Impact of Landslides and Innovative Landslide-Mitigation Measures on the Natural Environment

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Synopsis

Landslides impact the Earth's natural environment, including effects on (1) the morphology of the Earth's subaerial and submarine surfaces; (2) forests and grasslands, and (3) habitats of native flora and fauna. Morphologic effects are part of a general tendency of surface degradation by mass wasting and erosion. The effects of landslides on vegetation and wildlife are mostly negative; in some cases, they are catastrophic. However, landslide-caused disasters to flora and fauna are generally local in nature, which allows for species recovery with time. In the long term, landslides may even have positive effects on the habitats of flora and fauna.

Biotechnical approaches to landslide mitigation have much less impact on the environment than traditional concrete and steel retaining structures. Biotechnical slope protection utilizes mechanical elements (structures) in combination with biological elements (plants) to prevent and correct slope failure and erosion with minimum impact on the environment.

Keywords

Landslide, environment, morphology, bioengineering, mitigation

1. Introduction

Much has been written on the impacts of landslides on the *total* environment, including effects on people, their homes and possessions, farms and livestock, industrial establishments and other structures, and lifelines. However, few authors have discussed the effects of landslides on the *natural* environment, i.e., on (1) the morphology of the Earth's surface, particularly that of mountain and valley systems, both on the continents and beneath the oceans; (2) the forests and grasslands that cover much of the continents, and (3) the native wildlife that exist on the Earth's surface and in its rivers, lakes, and seas. This paper deals with these effects. In addition, current approaches used to reduce the impacts of landslide-mitigation measures on the natural environment are discussed.

We will use landslide terminology as presented by Varnes (1978) and Cruden and Varnes (1996). As used, the term "landslide" will include all types of gravity-induced mass movements, ranging from rock falls through slides/slumps, avalanches, and flows, and it includes both subaerial and submarine mass movements triggered mainly by precipitation (including snowmelt), seismic activity, and volcanic eruptions. For simplification, the term "debris flow" will include mud flows, debris torrents, and lahars (volcanic debris flows).

2. Impacts on Morphology of the Earth's Surface

The surface of the Earth, both on the continents and beneath the oceans is continually modified by internal forces and the forces of gravity; both, particularly the latter, produce landslides. The net morphologic effect of landslides is to reduce slopes to angles at which they possess long-term stability. *"The processes involved vary enormously from extremely large rapid movements to extremely slow micro-displacement. The result is denudation in the source area, frequent erosion along the transport path, and then deposition, the degree of whose permanence varies widely."* (Small and Clark, 1982, p. 27). We have made no attempt to quantify the worldwide, or even regional, morphologic significance (i.e., the average rate of downcutting) of landslides, an amount that is extremely difficult to determine for large areas. However, we do present case histories of some of the world's largest landslides, which provide useful information on the maximum effects of individual or regional landslide events, and which have provided local information on rates of slope recession and cliff retreat.

2.1 Subaerial landslides

2.1.1. Morphologic impacts of large subaerial landslides

The world's largest landslides are prehistoric, but their remains are displayed as significant morphologic features on the Earth's surface. Most very large landslides have been triggered by earthquakes or volcanic eruptions. In a study of 40 major historic earthquakes, Keefer (1984) has shown that landslides can be triggered over an area as large as 500,000 km^2 by a M=9.2 earthquake (Fig. 1).

