. Losses were considerable: 26 houses, 14 bridges, 11 km of roads, 2,500 ha of coffee and sugar cane plantations, 20 days of power production at the Cachí (110 MW) hydropower plant, and at least three people killed (Mora et al., 1988). Total losses from this storm (landslides and flooding) were estimated at $12.5 million ($19 million).

The ash eruptions of Irazú Volcano from March 1963 through February 1965 indirectly

Figure 9. The January 2001 earthquake-induced slide that demolished much of the Las Colinas neighborhood of Santa Tecla, suburb of San Salvador, the capital of El Salvador. (Photo courtesy of AP/Wide World Photos)

Figure 10. Destruction of a section of the Pan-American Highway east of Ilopango, El Salvador, by a 500,000-m^3 landslide triggered by the January 2001 El Salvador earthquake (M7.6). (Photo by E.L. Harp, U.S. Geological Survey)

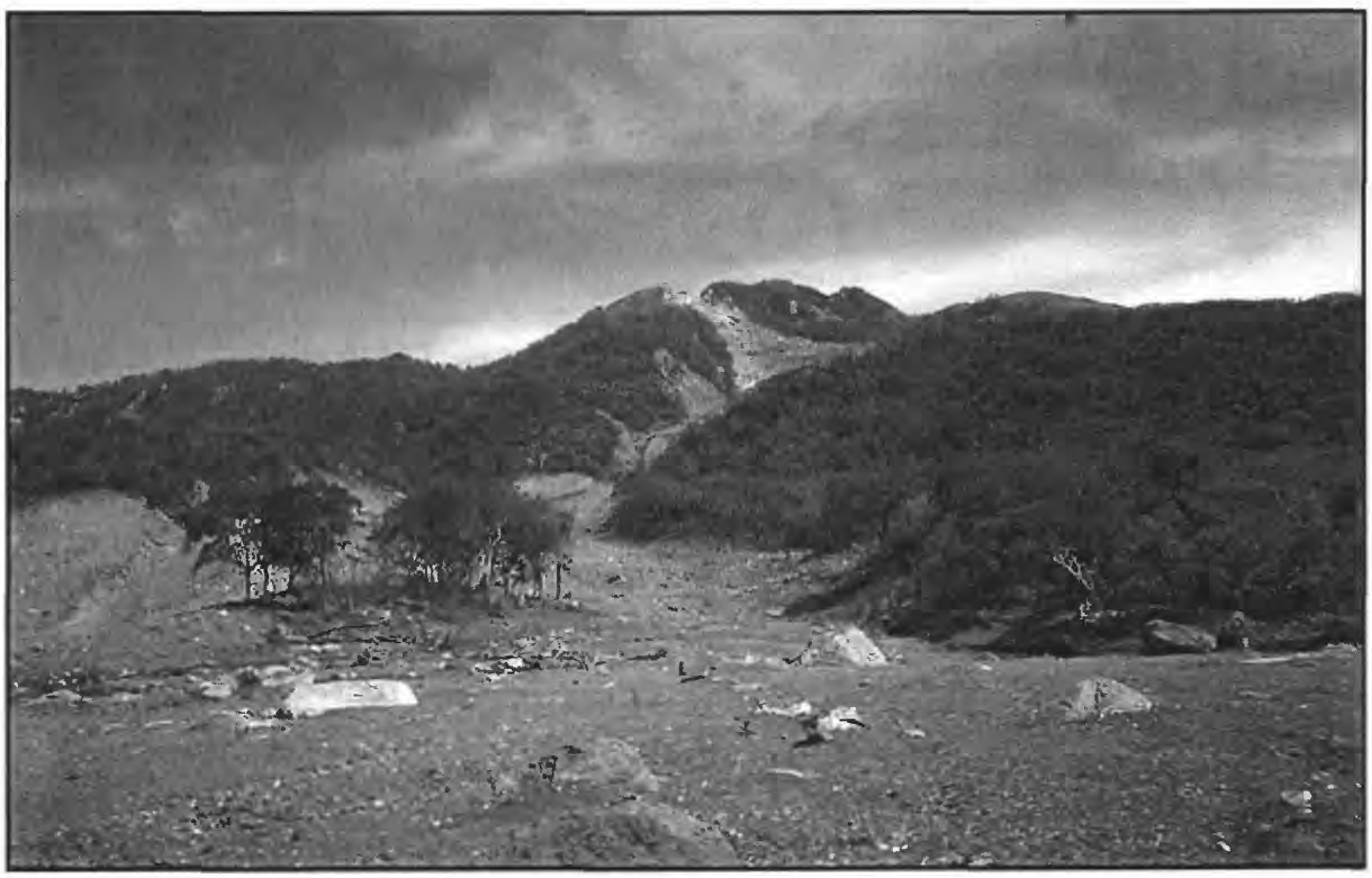

Figure 11. Landslide on Casita Volcano Nicaragua, which was triggered by 1998 Hurricane Mitch. The landslide began as a small flank collapse of the volcano, but was soon transformed into a large debris flow, which obliterated two towns on the lower slopes of the volcano. (Photo by K.M. Scott, U.S. Geological Survey)

resulted in landslide activity that caused major devastation. Rain falling on the ash caused repeated floods of water, mud, and rock debris from the slopes of the volcano. Debris flows were especially severe in the Río Reventado watershed on the southwest slope of Irazú (Waldron, 1967). In December 1963, a large debris flow in the valley of the Río Reventado destroyed more than 300 homes and killed more than 20 people at the town of Cartago.

2.3.9 Panama

Landslide activity in Panama can be divided into geographic categories: (1) landslides outside the Panama Canal Zone caused by heavy rainfall or earthquake activity, and (2) construction and post-construction landslides along the Gaillard Cut of the Panama Canal. Most of the recorded slope failures not related to the Canal have been caused by earthquake activity in this seismically active nation; historic instances of landslide damage are as follows (Stewart and Stewart, 1989):

In 1882, parts of the Panama Railroad were destroyed by landslide activity triggered by an earthquake epicentered just off the north coast of Panama in the Caribbean Sea. These slides occurred mainly in constructed railroad fills.

In 1914, earthquake-triggered submarine sliding destroyed a small banana dock near the town of Tonosi on the south-central coast. In 1934, an earthquake (estimated M7.7) triggered a submarine slide, which caused a large banana loading dock at Puerto Armuellas on the southeast coast to slide into the sea; part of the town was also destroyed by the slide. Damages amounted to more than $1 million (~$13 million).

The greatest known landslide damage in Panama occurred in 1976 as the result of a series of earthquakes (magnitudes as great as 7.0) epicentered just off the northeast shore of Panama near the Panama-Colombia border. This seismic activity occurred during the rainy season when the ground was saturated; as a result, the saturated soils liquefied and massive landslides occurred. Along the Pacific Coast in the drainage basin of the Río Jacque, approximately two thirds of a 1,000-km^2 area was denuded. The streams and rivers were completely plugged with debris and mud that flowed from the mountain sides, filling the valleys with 5-15 m of slide debris. The town of Jacques, built on delta deposits of the Río Jacque, was particularly hard hit; damages from landslides and settlement in the town totaled about $1-2 million ($3-6 million).

Of greater economic importance have been construction and post-construction slope failures along the Gaillard Cut in the Continental Divide segment of the Panama Canal near its Pacific Ocean terminus. The many major slope failures (Fig. 12) that occurred during construction of the 12-km-long Gaillard Cut (Lutton et al., 1979) constitute possibly the world's most extreme case of damage to a transportation system. Slope failures not only severely disrupted construction, delaying completion of the canal by nearly 2 years, but also caused closing of the canal on seven different occasions after it was opened to traffic in 1914. Although detailed costs of damages from Panama Canal landslides from the construction period to present are not available, the following data published by the Panama Canal Company indicate the economic severity of the effects of these slope failures (MacDonald, 1942):

- Between beginning of construction and 1940, 57 million m^3 of landslide material was removed from the canal;
- During construction, excavation was disrupted for weeks at a time because landslides blocked haulage railroad tracks;
- Steam shovels, drilling equipment, locomotives, railway cars, and other equipment were destroyed by landslides;
- Construction costs were increased by millions of dollars due to landslide activity, and
- Many millions of dollars in shipping tolls were lost by delay in opening the canal and by periods of closure due to landslides.

Figure 12. The 1913 Cucaracha landslide, Gaillard Cut, Panama Canal, which occurred during construction of the canal. Note construction railroad tracks on the bottom of the future canal. Activity of this 2.2-million-m3 earth slide-earth flow continued during and after filling of the canal (see Fig. 13). (Photo courtesy of the Panama Canal Commission)

Figure 13. October 1986 reactivation of the Cucaracha landslide, Gaillard Cut, Panama Canal. The landslide extended nearly across the channel, but much of the toe had been removed by dredges (in the photo) by the time this photo was taken. (Photo courtesy of the Panama Canal Commission)

Although landslides have not closed the canal since 1920, they still threaten navigation and pose a continuing and expensive maintenance problem for the Panama Canal Authority, now an agency of the Republic of Panama. For example. a 4.6-million-m^3 reactivation of the Cucaracha landslide (Fig. 13) nearly closed the canal in 1986 (Berman, 1999).

2.4 Socioeconomic Losses in South America

For most South American countries, published information about landslides is scanty, and, for the most part, is restricted to descriptions of major destructive landslides and characteristics and distribution of landslides related to major earthquakes (Ericksen et al., 1989). Other information about landslides, most of which is unpublished, is found in "in-house" reports by government agencies, dealing with construction of roads, hydroelectric projects, and other public works. As a consequence, available information on landslide damage in these countries is incomplete, which makes reliable estimates on extent of destruction and casualties difficult to obtain. Thus, the following section will deal mainly with published socioeconomic information related to major events (also presented in Schuster et al., in press) and ignores the sum of the effects of the many smaller landslides that occur almost annually in many countries.