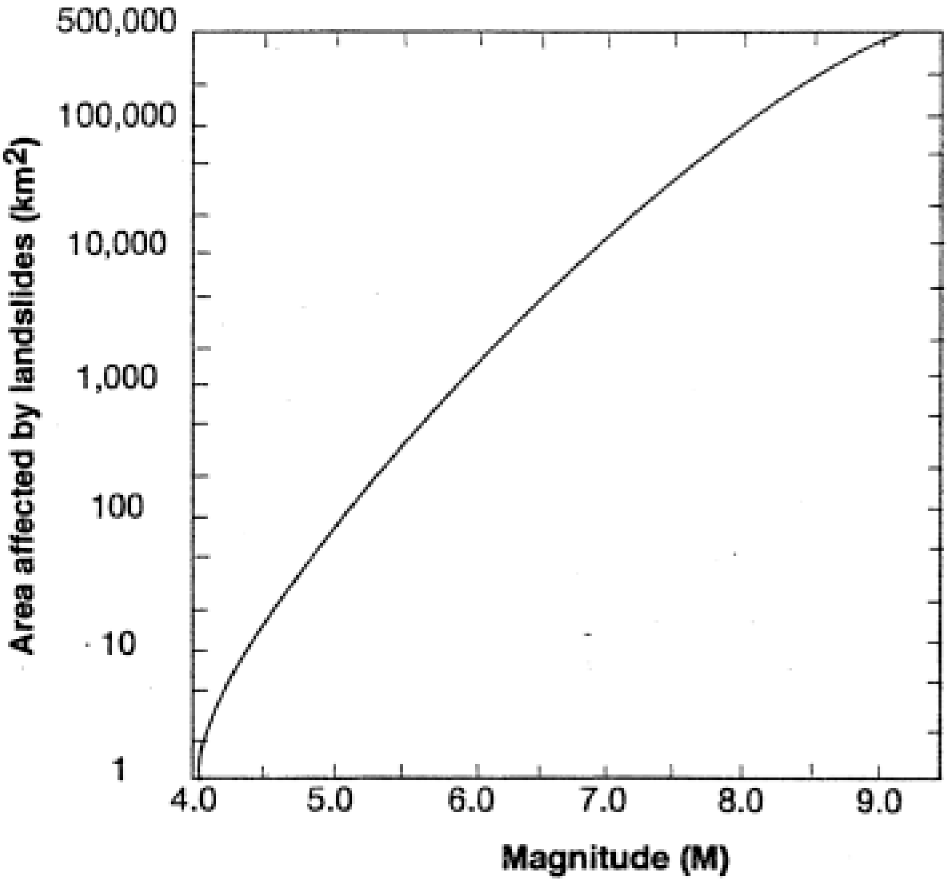


Fig. 1. Area affected by landslides triggered by earthquakes of different magnitudes (after Keefer, 1984)

In 1977, Wolfe (1977) identified what may be the world's largest subaerial landslide: an 18x25-km displaced block of limestone on Samar Island, the Philippines. This block was interpreted by Wolfe to be an earthquake-triggered Holocene landslide, possibly as large as 135 km^3 in volume.

Another huge prehistoric landslide that was probably earthquake-induced is the Simareh landslide in southwest Iran (Fig. 2) (Harrison and Falcon, 1938; Watson and Wright, 1969). Composed of limestone debris, this landslide, which occurred about 10,000-11,000 yrs B.P. (Watson and Wright, 1969; Ambraseys and Melville, 1982) has a surface area of 166 km^2 and an estimated volume of 24-32 km^3, making it one of the world's largest subaerial landslides (Shoaei and Ghayoumian, 2000).