2.4.1 Venezuela

Total annual landslide losses in Venezuela have been estimated recently by Zuloaga (1995) at $55 million ($62 million). Until the year 2000, most of these losses had occurred in Metropolitan Caracas

Based on Venezuelan sources, Larsen et al. (2001) have reported that, on the average, at least one or two severe flash-flood/landslide events have been recorded per century along the northern coast of Venezuela since the 17th century. In the nearby states of Aragua and Carabobo, such events were recorded in 1693, 1789, 1798, 1804, 1808, 1812, 1890, 1892, 1902, 1912, 1914, 1927, 1933, 1945, 1946, 1951, 1956, 1962, 1963, and 1987. Thirteen such events occurred in the 1970's. In the September 1987 event, an unusually heavy rainfall of 174 mm in less than 5 hrs occurred in the Río Limón drainage in Aragua State, 100 km west of Caracas. The heavy rain triggered thin slips and slumps in residual soils on steep slopes; these failures were soon transformed into high-velocity debris flows that caused the worst landslide disaster in the history of Venezuela (Elizalde et al., 1987; Salcedo and Vignali, 1987; Montes, 1989). The debris flows passed through the city of El Limón and the small towns of Cana de Azucar and El Progresso; approximately 1,500 homes, 500 vehicles (Fig. 14), three bridges, and 25 km of roads were damaged or destroyed by the event. About 210 people were killed, 400 were injured, and more than 30,000 people were temporarily stranded without means of reaching nearby towns and cities by road.

In Caracas, the capital and largest city of Venezuela, landslide problems can be divided into two groups from the socioeconomic point of view: (1) landslides in low-income "barrios," where property damage due to the slides commonly is not significant because of low property values, but loss of life can be high, and (2) slides in moderate- to high-cost residential areas (Schuster et al., in press). Of the approximately 4 million inhabitants of Caracas, it has been estimated that about 40 percent live in low-income barrios that grow in population at an annual rate of about 20 percent.

Every year the hills of Caracas are subjected to landslides, most of which are associated with heavy rain that falls mainly from May to October in areas where annual rainfall averages about 1,000-1,100 mm. An excellent example of a

Figure 14. Vehicles destroyed by the September 1987, Río Limón debris flow, Venezuela. (Photo by D.A. Salcedo, Universidad Central de Venezuela)

catastrophic landslide in Caracas was the September 1993 landslide that completely destroyed seven expensive homes (Fig. 15) and a 150-m section of street in a high-cost residential neighborhood (Schuster et al., in press). This landslide caused no casualties, but blocked the main access to the suburban development, adversely affecting 20,000 families. Total damage was estimated at $2 million ($2.4 million), and engineering remedial measures cost another $6 million ($7.1 million).

Several hundred thousand people reside in a narrow coastal zone on the north slope of the Cordillera de la Costa in the state of Vargas, north of Caracas. In mid-December 1999, this area was hit by Venezuela's worst natural disaster of the 20th century; several days of torrential rain (911 mm in 3 days) triggered avalanches/flows of mud, boulders, water, and trees that killed as many as 30,000 people (Salcedo, 2000; Wieczorek et al., 2000; Larsen et al., 2001). The Venezuelan Civil Defense agency reported that landslides and floods destroyed more than about 23,200 homes, damaged at least another 64,700 homes, and did much damage to infrastructure and lifelines (Salcedo, 2000) (Fig. 16). In addition, much of the two-lane coastal highway was destroyed or damaged (Sancio and Barrios, 2000). The disaster caused economic losses of about $1.8 billion (Salcedo, 2000) to $2 billion (Merifield, in press). The landslides were mainly debris flows a few meters or less in depth, but, in many cases, hundreds of meters wide.

Figure 15. Homes in a high-cost residential neighborhood of Caracas, Venezuela, that were destroyed in September 1993 by a rainfall-triggered landslide. (Photo by D.A. Salcedo, Universidad Central de Venezuela)

Figure 16. December 1999 debris-flow damage to the city of Caraballeda, north coast of Venezuela. (Photo by L.M. Smith, Waterways Experiment Station, U.S. Army Corps of Engineers)

2.4.2 Colombia

Because of its high annual rainfall, mountainous topography, and frequent seismic and volcanic events, Colombia has a long history of catastrophic landslide activity. Although the authors know of no tabulations of socioeconomic costs of Colombian landslides, the following three case histories indicate the severity of the worst of Colombia's landslide problems:

Nevado del Ruiz debris flow – In November 1985, Nevado del Ruiz, the northernmost active volcano in the Andes, located in the Central Cordillera of Colombia, 140 km west of Bogota, erupted, triggering catastrophic debris/mud flows (lahars) that killed more than

22,000 people and destroyed more than $212 million ($339 million) in property (Herd, 1986; Garcia, 1988; Voight, 1990; Mileti et al., 1991). The relatively small eruption ejected materials that melted part of the glacial ice cap at the summit of the volcano, releasing a series of lahars that descended through steep, narrow river canyons at velocities as great as 50 km/hr.

The main flow, which descended the eastern side of the volcano, down the valley of the Río Lagunillas, devastated the city of Armero (population: 29,000) (Fig. 17). More than 20,000 people perished in Armero, most of them crushed or buried in their homes, and 5,000 more were injured (Voight, 1990). Another lahar descended the western slope of the volcano through the narrow canyon of the Río Chinchina, destroying 400 homes and causing an estimated 1,800 deaths near the town of Chinchina (Mileti et al., 1991).

In addition to the fatalities noted above, lahars damaged or destroyed 5,000 homes, 343 commercial establishments, 58 industrial plants, 50 schools, and two hospitals, and buried 3,400 ha of agricultural land (Voight, 1990). Sixty percent of the region's livestock, 30 percent of its grain sorghum and rice crops, and half a million bags of coffee were lost due to the flows and to volcanic ash, which blanketed the area northeast of the volcano.

Figure 17. Remains of the city of Armero, Colombia, following the 1985 eruption of Nevado del Ruiz, which triggered debris/mud flows (lahars) that overwhelmed the city of 29,000. (Photo by Steve Raymer, courtesy National Geographic magazine)

The eruption of Nevado del Ruiz was not a surprise. Alerted by nearly a year of precursory activity of the volcano, scientists had prepared a hazard zoning map that accurately predicted the tragic effect of the eruption weeks before it occurred (Voight, 1990; Mileti et al., 1991). The tragic loss of life was due in large part to failure of local authorities to plan and carry out an adequate emergency-response program.

Similar volcanic debris/mud flows had devastated the same valleys after eruptions of Nevado del Ruiz in 1595 and 1845 (Mojica et al., 1986; Voight, 1990). Acosta (1846; translated and quoted by Voight, 1990) described the 1845 event: "Then, descending along the Lagunillas from its sources in the Nevado del Ruiz, came the immense flood of thick mud which rapidly filled the bed of the river, covered or swept away the trees and houses, burying men and animals. The entire population perished in the upper and narrower parts of the Lagunillas valley." Armero, which did not exist during these earlier disasters, was built on the site of these older lahars (Voight, 1990).

Villa Tina Landslide, 1987 – In September 1987, the small, but sudden and disastrous, Villa Tina landslide occurred in residual soils on the outskirts of the city of Medellin, about 300 km northwest of Bogota. Although the failure surface was at a depth of only 1-1.5 m and the total volume of slide material was only about 20,000 m^3, 80 houses were destroyed and at least 217 people were killed by the fast-moving slide (Tokuhiro, 1999). Although there had been no rainfall in the area for a considerable period before the disaster, the landslide mass contained a significant amount of water. The post-landslide investigation concluded that water from a water-supply pond upslope from the slide had penetrated the soil mass, causing the failure.

Landslides Triggered by the 1994 Paez Earthquake – In June 1994, a M6.4 earthquake shook the Río Paez drainage in southwestern Colombia. Several villages along the Río Paez and its tributaries were destroyed, some by earthquake shaking, some by earthquake-triggered landslides (mainly earth/debris/mud flows), and some by both (INGEOMINAS, 1994; Schuster, 1995; Martinez et al., 1999; Scott et al., in press). The earthquake and resulting mass movements caused 271 deaths; 156 people were injured, and almost 1,700 were reported missing (United Nations Department of Humanitarian Affairs, 1994). In addition, six bridges and 100 km of roads were destroyed by debris flows.

The Paez earthquake triggered landslides over an area of about 250 km^2 in the Río Paez basin. Almost all of these events originated as thin (about 1-2 m thick) translational slides in saturated residual soils on steep slopes (>30°). These thin slides were almost immediately transformed into either debris flows or earth flows as they moved rapidly down the steep slopes onto flatter terrain and into the Río Paez and its tributaries. Locally, more than 50 percent of the slopes were denuded (Figs. 18 and 19). These flows caused a major part of the earthquake-related damage and casualties.

The largest flows followed the valleys of the Río Paez and its tributaries for a maximum distance of 120 km from the source area (Martinez et al., 1999). In the upper 35 km, debris/mud flows destroyed farms and villages located near the rivers (Fig. 19). In the downstream 85 km, mud flows in the Río

Figure 18. Destruction of vegetative cover on valley walls of the upper Río San Vicente, a tributary of the Río Paez, southwestern Columbia, by thin slides, debris avalanches, and debris flows triggered by the June 1994 Paez earthquake. (July 1994 photo)

Figure 19. Debris flows at the village of Irlanda, southwestern Colombia. The main flow followed the Río Paez (right-side of photo); smaller flows entered from valley wall at the left. Homes, a school, and other buildings were destroyed in Irlanda (center and foreground). (U.S. Geological Survey photo, July 1994)

Paez destroyed roads and bridges before dumping into Betania Reservoir on the Río Magdalena, a major river that flows into the Atlantic Ocean.

2.4.3 Ecuador

Landslide events in Ecuador can be classed in two large groups based on the socioeconomic problems that they cause (Benitez, 1989):

- Slope failures along transportation corridors (roads and railroads).
- Slope failures in rapidly growing metropolitan areas.

Slope failures along road and railroad corridors are mainly the result of lack of government standards and regulations that would require adequate geological/ geotechnical studies. Slope failures in metropolitan areas usually are related to a lack of urban planning that would take into account geologic and geotechnical factors. As in most Latin American countries, unplanned urban growth is a serious socioeconomic problem that is perhaps unavoidable under the present conditions.

In Ecuador, reports of damages caused by most landslides are limited to local newspapers. However, there have been a few major events that have been reported in the technical literature; outstanding examples are:

Chunchi landslide, 1983 – In March 1983, during the wettest year in Ecuador for the 20th century, a 1-million-m^3 landslide in the vicinity of the town of Chunchi, about 60 km north of Cuenca, on the western slope of the Andes in south-central Ecuador, slid about 3 km, blocking the Pan-American Highway and burying vehicles (Torres, 1983; Benitez, 1989). More than 150 people were killed.