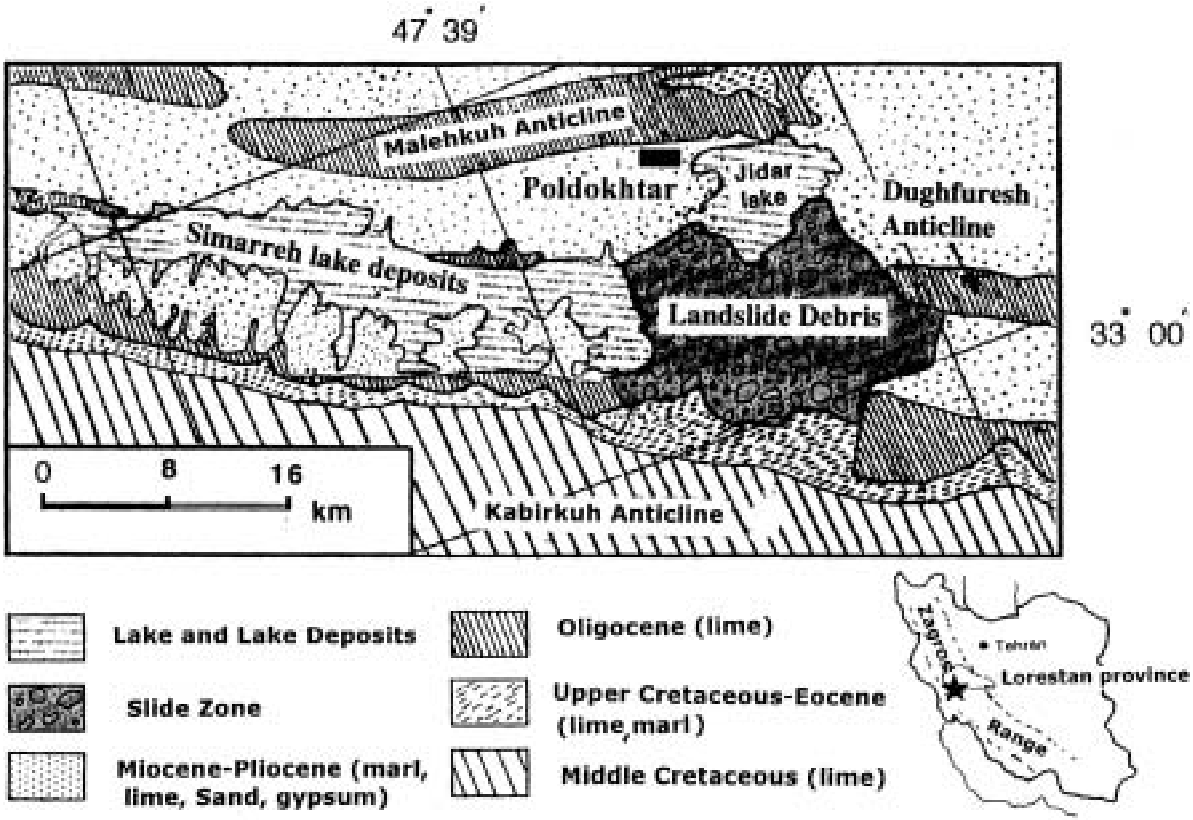


Fig. 2. Geologic map of the prehistoric Simareh (Seimareh, Saidmarreh) landslide in southwestern Iran, showing 40-km-long Simareh Lake, which has been filled by lactustrine sediments to form a large dissected plain. Note that smaller Jaidar Lake was also impounded by the landslide and has also since been filled by sediment. Location of landslide within Iran is indicated on index map by star. (After Shoaei and Ghayoumian, 2000.)

Major earthquakes also have triggered multiple historic landslides over large areas. These often consist of thousands of individual landslides that in total have significant effects on the Earth's surface. Some significant examples from the 20th century are:

- In May 1960, one of the world's strongest earthquakes (M_w=9.2)(Kanamori, 1977) struck the coast of south-central Chile causing numerous major landslides and hundreds of surficial slides (Davis and Karzulovic, 1963; Weischet, 1963). The largest individual mass movements were three contiguous landslides with a total volume of 40 million m^3.
- The M=9.2 Alaska earthquake in 1964 dislodged landslides from slopes over an area of about 260,000 km^2 (Plafker et al., 1969).
- The 1987 Reventador earthquakes (M=6.1 and 6.9) in northeastern Ecuador occurred after about one month of heavy rain, causing thousands of small landslides, which

began as small slips on steep slopes (Schuster et al., 1996). These thin slides liquefied, and turned into major debris flows in the region's tributaries and main streams (Fig. 3). Hundreds of square kilometers of the Earth's surface were modified by the landslides, which had a total volume estimated at 110-120 million m^3 (Hakuno et al., 1988; Nieto et al., 1991).

Fig. 3. Looking downstream at the confluence of the Malo River (flowing from the left) with the Coca River, northeastern Ecuador, following debris-flow activity induced by the 1987 Reventador earthquakes. A debris flow issuing from the Malo River during the night of 5 March 1987 formed a short-lived dam of the Coca River, resulting in deposition of ~15 m of sediment in the Coca channel (Nieto et al., 1991).

- An event similar to that in Ecuador occurred in southwestern Colombia in 1994. The M=6.4 Paez earthquake caused thousands of thin residual slides on steep slopes; these thin slides liquefied and turned into damaging debris avalanches and debris flows (Fig. 4) (Martinez et al., 1995). A total of 250 km^2 of the ground surface of the area was affected.

Volcanic eruptions also have triggered major landslides that have significantly impacted the Earth's surface. Possibly the largest of these is the ~300,000-yr-old debris avalanche (Fig. 5) that originated as the probable result of a major eruption of 4317-m-high Mount Shasta in the Cascade Range of northern California (Crandell et al., 1984). This debris avalanche today extends 43 km westward from the base of the volcano and has an estimated volume of 26 km^3.

Another major North American example of a volcanic landslide that has had major effects on morphology is the large debris flow (lahar) that was triggered by an eruption of Mount Rainier volcano in the Cascade Range of the State of Washington, U.S.A., about 5700 yrs B.P. (Crandell and Waldron, 1956; Crandell, 1971). This debris flow, which is known as the "Osceola mudflow," traveled 110 km down the valley of the White River and onto the surface of the Puget Lowland (Fig. 6). It was deposited over an area of at least 505 km^2 (Dragovich et

Fig. 4. Destruction of vegetative cover on the valley walls of the upper San Vicente River, southwestern Colombia, by slides, debris avalanches, and debris flows triggered by the 1994 Paez earthquake.

Fig. 5. Aerial oblique view to the south of the ancestral Mount Shasta, California, debris avalanche (foreground and middle distance). (Photo by D.R. Crandell, U.S. Geological Survey.)

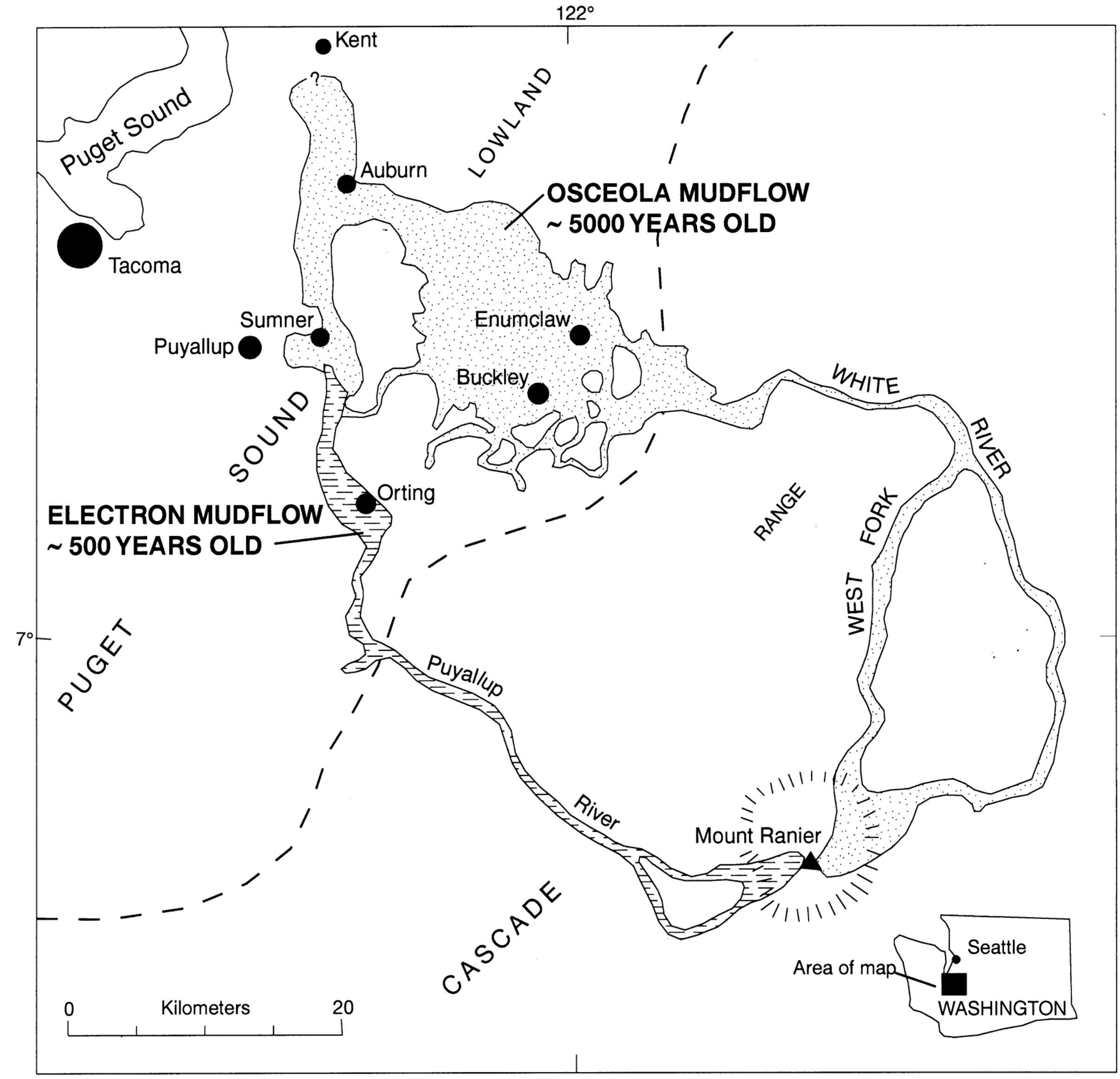


Fig. 6. Map showing area covered by two large debris flows that extended from Mount Rainier, Washington State, U.S.A., onto the Puget Lowland during the Holocene (after Crandell, 1971).