Landslides from the 1987 Reventador earthquakes – In March 1987, two major earthquakes (M_s6.1 and 6.9) occurred near Reventador Volcano along the eastern slopes of the Andes in northeastern Ecuador. Socioeconomic losses directly due to earthquake shaking were small compared to those caused by earthquake-triggered mass movements and flooding (Ishihara and Nakamura, 1987; Nieto and Schuster, 1988, 1991; Schuster, 1991; Tibaldi, et al., 1995; Schuster et al., 1996).

Valley slopes in the Reventador area, which range from 35°-45°, were covered by residual soils and subtropical forest/vegetation. About 600 mm of rain fell in the area in the month preceding the earthquake; thus, the residual soils had high moisture contents. More than 90 percent of the slope failures began as thin slips or slides in these saturated soils (Fig. 20). These thin slides were almost immediately transformed into debris avalanches and debris flows that flowed down the slopes into the tributaries and on into major rivers: the Salado, Quijos, Malo, Due, Due Grande, Aguarico, and Coca, which are tributaries of the Amazon (Fig. 21). Debris/earth slides, debris avalanches, debris/mud flows, and resulting floods destroyed about 40 km of the Trans-Ecuadorian oil pipeline and the only highway from Quito to Ecuador's northeastern oil fields. Estimates of the total volume of earthquake-induced mass wastage ranged from 75 million m^3 (Crespo et al., 1987) to 110 million m^3 (Okusa et al., 1989). Nearly all of the estimated 1,000 deaths from the earthquakes were a consequence of mass wasting and flooding. Direct economic losses have been estimated at $1 billion ($1.5 billion). In addition, although the effects of widespread landslide denudation on the agricultural and hydroelectric development of the region were difficult to evaluate, they undoubtedly were large (Nieto and Schuster, 1988). For example, plans to build a hydroelectric dam on the Río Coca had to be scaled back because of the large amount of sediment deposited at the site and the potential for future events of this type.

La Josefina landslide, 1993 – In March 1993, a massive rock slide dammed the Río Paute, approximately 20 km northeast of the city of Cuenca in south-central Ecuador (Chamot, 1993; Ortiz et al., 1994; Canuti et al., 1999; Plaza-Nieto and Zevallos, 1999). The 20-25-million-m^3 translational slide in igneous rocks overlain by colluvial deposits was caused by heavy rain and probable instability related to a 160-m-deep open-pit mine excavation at the base of the slope. The Río Paute valley is heavily populated. Plaza-Nieto and Zevallos (1999) found that 35 deaths were directly attributable to the landslide. The economic losses due to the landslide were devastating, as were the effects on the terrain and environment.

The slide formed a 100-m-high natural dam of the Río Paute at its junction with the Río Jadan (Chamot, 1993). The impoundment behind this dam flooded the upstream valley for a length of 10 km,

Figure 20. View of valley wall of the Río Malo, a tributary of the Río Coca, northeastern Ecuador, after the 1987 Reventador earthquakes. Note the severe denudation of slopes due to thin slips/avalanches/flows and of the valley bottom due to debris flows and flooding.

Figure 21. Looking downstream at the confluence of the Río Malo (flowing from lower left) and the Río Coca, northeastern Ecuador. Both river channels have been choked by sediment left behind by debris flows triggered by the 1987 Reventador earthquakes.

submerging homes, industries, and agricultural land. After 33 days, the dam failed, resulting in a peak discharge of 10,000 m^3/sec. The resulting outburst debris/mud flow flooded the valley downstream for a distance of 50 km; at that point, the flow entered the Amaluza Reservoir, the impoundment behind Amaluza Dam. The flood of debris caused very serious damage in the Río Paute valley between the landslide dam and the Amaluza Reservoir; hundreds of homes and several industrial complexes were devastated. However, because the flood was anticipated, people and livestock had been evacuated. Thus, there were no casualties.

Before the landslide dam failed, Amaluza Reservoir, which had a total capacity of 120 million m^3, was lowered 31 m to provide a storage volume of 51 million m^3 for the expected flood (Canuti et al., 1999). In spite of these precautions, the powerhouse turbines suffered damage due to high concentrations of suspended sediment.

Such natural dams occur frequently throughout the world. They cause damages due to upstream flooding, and may cause catastrophic downstream flooding when they fail. In the case of La Josefina, a determined effort was made to prevent failure of the landslide dam by excavation of a spillway channel across the blockage. In 14 days, 160,000 m^3 of landslide material were excavated, creating a channel 18 m deep and 407 m long. Although the dam failed catastrophically due to erosion of this channel, this mitigative measure prevented additional accumulation of 130 million m^3 of water in the lake and upstream flooding of an additional 250 ha of land. If the channel had not been excavated, the peak discharge upon failure of the landslide dam would have been about 30,000 m^3/sec instead of the 10,000 m^3/sec that actually occurred, resulting in an even greater disaster (Plaza-Nieto and Zevallos, 1999).

2.4.4 Peru

Steep slopes, deep valleys, strong earthquakes, and heavy orographic rains act together to create favorable conditions for landslide hazards in the Andes of Peru (Michelena, 1989). As is the case for the rest of the west coast of South America, unusually heavy rains occur along the coast of Peru during El Niño disturbances, which occur about every 5 yrs. These climatic and slope factors are especially relevant in the case of residual soils overlying bedrock, in which the contact surfaces can be "lubricated" by groundwater. The slides that occur in these materials often liquefy; this has been noted earlier for landslides in Colombia and Ecuador.

No systematic inventory of socioeconomic effects of landslides in Peru is known by the authors. However, the following outstanding examples provide an indication of the extremes that can be expected here:

Huaraz Debris Flow, 1941 – In 1941, a major debris flow destroyed about one quarter of the city of Huaraz in the Department of Ancash, killing an estimated 4,000-6,000 inhabitants (Bodenlos and Ericksen, 1955; Ericksen et al., 1989). The event was an outburst debris flow resulting from the sudden failure of a moraine dam in the Cordillera Blanca northeast of Huaraz. The flow, with a volume of at least 10 million m^3, swept 23 km down the valley of Cohup Creek, through the northern environs of Huaraz and into the Río Santa, which it temporarily dammed. Two days later, the natural dam failed; water and debris swept down the Río Santa to the Pacific Coast, destroying settlements and farms in the lower valley.

This disastrous debris flow was the first major catastrophe to strike Huaraz in its 300-yr existence. However, it was only a prelude to more serious disasters in the area in 1962 and 1970 (see below).

Rock Slide of Cerro Condor-Sencca, 1945 – In August 1945, a large catastrophic rock slide dammed the Río Mantaro at Cerro Condor-Sencca in the Department of Ayacucho in the Peruvian Andes. The 5.5- million-m^3 slide formed a 100-m-high natural dam that impounded a lake 20-km long (Snow, 1964).

Because the site was unpopulated, the landslide caused neither casualties nor direct economic losses. However, after 73 days, the dam failed catastrophically by overtopping and erosion, releasing a flood (probably a debris flow) with a discharge that exceeded 35,000 m^3/sec, 50 times the average annual maximum flood on the Río Mantaro. Because the Mantaro valley was sparsely populated in this stretch, damage due to flooding was not severe. However, 13 bridges were destroyed, and agricultural areas on eroded river terraces were damaged. The greatest changes caused by this outburst debris flow/flood were to the morphology of the river valley. The channel level was elevated for several kilometers downstream from the natural dam due to deposition of coarse materials from the debris flow. Snow (1964) noted that construction of hydroelectric dams had been proposed for this stretch of the Río Mantaro, and that the possibility of future changes in the stream regimen should be considered in siting/design of such structures.

Nevados Huascaran Debris Avalanche, 1962 – In January 1962, a large debris avalanche resulted from the catastrophic failure of a hanging glacier on the north peak of Nevados Huascaran in the Cordillera Blanca of Peru (McDowell and Fletcher. 1962; Morales, 1966; Cluff, 1971). The original ice avalanche turned into a high-velocity debris avalanche as it gathered a great volume of granodiorite blocks and debris and descended 4,000 m down the steep slopes of the highest peak in the Peruvian Andes, destroying everything in its path. A total volume of about 13 million m^3 of rock, soil, and ice was deposited by the avalanche. Nine towns were destroyed and 4,000-5,000 people were killed, mostly in the town of Ranrahirca (Morales, 1966; Plafker and Ericksen, 1978). Cultivated fields were devastated, thousands of livestock were killed, and great destruction occurred in an area noted for its beauty and fertility.

Nevados Huascaran Debris Avalanche, 1970 – The greatest number and most destructive landslides in Andes known to have been triggered by any single event were those resulting from the M7.75 earthquake of 31 May 1970 that was epicentered off the coast of Peru (Cluff, 1971; Plafker et al., 1971; Plafker and Ericksen, 1978). This earthquake triggered thousands, or perhaps tens of thousands, of landslides within a 30,000-km^2 area The farthest landslide activity was about 200 km from the epicenter.

By far the most disastrous of the landslides triggered by this earthquake originated from the same north peak of Nevados Huascaran that was the source of the 1962 debris avalanche described above. The 1970 debris avalanche consisted of 50-100 million m^3 of rock, snow, and ice (Fig. 22). This mass traveled 14.5 km in falling nearly 4,000 m from its source to the city of Yungay at an average velocity of from 280 to 335 km/hr (Plafker et al., 1971). Many farms and small settlements were obliterated, but the greatest damage and loss of life was in a densely populated area at the foot of the mountain. The city of Yungay (pre-landslide population: 18,000) and part of the remainder of Ranrahirca (pre-landslide population: 1,850) were buried by the high-velocity avalanche; more than 18,000 people were killed in the two towns. Yungay has been rebuilt at a new site a few kilometers north, out of the path of future avalanches.

Figure 22. The 1970 debris avalanche on Nevado Huascaran, Peru, which destroyed the town of Yungay and much of the town of Ranrahirca (lower foreground), killing about 18,000 people. (Photo courtesy of Servicio Aerofotografico Nacional de Peru, June 13, 1970)

As was the case in 1962, the avalanche continued beyond Yungay into the valley of the Río Santa, forming a large destructive flow of debris, mud, and water that passed down the valley to the Pacific Ocean, causing extensive damage to structures and lifelines (Plafker et al., 1971).

Chungar Rock Avalanche and Resulting Displacement Wave, 1971 – In March 1971, a catastrophic wave of water formed by a high-velocity rock avalanche struck the camp of the Chungar Mining Company on the shore of Lake Yanahuin in the Province and Department of Pasco in the Peruvian Andes, killing an estimated 400-600 people and destroying all but a few of the surface facilities of the mine (Plafker and Eyzaguirre, 1979). The rock avalanche (estimated volume: 100,000 m^3) fell from an outcrop of jointed limestone situated about 400 m above the lake. Water displaced by the rock mass formed a wave that inundated the opposite shore of the lake to a height of 30 m, devastating almost all of the mining camp except for two concrete-block bunkhouses. In addition, water poured into a mineshaft, drowning several miners.

Mayunmarca Landslide, 1974 – In April 1974, a massive rock slide–debris flow dammed the Río Mantaro (a tributary of the Amazon) in the Andes of central Peru, about midway between the cities of Huancayo and

Ayacucho (Hutchinson and Kojan, 1975). The total estimated volume of the rock slide ranged from 1 billion m^3 (Kojan and Hutchinson, 1978) to 1.6 billion m^3 (Lee and Duncan, 1975).

The slide originated at the head of a tributary valley of the Río Mantaro that was occupied by several small villages, the principal one being Mayunmarca. Estimates of the average velocity down this tributary ranged from 120-140 km/hr (Kojan and Hutchinson, 1978). The landslide reportedly killed 317 people and injured 134 (Kojan and Hutchinson, 1978; Carrillo-Gil and Carrillo-Delgado, 1988). Most of these were inhabitants of Mayunmarca and nearby villages, which were destroyed or badly damaged by the slide.

In its lower reaches, the slide was transformed into a massive debris flow that dammed the Río Mantaro to a height of about 150 m. The total volume of water impounded in the 30-km-long lake was estimated at 670 million m^3. Forty three days after it formed, the dam was overtopped and breached catastrophically (Kojan and Hutchinson, 1978). The resulting outburst debris flow traveled 800 km downstream at an average speed of 11 km/hr. Because of adequate warnings, apparently there were no deaths from this flood. However, it caused extensive damage: approximately 20 km of the main highway from Huancayo to Ayacucho were destroyed by the flow or by related landslides, and three bridges were demolished. About 1,000 people had to be evacuated from their homes, and many of their farms were destroyed.

Tablachaca Landslide No. 5 – During the 1980's, a very expensive remedial project was undertaken to control movement of Tablachaca "Derrumbe No. 5 ," a 3-million-m^3 creeping mass of rock and colluvium that endangered Tablachaca Dam on the Río Mantaro in south-central Peru. This 80-m-high concrete dam is Peru's largest producer of electric power. During the late 1970's, it was noted that part of an ancient rock slide in phyllite that formed the right abutment of the dam had reactivated (probably because of the destabilizing effects of the reservoir), and was moving slowly toward the dam (Figs. 23 and 24) (Novosad, 1979; Novosad et al., 1979). Deere and Perez (1985) reported that approximately $40 million ($64 million) was spent by the Peruvian government on successful landslide remedial measures consisting of a 460,000 m^3 earth buttress at the toe of the slope, rock excavation, drainage adits and horizontal drains, and prestressed rock anchors (Morales Arnao et al., 1984; Repetto, 1985; de la Torre et al., 1997).

2.4.4.1 Chile

As is the case for other Andean countries, information on "common" landslides in Chile is scanty. Socioeconomic information is available mainly for the more catastrophic events; examples follow:

Lago Riñihue Landslide, 1575 – In December 1575, an earthquake-triggered landslide (estimated volume: 100 million m^3) blocked the outlet of Lake Riñihue in Valdivia Province on the coast of southern Chile (Davis and Karzulovic, 1961; Wright and Mella, 1963). After nearly 4 months, the natural dam failed, causing a catastrophic flood that destroyed a large part of the city of Valdivia,

Landslides from the 1960 Chilean Earthquake – In December 1960, one of the world's strongest historic earthquakes (M_w9.5) (Kanamori, 1977) hit the same general part of southern Chile as the 1575 event causing numerous major landslides and hundreds of smaller shallow slides (Davis and Karzulovic, 1961, 1963; Weischet, 1963; Wright and Mella, 1963; Ericksen et al., 1989). Locally as much as 75 percent of surficial soils and timber cover was stripped by landslide activity.

Landslides were especially abundant in the Provinces of Osorno and Valdivia. At the eastern end of Lago Rupanco, about 80 km ESE of the city of Osorno, some 125 people were killed by debris avalanches and debris flows (Wright and Mella, 1963). Some of the victims were swept into the lake by debris avalanches from the steep slopes bordering the lake; others were enveloped in rapidly-moving "rivers" of mud, rocks, and trees that developed wherever landslides converged. The agricultural community of Gaviota at the head of the lake was practically obliterated by these mass movements. Much

Figure 23. Creeping rock slide (arrows) endangering Tablachaca Dam, Río Mantaro, Peru, before costly control measures, consisting mainly of a reservoir-level earth buttress, surface and subsurface drainage, and rock anchors, were used to reduce the threat of slope failure to Peru's largest hydropower dam. (Photo, February 1982)

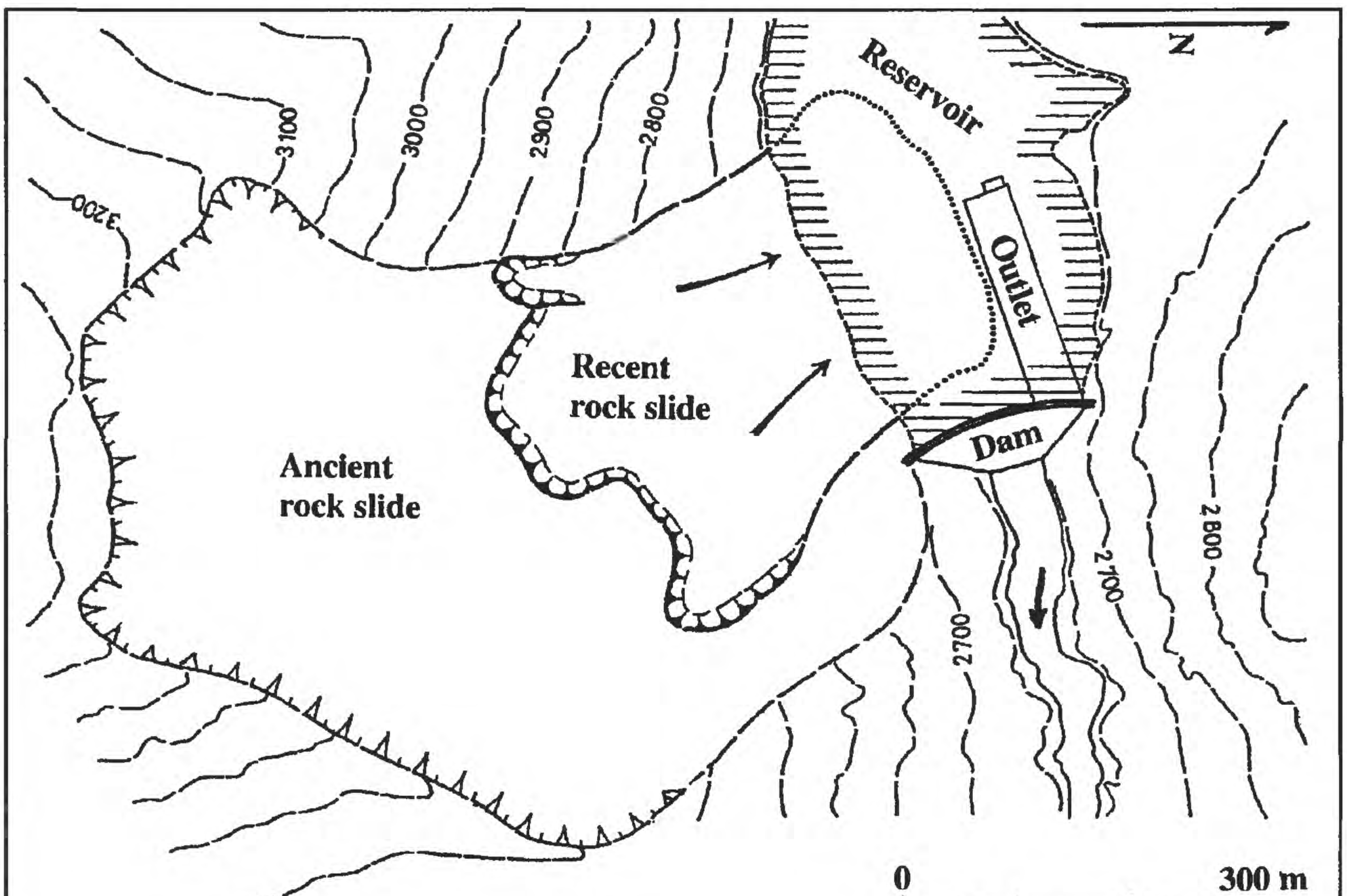

Figure 24. Map of right-abutment landslide, Tablachaca Dam, Peru (Novosad, 1979).

of the debris from the disaster surged into the lake, creating a wave that extended the damage around the lakeshore far beyond the area directly affected by avalanches and debris flows.

The largest mass movements triggered by this earthquake were three contiguous landslides (total volume: ~ 40 million m^3) that dammed the Río San Pedro near the outlet of Lago Riñihue, a large moraine-dammed lake in Valdivia Province, 65 km east of the city of Valdivia (Davis and Karzulovic, 1963). The new lake impounded by the natural dam had an estimated volume of 2.5 billion m^3. Spillway channels were dug across the crest of the dam in an attempt to prevent failure upon overtopping. The effort was partially successful; however, the natural dam failed, flooding the broad valley downstream, just east of Valdivia, to depths of 5-6 m. Because of sufficient warning of flooding, there were no casualties. However, the flood carried away many buildings, washed out railroad grades and roads, and covered large areas with flood deposits.

Landslides from the 1985 Earthquake in Central Chile – On 3 March 1985, a major earthquake (M_s7.8) occurred on the coastline of Chile west of Santiago (Plafker, 1985). Landslides or incipient landslides caused significant damage to structures, roads, and utilities in Valparaiso, Viña del Mar, in suburbs along the coast north of Viña del Mar, and in San Antonio. Except for one large rock fall that temporarily closed a highway in the Andes Mountains northeast of Santiago, landslide activity in this high range generally appears to have been minor, considering the earthquake magnitude. This may be in part because the earthquake occurred at the end of the dry season at a time of minimum ground saturation.