al., 1994). If this event were to recur today, it would bury the small cities of Auburn, Enumclaw, and Sumner, Washington.

The world's largest historic landslide is the 1980 Mount St. Helens rock slide–debris avalanche in the Cascade Range of southwestern Washington State, U.S.A. (Fig. 7), which was triggered by a catastrophic volcanic eruption (Voight et al., 1983). This 24-km-long, 2.8-km^3 landslide buried about 60 km^2 of the valley of the North Fork Toutle River under a cover of hummocky-surfaced, poorly sorted debris, ranging in size from clay to blocks of volcanic rocks with individual volumes as large as several thousand cubic meters (Schuster, 1989).

In high-mountain regions, large catastrophic landslides often occur due to failure of valley walls that have been oversteepened by glaciers and debuttressed by deglaciation. In the Upper Indus Basin of northern Pakistan such activity has had a major effect on the valley morphology of the Karakoram Range. In a study of this region, Hewitt (2002) has identified 180 large rock-avalanche deposits that have formed cross-valley barriers (i.e., landslide dams) on Upper Indus streams. More than one half of these individual Karakoram landslides originally covered more than 10 km^2 of valley floor and were more than 50 million m^3 in

Fig. 7. Debris avalanche in the upper valley of the North Fork Toutle River, southwestern Washington State, U.S.A. View is to the east toward the devastated cone of Mount St. Helens. (May 1980 photo by Austin Post, U.S. Geological Survey.)

volume. Two of the events covered more than 50 km^2 each and exceeded one billion (10^9) m^3 in volume. Debris thickness ranged from 5 m to more than 500 m (Hewitt, 1998). Roughly one rock avalanche occurred in every 14 km of valley surveyed (Hewitt, 2002). Nearly all of these rock-avalanche dams have been at least partially breached. "*Lacustrine deposits were found upstream of almost every example, although most lakes are now drained or filled with sediment. However, though breached, at least 120 of the landslide dams are not completely cut. They persist as local base level and steps in the river profiles.*" (Hewitt, 2002, p. 67).

Although they are not commonly as large or catastrophic as the events noted above, landslides caused by precipitation obviously also have major effects on the morphology of the Earth's surface. Nearly all of the nations of the World are subject to some degree of "gravitational leveling" by precipitation-induced mass movements.

2.1.2. Rate of slope recession due to landslide activity

Landslides obviously are one of the main geomorphic processes that lead to slope retreat. However, as has been noted by Iida and Okunishi (1983, p. 68): "*The geomorphic significance of landslides (or the average rate of denudation) has not been evaluated because they occur irregularly and discontinuously in time and space.*" In spite of this, landslide researchers can reasonably estimate the volumes of most individual large landslides, and they know that landslides triggered by major earthquakes or volcanic activity can denude hundreds or even thousands of square kilometers of the Earth's surface. For example, Keefer (1994) has modeled the long-term sediment production of earthquake-triggered landslides for 12 seismically active regions. His modeling indicated that rates of sediment production by earthquake-induced landslides have been very high (>200 $m^3/km^2/yr$) in four of the studied regions (Island of Hawaii, Irian Jaya, New Zealand, and the San Francisco Bay Region of northern California) and moderately high (20 to 200 $m^3/km^2/yr$) in five others (Peru, Turkey, southern California, all of onshore California, and central Japan).