El Alfalfal (Río Colorado) Rock Slide–Avalanche and Debris Flow, 1987 – In November 1987, a catastrophic debris flow on the Río Colorado in central Chile destroyed the campsite, access roads, bridges, and equipment that were supporting construction of the El Alfalfal hydroelectric power plant, causing 29 deaths and considerable damage, not only to the under-construction power plant, but also to the then-operational Maitenese hydroelectric power plant (Valenzuela and Varela, 1991; Casassa and Marangunic, 1993; Hauser, 1993). The debris flow originated as a massive rock slide–rock avalanche or rock fall–rock avalanche (estimated volume: 2.5 to 5.5 million m^3) in sedimentary rocks at an elevation of 4,700 m on the headwaters of a tributary of the Río Colorado (Valenzuela and Varela, 1991). The volume of rock in the initial landslide was estimated at between 2.5 and 5.5 million m^3. The ensuing debris flow traveled about 50 km down the Río Colorado to within 50 km of Santiago, the capital city of Chile. The landslide resulted in considerable public alarm in Chile because it affected an area so close to Santiago.

The Alfalfal hydroelectric plant was finally completed in 1990 after a 1-yr delay caused by the debris flow and after modification of the design of the water intakes to minimize the possibility of damage due to future debris flows (Schuster et al., in press). The Maitenes power plant returned to operation in 1992; a rock embankment was built around the powerhouse to protect it from future debris flows.

Antofogosto Debris Flow, 1991 – In June 1991, after unusually heavy rain, the Chilean coastal city of Antofagasta, 1300 km north of Santiago, was hit by several debris flows and flash floods, resulting in the following casualties and property losses: 101 people killed, 48 missing, 402 houses destroyed, and 2,000 houses damaged (Van Sint Jan and Tallone, 1993; Van Sint Jan, 1994). In addition, Antofagasta's roads, railroads, and water-supply system were damaged, affecting a total of 21,000 people. Total losses were estimated at $27 million ($34 million).

2.4.4.2 Argentina

Although there is abundant geologic evidence of prehistoric landslides on the eastern slopes of the Andes Mountains in Argentina, information on historic catastrophic landslides in Argentina has not been widely circulated. Notable exceptions have been damaging debris flows that have occurred regularly in Jujuy and Salta Provinces in extreme northern Argentina (Marcuzzi et al., 1994; Chayle and Wayne, 1995). An example of these debris flows and the case of the catastrophic early-20th-century failure of a prehistoric landslide dam in the high Andes at the Chilean border follow:

Outburst Debris Flow on the Río Barrancas and Río Colorado, 1914 – The Río Barrancas, which forms the boundary between the northwestern Argentine provinces of Neuquen and Mendoza, was dammed in prehistoric time by a large landslide, forming Lago Cari Lauquen (Fig. 25). About 60 km downstream from the natural dam, the Río Barrancas joins the Río Grande, which flows a distance of about 1,000 km to the Atlantic Ocean.

In 1914, the Río Barrancas breached this high landslide dam; overnight, the original 21-km-long Lago Cari Lauquen was reduced to a "permanent" length of about 5.6 km and its surface was lowered about 95 m (Groeber, 1916). The catastrophic dam failure resulted in a debris flow/flood of water, rock, and soil, with an estimated volume of 2 billion m^3, which devastated the downstream valleys of the Río Barrancas and Río Colorado.

Even though no data are readily available on casualties or damage costs in the lightly populated downstream valleys, Groeber (1916) reported that cattle ranches and farms along the 60-km canyon and valley of the Río Barrancas upstream from its junction with the Río Colorado completely disappeared; fields of wheat, corn, and alfalfa were buried by debris. In addition, two small towns in the valley were devastated.

The debris flow/flood continued down the Río Colorado, well into La Pampa and Río Negro Provinces, more than 300 km from the remnant of the natural dam. Ranches and farms on both sides of the valley were wiped out, as were roads along river terraces. Twenty years later, Groeber (1933) noted that farmland in the valleys of the Río Barrancas and Río Colorado had not recovered.

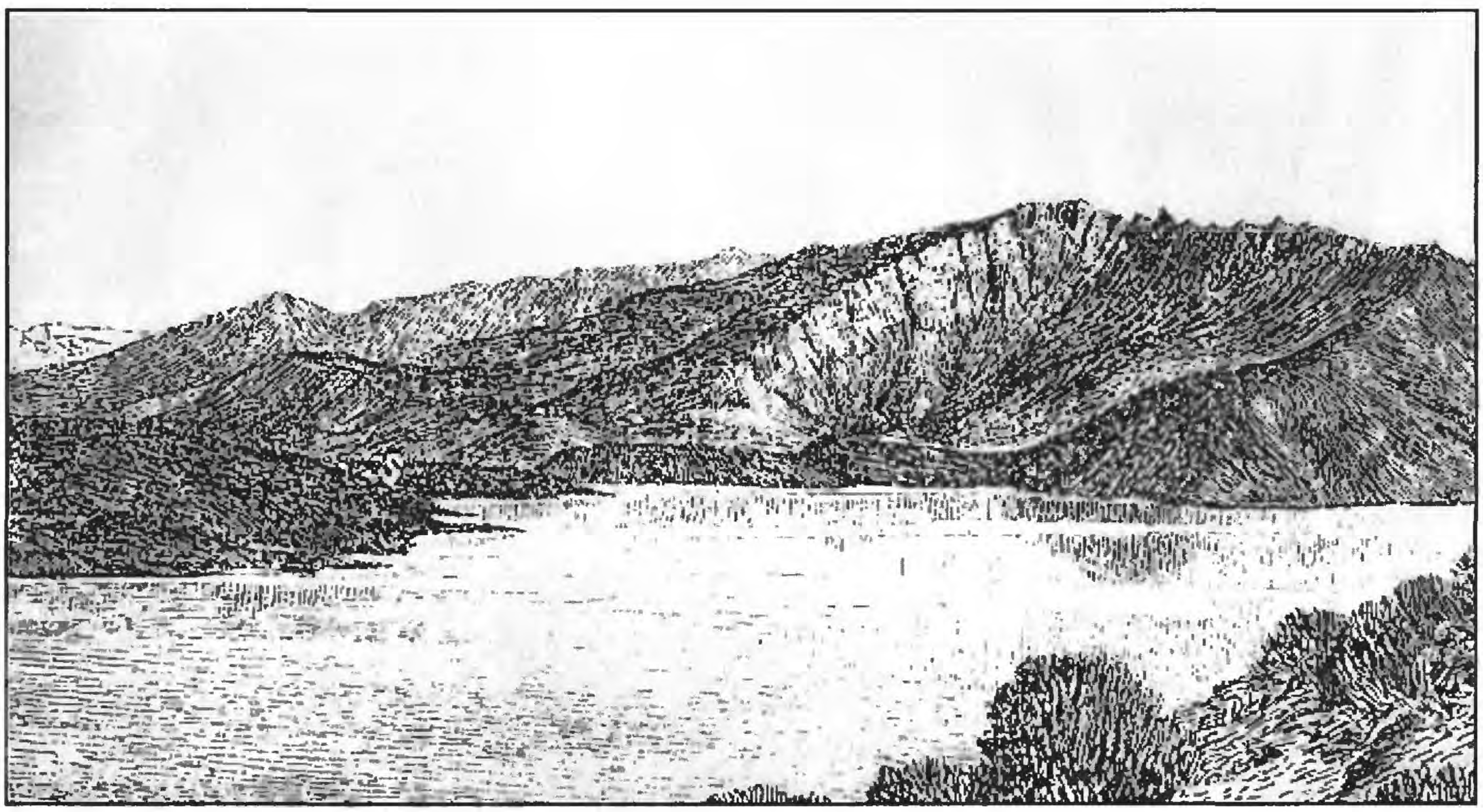

Figure 25. Sketch of Lake Cari Lauquen on the Río Barrancas, Argentina, and of source of prehistoric landslide that dammed the river. Sketch shows status of the lake after partial failure of the natural dam in 1914. Location of outlet of the lake is indicated by the "S" near left edge of sketch. (Sketch by P. Groeber; Groeber, 1916)

An interesting consequence of failure of the prehistoric landslide dam and resulting lowering of the lake surface was that some 16 km^2 of the old lake bottom were uncovered to form a ground surface of sandy/clayey lacustrine/alluvial soil suitable for agricultural development (Groeber, 1916).

Río Escoipe Debris Flow, Salta Province, 1976 – Damaging debris flows have occurred regularly in Jujuy and Salta Provinces in extreme northern Argentina (Marcuzzi et al., 1994; Chayle and Wayne, 1995). Probably most severe of these damaging events was the rainfall-triggered debris flow of January 1976 that swept down the Río Escoipe in Salta Province, almost totally destroying the prosperous town of San Fernando de Escoipe, which was buried under 3 m of mud and rock (Igarzabal, 1979; Wayne, 1987). Only a few houses located on elevated slopes on the outskirts of the town were spared.

Debris flows similar to the Río Escoipe event destroyed housing and disrupted roads and railroads at the villages of Purmamarca (January 1984) and Humahuaca (January 1986 and March 1990) along the Río Grande in Jujuy Province (Wayne and Alonso, 1991).

Storms such as the one that destroyed San Fernando de Escoipe in 1976 seem to have occurred in years affected by the El Niño Southern Oscillation phenomenon (Alonso and Wayne, 1992). Nearly all of the precipitation in northern Argentina occurs from January to March, and major debris flows occur when these storms drop large amounts of rain in a few hours on saturated slopes.

2.4.4.3 Brazil

In its summer season of December to March, the combination of steep slopes, heavy rainfall, residual soils, and weathered rocks have made the coastal mountains of mid-southern Brazil particularly susceptible to major, catastrophic landslide activity. Urban growth in Río de Janeiro and nearby cities has spread from the lowlands onto the slopes, and the attendant construction of highways has required huge side-hill cuts and fills. These human activities have caused many slope-stability problems in urban areas (Da Costa Nunes et al., 1979).

Because of space limitations, all of these landslide events cannot be discussed here; instead, we will briefly review the most-significant occurrences: the 1966-67 disasters in Río de Janeiro Province and the 1988 major landslides in the vicinity of Río de Janeiro and Petropolis, a neighboring city about 50 km to the north.

Landslides in Río de Janeiro and the Serra das Araras, 1966-67 – Unusually heavy rain fell in mid-southern Brazil during the summers of 1966 and 1967 (Barata, 1969; Da Costa Nunes, 1969; Jones, 1973). In 1966, the area most affected was metropolitan Río de Janeiro, where total loss of life from floods/landslides was estimated to have reached 1,000.

In the summer of 1967, a 100-km^2 area lying 50-70 km west of Río de Janeiro along the escarpment of the Serra das Araras was heavily impacted. Slides, avalanches, and flows resulted in immense human and material losses along the most important transportation route in Brazil, the heavily traveled Río de Janeiro-Sao Paulo highway. In this area, deaths from floods and landslides were estimated to be as high as 1,700, and significant damage was done to important hydroelectric installations (Da Costa Nunes, 1969; Jones, 1973; Da Costa Nunes et al., 1979).

In terms of casualties, one of Brazil's worst individual landslide events (Fig. 26) occurred in the Bairro Jardim-Laranjeiras district of Río de Janeiro on 18 February 1967. A high-velocity debris avalanche caused by heavy rain destroyed three buildings, two of which were apartment houses, killing 110 people in the most tragic individual accident of its kind in Brazil (Da Costa Nunes et al., 1979).

Landslides in Petropolis and Río de Janeiro, 1988 –In February 1988, heavy and persistent rainfall along the mountainous mid-southern coast of Brazil caused thousands of landslides to occur in nearly the same region as in 1966-67. Río de Janeiro and Petropolis again became disaster areas, with a total landslide death toll of 320 (Nieto and Barany, 1988; Ogura and Filho, 1991). In Petropolis alone, 171

Figure 26. February 1967 Bairro Jardim-Laranjeiras landslide, Río de Janeiro, which destroyed two apartment buildings and killed 110 people (Da Costa Nunes et al, 1979). (March 20, 1967 photo by Ruy Macial, Geo-Rio, Rio de Janeiro)

were killed, 600 were injured, and 4,263 were left homeless. Perhaps as many as 80 percent of the landslides in these cities were related to human activities, mainly cuts and fills for highways and other construction.

3 ENVIRONMENTAL IMPACTS OF LANDSLIDES

3.1 Introduction

Landslides impact the following aspects of the natural environment of the Western Hemisphere: (1) topography/morphology of both the subaerial and submarine surfaces of the earth, (2) rivers, streams, forests and grasslands, and (3) the habitats of native fauna, both on the Earth's surface and in its streams and oceans (Schuster, in press).

3.2 Effects on Surface/Morphology

The topography/morphology of the Earth's surface, both on the continents and beneath the oceans, is continually being modified by gravitational mass movements. Little attempt has been made to quantify worldwide, or even regional, topographic denudation caused by landslide activity because these processes occur irregularly and discontinuously in space and time. However, case histories of some of the world's largest landslides provide useful information on the maximum topographic effects of individual or regional landslide events.

3.2.1 Topographic Effects of Large Subaerial Landslides

The largest subaerial landslides are prehistoric, but their remnants are displayed as significant topographic "blemishes" on the Earth's surface. Most of the very large individual landslides have been triggered by earthquake or volcano activity. However, heavy regional rainfall can result in widespread landslide activity, often denuding high percentages of surficial geologic materials, and thus impacting flora and fauna over large areas. Examples of some of the Western Hemisphere's largest landslides, both prehistoric and historic, follow:

3.2.1.1 North American Events

Prehistoric Mount Shasta Debris Avalanche, California, U.S.A. – About 300,000-360,000 yr B.P., a major eruption of Mount Shasta volcano in the Cascade Range of northern California resulted in a huge debris avalanche (estimated volume: 26 km^3) that extended 43 km northwestward from the base of the volcano (Crandell et al., 1984) (Figs. 27 and 28). This huge landslide deposit and its moon-like surface were not recognized as such until after the 1980 eruption of Mount St. Helens (described below), which resulted in a similar, but smaller, disruption of the Earth's surface.

Figure 27. Mount Shasta, California, and the ancestral debris avalanche (foreground) triggered by an eruption some 300,000 yrs B.P.

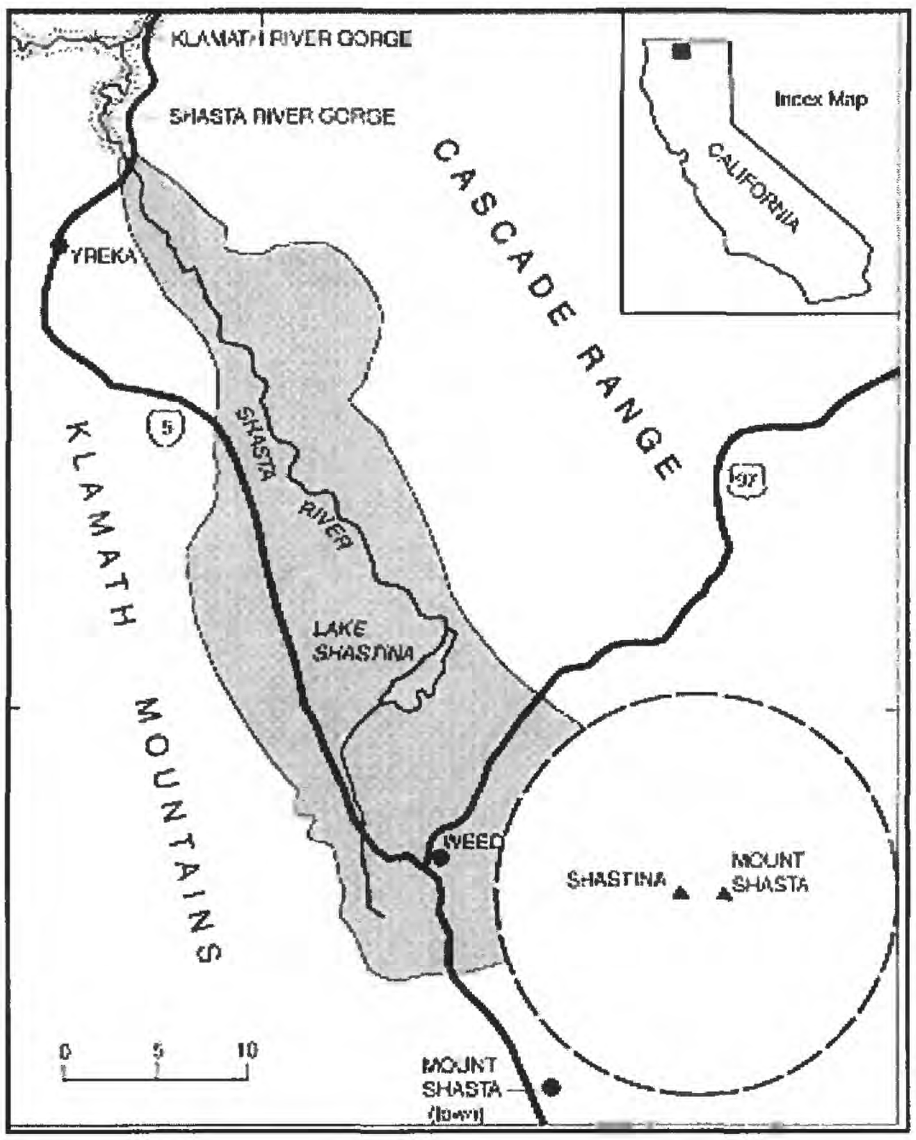

Figure 28. Sketch map of ancestral Mount Shasta debris avalanche. Dashed circle shows approximate outline of base of Mount Shasta (after Crandell et al., 1984).

Prehistoric "Osceola Mudflow," State of Washington, U.S.A. – About 5,600 calendar yr B.P., eruptions of Mount Rainier in the Cascade Range of southwestern Washington State triggered a water-saturated debris avalanche that turned into a 3.8-km^3 debris flow (lahar), commonly known as the "Osceola Mudflow," that was distributed over an area of at least 505 km^2 (Crandell, 1971; Dragovich et al., 1994; Vallance and Scott, 1997). The debris flow filled valleys of the White River system to depths of more than 100 m, flowed northwestward more than 120 km, and buried more than 200 km^2 of the Puget Sound Lowland near the city of Tacoma.

Landslides Triggered by the 1964 Alaska Earthquake, U.S.A. – Although historic landslide events usually have not been of the magnitude of the great prehistoric examples noted above, many large historic landslides have had significant impact on topography/ surface morphology. For example, the 1964 M9.2 Alaska earthquake triggered landslides with a total area of about 260,000 km^2 (Plafker et al., 1969).

Mount St. Helens Rock Slide – Debris Avalanche, State of Washington, U.S.A, 1980 – The massive 1980 eruption of Mount St. Helens in the Cascade Range of southwestern Washington caused a 2.8-km^3 rock slide – debris avalanche (Fig. 1) that covered about 60-km^2 of the valley of the North Fork Toutle River with hummocky, poorly sorted debris (Voight et al., 1983). Thus, although this is the world's largest historic slide, it had only a minor impact on topography as compared to the examples noted above.

3.2.1.2 South American Events

Some major landslide events consist of thousands of smaller landslides that in total have significant regional effects on the Earth's surface. Outstanding South American regional examples are the landslides triggered by the 1987 Reventador earthquakes in Ecuador and the 1994 landslides caused by the Paez earthquake in Peru:

Landslides Triggered by the 1987 Reventador Earthquakes – The 1987 Reventador earthquakes (M6.1 and 6.9) in northeastern Ecuador occurred following a month of heavy rain, causing thousands of small slides in saturated soils on steep slopes (Schuster et al., 1996). These thin slides were almost immediately transformed into debris flows in the area's streams (Fig. 21). Hundreds of square kilometers of the Earth's surface were modified by the slides/flows (Fig. 20), which had a total volume estimated at 75-110 million m^3.

Landslides triggered by the 1994 Paez Earthquake, Colombia – A similar regional landslide event occurred in Cauca Province of southwestern Colombia in 1994. The M6.4 Paez earthquake caused thousands of thin residual-soil slides on steep slopes (Fig. 18); these thin slides turned into destructive debris flows that affected large areas of downstream valleys (Martinez et al., 1999). A total of 250 km^2 of the slope and valley surfaces of the region were directly affected.

3.2.1.3 Rates of Denudation of Slopes Due to Landsliding

As noted above, landslide experts have a reasonable understanding of the volumes of many individual large landslides, and they know that landslides associated with large earthquakes or major volcanic eruptions can denude areas of hundreds to thousands of square kilometers, thus greatly altering the characteristics of mountain slopes and drainage basins. However, much less is known about rates of denudation of slopes that are affected by many small landslides that impact large areas, particularly those caused by heavy rainfall.

A few field studies have attempted to predict rates of slope retreat due to landslide activity based on extrapolation of observed rates. One of the first such studies was of residual-soil avalanches on the island of Oahu, Hawaii, by Wentworth (1943). During an 8-yr study period of a 39-km^2 area, Wentworth noted some 200 thin soil avalanches, with an average area of 0.4 ha and thickness of about

0.3 m, resulting in projected removal of an estimated 0.3 m of residual soil over the total area in 400 years.

Based on study of precipitation-caused landslides that occurred during the period 1974-76 in the forested Northern Rocky Mountains of the State of Idaho, U.S.A., Megahan et al. (1978) found that a total volume 183,040 m^3 of landslide material was produced over an area of 5,670 km^2, for a mean annual erosion rate of approximately 32 $m^3/km^2/yr$. For similar forested slopes in Oregon, Washington, and British Columbia, Swanston and Swanson (1976) reported annual rates of soil/rock removal by debris avalanches that ranged from 11 to 72 m^3/km^2.

Similarly, Larsen and Torrez Sanchez (1992) calculated the rates of landslide removal of material from tropical slopes of the forested Luquillo Mountains of eastern Puerto Rico, where 1.1 percent of the surface area is disturbed by landslides every 100 yrs. Based on their estimated volume of landslide denudation of about 11,800 m^3 for the landslides caused by 1989 Hurricane Hugo, they calculated a mean surface-lowering rate for the study area of 0.16 m/1,000 yrs.

3.2.2 Topographic Effects of Submarine Landslides

Submarine landslides are an important natural slope process by which great masses of sediment move from shallower to deeper regions of the ocean floor. In doing so, they affect major changes in submarine topography. The morphology and mechanics of landslides above and beneath the surface of the sea have many similarities, as well as significant differences. Enormous size is one way that submarine mass movements differ from those above sea level; volumes as large as 20,000 km^3 have been reported for submarine landslides (Hampton et al., 1996). The world's largest submarine landslides (mostly prehistoric) lie off the coasts of South Africa and Norway. However, there are a few very large landslides in the oceans of the Western Hemisphere; outstanding examples are:

Hawaiian Islands Submarine Landslides, U.S.A. – Prehistoric submarine landslides are exposed over an area of 100,000 km^2 of the sea floor between the islands of Kauai and Hawaii in the State of Hawaii (Moore et al., 1989). These huge landslides cover an area five times as large as the land area of the islands. Some individual debris avalanches are more than 200 km long and about 5,000 km^3 in volume, ranking them among the largest landslides on Earth. These landslides, which are related to the building of the islands by volcanic activity, are of two general types: slumps and debris avalanches. The slumps were slow-moving, wide (as much as 110 km), and thick (as much as 10 km). The debris avalanches were fast-moving, long (as much as 230 km) compared to their widths, and much thinner (0.05–2 km) than the slumps.

Valdez, Alaska, U.S.A., 1964 – The 1964 Alaska earthquake resulted in almost instantaneous catastrophic failure of the steep submerged shore at the harbor of the town of Valdez, Alaska (Coulter and Migliaccio, 1966). The submarine slide then retrogressed beyond the shoreline, submerging areas of coastal land and harbor facilities; almost 75 million m^3 of shoreline of Valdez harbor disappeared into the sea (Fig. 29).

Kitimat Arm, British Columbia, Canada, 1975 – In 1975. a large submarine landslide in Kitimat Arm, British Columbia, exhibited characteristics similar to those of the Valdez slide. The Kitimat Arm slide initiated offshore, retrogressed to beyond the shoreline, and generated a tsunami (Prior et al., 1982).

Contributions of Landsliding to Development of Submarine Canyons – Huge submarine canyons incise many of the world's continental slopes, and the presence of large submarine fans at the mouths of these canyons attests to their importance as major conduits of sediment transport (Hampton et al., 1996), much of which probably occurs as landslides, particularly flows and avalanches. Slope failures may be the dominant process that enlarges and sculpts certain submarine canyons. As an example, Carlson and Karl (1988) have speculated that large submarine canyons along the Beringian margin west

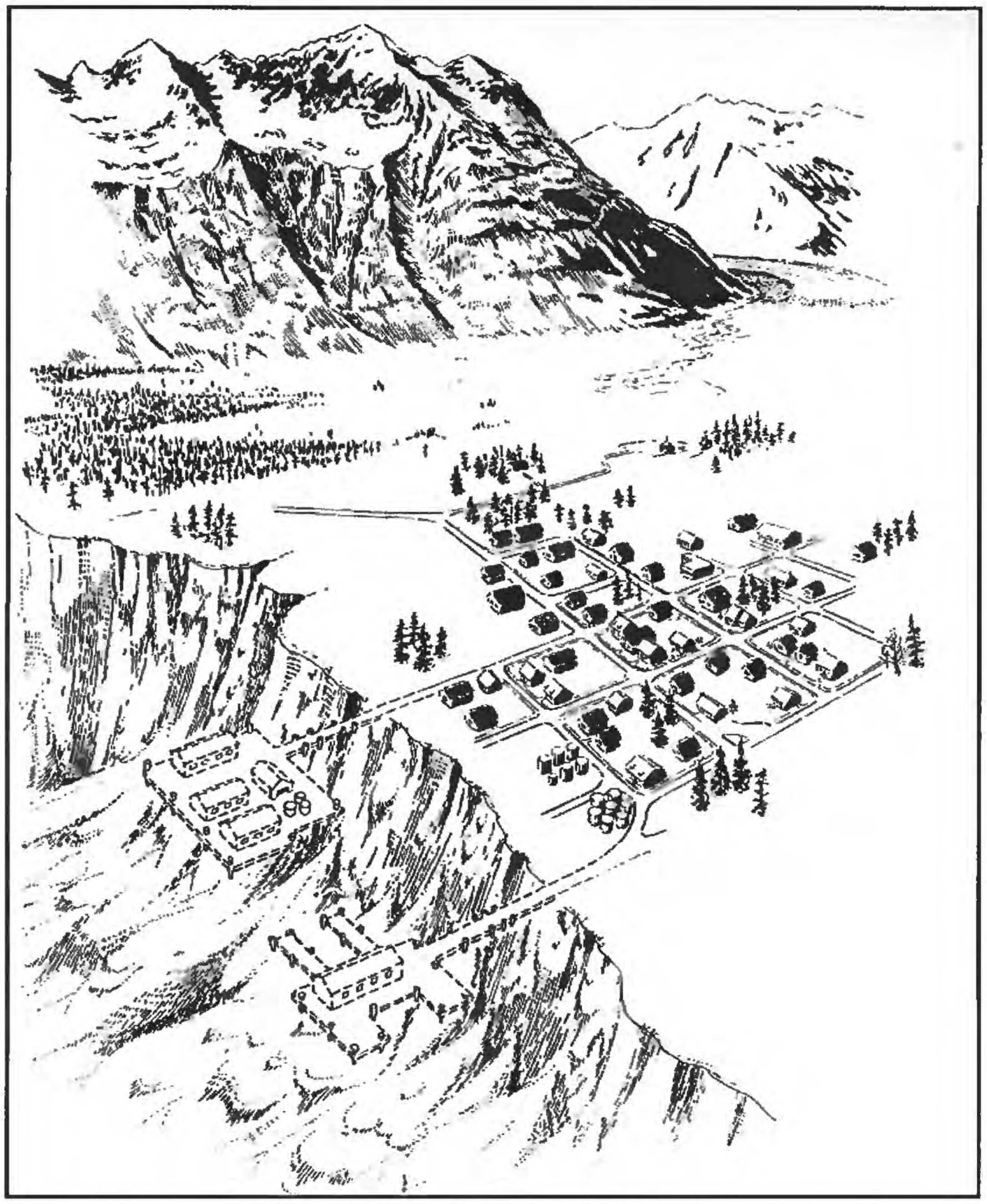

Figure 29. Destruction of port facilities at Valdez, Alaska, U.S.A., by a submarine landslide triggered by the March 1964 Alaska earthquake (Coulter and Migliaccio, 1966). (Sketch by David Laneville, U.S. Geological Survey)

of Alaska originated during Pleistocene submarine landslide activity.

3.3 Impacts of Landslides on Stream Environments

The main types of landslides that affect streams are debris flows, which may follow the stream channel for great distances (occasionally 100 km or more). Debris flows provide important sediment transport links between hillslopes and alluvial channels, and thus are an important factor in drainage-basin sediment budgets (Benda and Dunne, 1987). In addition, debris flows influence the spatial and temporal distributions of sediment in stream channels, either because they deposit sediment in the channels or because the deposits provide a source for accelerated transport of sediment farther downstream (Benda, 1990).

Swanston (1991) noted the types of stream sediment and channel changes that occur due to introduction of materials by different types of landslides. Slumps and earth flows cause low-level, long-term contributions of sediment and large woody debris to channels; partial channel blockages; local channel constriction below the point of landslide entry; and shifts in channel configuration. Debris avalanches and debris flows cause large, short-term increases in sediment and large woody debris; channel scour; large-scale redistribution of bed-load gravels; damming and constriction of channels; accelerated channel erosion and bank undercutting; and alteration of channel shape by flow obstruction.

Delivery of landslide-derived sediment to stream channels can be high. Based on studies of 19 earth flows entering the Van Duzen River basin in northern California, Kelsey (1978) estimated that the annual yield of sediment to the river as a result of these flows was 41,455 m^3, or about 2,182 m^3 per event.

As an outstanding example of a long-runout debris flow, remobilization of the already-saturated surface of the June 1980 Mount St. Helens debris avalanche (Fig.1) formed a debris/mud flow that continued 95 km beyond the terminus of the debris avalanche (Schuster, 1989). This large flow filled and permanently modified the channels of the Toutle and Cowlitz Rivers and continued into the much larger Columbia River, which was partially blocked by the sediment. Between June 1980 and May 1981, approximately 45 million m^3 of sediment was dredged from the Cowlitz and lower Toutle Rivers to restore their original channels (United States Army Corps of Engineers, 1984). The mud flow deposited another 34 million m^3 of sediment in the Columbia River, much of which had to be removed by dredging to allow passage of cargo ships to the major upstream port of Portland, Oregon.

Today, nearly 20 years after the eruption of Mount St. Helens, the Toutle River still is receiving large amounts of sediment that is eroded from the debris avalanche and downstream debris flow. According to the U.S. Geological Survey, sediment levels in the Toutle currently range from 10 times to more than 100 times the amount before the eruption (Bernton, 2000). Sediment levels may remain high for decades, increasing flood risks for downstream communities and threatening efforts to restore salmon and steelhead trout runs that were nearly wiped out by the original debris avalanche and debris flows.

Studies of sediment production in streams in the Rocky Mountains of northern Idaho, U.S.A., have indicated that the amount of sediment reaching streams is as follows: 40 percent from rotational landslides, 40 percent from debris avalanches, and 20 percent from surficial-flow erosion (Wilson et al., 1982).

In a similar study in Puerto Rico, Larsen and Torres Sanchez (1992) found that 81 percent of the estimated 300 t/km^2 of sediment transported from the Mameyes River basin was contributed by mass wasting. They found landslides to be the primary suppliers of sediment to the channels.

Debris flows triggered by the aforementioned 1994 Paez earthquake, Colombia, followed the Río Paez (Fig. 19) and its major tributaries, the ríos San Vicente (Fig. 18) and Moras, into the much larger Río Magdalena and Betania Reservoir, some 120 km downstream (Martinez et al., 1999). The debris-flow deposits formed new river terraces with heights of 10-40 m above pre-earthquake river levels.

3.4 Effects of Landslide Dams on Streams and Valleys

Landslide dams form in a wide variety of physiographic settings, ranging from rock avalanches in steep-walled, narrow valleys to sensitive-clay failures in flat river lowlands (Costa and Schuster, 1988). These natural dams range in height from as low as 1-2 m to the towering 550-600-m height of Usoi landslide dam in southeastern Tajikistan. Landslide dams can affect valley/stream environments as follows (Schuster, 1995):

- Deposition of lacustrine, alluvial, and deltaic sediments in the lake impounded by the dam, resulting in changes in stream gradient and valley-floor morphology upstream from the dam.
- Formation of avulsively-shifting channels downstream from the dam by the introduction of high sediment loads by erosion/and or breaching of the dam mass.
- Secondary landsliding along the shore of the impoundment due to reservoir filling or to rapid drawdown when the natural dam fails.

The channel downstream from a landslide dam can be impacted by either erosion or Deposition. Leopold et al. (1964, p. 454-455) have noted that engineered dams trap as much as 95-99 percent of the sediment that passed before the dams were built. Clear water is released from the dam in place of the sediment-laden flows that existed before construction. The combination of clear water and changing flow regimen leads to erosion of the channel downstream from the dam and lowering or degradation of the stream bed. The same process occurs downstream from landslide dams.

When a large landslide dam fails, major deposition of sediment commonly is derived from the dam mass itself, and, at certain stretches in the stream, erosion may occur. As an example of downstream deposition, the partial failure in 1992 of a 100-m-high landslide dam on the Río Toro in Costa Rica deposited 10 m of sediment at the site of a proposed power plant 700 m downstream from the natural dam (Mora et al., 1999).

Secondary landsliding along the lake shore due to rapid drawdown caused by breaching of the dam occurs occasionally. An example of this phenomenon took place along the shore of the 30-km-long lake that was impounded by the above-mentioned 1974 Mayunmarca landslide dam on the Río Mantaro in Peru (Hutchinson and Kojan, 1975; Lee and Duncan, 1975; Kojan and Hutchinson, 1978).

These secondary landslides,mostly thin debris slides, had a minor effect on the morphology of the Río Mantaro valley.

3.5 Impacts of Landslides on Forest Cover

Widespread stripping of forest and jungle cover by mass movements has been noted in many parts of the world, but particularly in tropical areas as a result of large-scale, earthquake-induced landslide activity. American examples are:

Landslides from Panama Earthquake, 1976 – As noted above, in 1976 two shallow earthquakes (M6.7 and 7.0) struck the sparsely populated, forest-covered southeast coast of Panama, causing huge areas of mass movement. Garwood et al. (1979) calculated that landslides destroyed approximately 54 km^2 of tropical forest (12 percent of the affected area of 450 km^2).

Landslides from Earthquakes in Ecuador (1987) and Colombia (1994) – Similar forest destruction due to earthquake-induced landslides occurred in the previously mentioned 1987 Reventador (Ecuador) and 1994 Paez (Colombia) events. In both cases, the earthquakes occurred following long periods of rainfall, and the saturated residual soils on steep slopes failed as thin slides that rapidly transformed into debris flows. The Reventador slides/flows (Fig. 20) removed the subalpine forest/vegetation cover from more than 25 percent of the surface of the slopes of Reventador Volcano; more than 75 percent of the vegetation was stripped from the volcano's southwestern slopes (Schuster et al., 1996). The Paez landslides stripped soil and vegetation (mostly second-growth subalpine brush and timber) from 250 km^2 of steep valley walls (Fig. 18) (Martinez et al., 1999).

Numerous studies have been made of temperate forest damage due to landslides in southwestern Canada and the northwestern United States. Especially noteworthy have been studies of coniferous-forest damage due to landslides on the Queen Charlotte Islands off the British Columbia coast (e.g., Wilford and Schwab, 1982). In a detailed study of revegetation patterns of landslide-destroyed forests in the Queen Charlotte Islands, Smith et al. (1986) found that forest cover returned to landslide areas more slowly than to logged areas; forest productivity of landslide areas was reduced by about 70 percent when compared to similarly-aged logged areas.

In the northwestern U.S.A., numerous studies of the effects of landslides on forest cover have been conducted by the U.S. Forest Service (e.g., Swanston and Swanson, 1976; Megahan et al., 1978; Swanston, 1991; McClelland et al., 1999); most of these studies have dealt with the effects of logging operations in causing destructive landslides.

As an example of landslide-caused forest destruction in temperate South America, Veblen and Ashton (1978) estimated that the aforementioned landslides triggered by the 1960 Chilean earthquake denuded more than 250 km^2 of forest slopes.

In rare cases, forests have been destroyed by large water waves caused by high-velocity landslides. An outstanding example was the 1958 catastrophic destruction of virgin coniferous forest to an elevation of 530 m above the waters of Lituya Bay, southeastern Alaska, by a giant wave caused by a high-velocity rock slide (Miller, 1960).

3.6 Impacts of Landslides on Wildlife

Although most kinds of wildlife are able to retreat fast enough to prevent injury from all but the fastest-moving landslides, all wild creatures are subject to landslide-caused habitat damage and destruction. Fish are probably most affected because they are dependent on stream access and water quality for their livelihood, both of which are often affected by landslides. Especially susceptible to stream environment changes are anadromous fish (such as salmon), which live in the oceans but return to fresh-water streams to spawn. Their passages can be blocked by landslide dams or their spawning beds can be damaged or destroyed directly by landslide deposits or by sediment washed into the streams by landslides.

Much has been written on the impacts of landslides on anadromous fish that spawn along the West Coast of northern North America. As noted by Swanston (1991), landslides can have major effects on the habitats of these fish, including movement and redistribution of spawning gravels, addition of new sediment and woody debris to the channel system, changes in fish accessibility to viable spawning habitats, changes in availability of food organisms, and changes in seasonal and diurnal water temperatures.

As an example of stream-habitat deterioration, in their study of irrigation-induced landslides in south-central Washington State, U.S.A., Schuster et al. (1989) noted severe landslide-caused siltation of spawning beds for anadromous fish in the last free-flowing stretch of the Columbia River in the United States (Fig. 30).

Major debris flows, such as those in the Toutle and Cowlitz Rivers from the 1980 Mount St. Helens eruption (Schuster, 1989), in the Coca River and its tributaries from the 1987 Reventador earthquake, Ecuador (Schuster et al., 1996), and in the Paez River and its tributaries, Colombia, from the 1994 Paez earthquake (Martinez et al., 1999) most certainly killed a large percentage of the fish populations in these streams. However, within a few years stream regimens would have improved, and at least some species would have returned to the formerly barren stretches of river.

Figure 30. Irrigation-caused landslides have badly damaged salmonid spawning grounds in the last free-flowing stretch of the Columbia River, Washington State, U.S.A.

Although wild animals and birds are usually less likely than fish to be directly affected by landslide activity, the senior author noted a case of destruction of a bird habitat due to landslide activity during his study of irrigation-induced landslides in fluvial-lacustrine sediments along the Columbia River in south-central Washington State. In the spring of 1981, hundreds of cave nests had been excavated by cliff swallows into the 25-m-high silt/sand head scarp of a major slide. During the visit, the swallows' eggs were in the process of hatching. A few days later, the slide reactivated and the scarp retrogressed catastrophically. Undoubtedly, nearly all of the newly-hatched birds and some of their parents were killed by the sudden habitat destruction.

4 SUMMARY AND CONCLUSIONS

In most nations of the Western Hemisphere, socioeconomic losses due to landslide activity are great and apparently are growing as human development expands into unstable hillslope areas under the pressures of increasing populations. The United States leads other American nations in economic losses with estimated total annual losses (direct and indirect) of about US$2 billion per year The number of landslide fatalities in the United States is estimated at about 25-50. Although more difficult to assess, economic losses in other American countries undoubtedly are smaller than in the United States; however, in major individual landslide events numbers of casualties in some years are huge. As extremes, 20,000 were killed in the 1970 Huascaran debris avalanche in Peru, approximately 25,000 died in the 1985 Nevado del Ruiz debris-flow disaster in Colombia, and as many as 30,000 were killed or are missing as a result of the 1999 landslides and floods in northern Venezuela.

Landslides, and especially those that cover large areas, can result in significant modifications in the Earth's natural environment. Both subaerial and submarine landslides affect the topography/morphology of the Earth's surface. On the continents, these surface changes occur most often in mountainous areas and stream valleys. The undersea margins of the continents and the offshore canyons are affected by submarine landslides. Forests and wildlife (especially fish) often are affected negatively by landslides. However, because landslides are relatively local events, both flora and fauna can recover with time if adequate habitats and viable populations remain to allow such recovery.

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