Less is known about rates of recession of natural slopes that are affected by many smaller landslides acting over larger areas, particularly those caused by heavy rainfall. Modeling methods for expected slope retreat have been offered by Mitchell and Bubenzer (1980) and others, but these approaches apply mainly to relatively homogeneous soils and do not separate slope retreat due to landslide activity from that due to erosion and other factors. However, numerous field studies have attempted to predict rates of slope denudation resulting from landslide activity based on extrapolation of observed rates of retreat. Most such studies have been primarily for limited areas and relatively short periods of observation. Examples from such studies of landslide-caused slope-recession are presented in Table 1 in terms of millimeters per year. In using Table 1, it must be remembered that it is difficult to separate slope recession caused by landslide activity from that caused by erosion, soil creep, and other non-landslide processes. Thus, processes other than landslides may have caused some of the recession noted.

The slope-recession values presented in Table 1 generally are 1 mm/yr or less, with the lowest values being for forested slopes in temperate climates. Most of the areas noted in Table 1 are for relatively steep slopes, and thus are landslide-prone. As noted by Young (1969), the loss of material from mountainous areas and steep slopes is on the order of ten times faster than from areas of low relief. Note that the highest value (3.9-10 mm/yr) in Table 1 represents a special case of cliff retreat in London Clay, i.e., a very steep slope in relatively weak material.

2.1.3. Loss of Soil Resources

In major landslides, all of the soil/colluvium down to bedrock is carried downslope, taking all of the trees and other vegetation with it. Because no soil is left for new plants to grow on, the bare tracks of landslides can remain visible for hundreds of years. There have been a few attempts to quantify losses of soil resources due to landslide activity. Noteworthy is the study by Wright and Mella (1963) of the affects of the aforementioned 1960 earthquake-induced landslides in south-central Chile on the soil resources of the area. They noted the complete destruction of:

> "*steep land soils that plunged, in the form of landslides, debris avalanches, and mudflows, directly into the depths of various lakes. The total area involved is probably in the neighborhood of 20,000 hectares. Practically none of this land was well adapted to agriculture, although about 10% (2,000 hectares) of the lower slopes had been partly cleared by farmers living along the lake margin, in*

an effort to provide additional grazing for the livestock on their small farms." (Wright and Mella, 1963, p. 1395).

Also noted was the "partial destruction" of some 15,000 ha of steep-land soils that were "transported" from hillslopes to valley floors by mudflows and debris flows where they formed a:

> "*rumpled heap of soil and forest debris of far lower agricultural value, for the moment, than the original valley soils that they overwhelmed. In some places the debris is spread out more evenly and in time may rapidly be developed into useful farmland. Some of the area damaged by this type of transportation was of little real agricultural value, but of the total area involved, some 10% (or 1,500 hectares) represents useful agricultural land now buried under debris.*" (Wright and Mella, 1963, p. 1397).

Table 1. Representative examples of slope recession from the geologic literature.

Location	Geology	Climate	Relief	Recession, mm/yr	Comments	References
Rocky Mts., NW USA, SW Canada	Igneous (granite)	Temperate maritime	Steep	0.011-0.072	Mainly from debris avalanches on forested slopes.	Swanston and Swanson, 1976
Rocky Mts., Idaho, USA	Weathered granite	Temperate	Steep	0.032	Landslides in forested area due to rain and snowmelt.	Megahan et al., 1978
Luquillo Mts., eastern Puerto Rico		Tropical	Steep	0.164	1.1% of forested terrain disturbed by landslides every 100 yrs.	Larsen and Torrez Sanchez, 1992
Morogoro River Basin, Tanzania	Meta-igneous	Tropical savanna	Steep	0.26-0.53	Low values in forested areas; high values in deforested areas.	Temple and Rapp, 1972
North Island, New Zealand	Weathered sandstone and siltstone	Temperate maritime	Hilly	0.25-1.0	Grass cover and forest. Far fewer landslides on forested slopes than on grass-covered.	Selby, 1976
Island of Oahu, Hawaii, USA		Tropical	Steep	0.75	Area of 39 km^2 in which 200 thin soil avalanches occurred.	Wentworth, 1943
Adelbert Range, Madang Region, Papua New Guinea	Sedimentary rocks	Tropical	Steep	0.8-1.0	Earthquake-triggered debris avalanches in tropical rain forest.	Pain and Bowler, 1973
Tanzawa Mountains, central Japan	Miocene volcanics	Subtropical, humid	Steep	1.0	Airphotos used to study earthquake- and rain-triggered debris avalanches in forested area.	Tanaka and Mori, 1976
Hawke Bay, North Island, New Zealand	Loess and volcanic ash	Temperate maritime	Hilly	3.8	Severe denudation due to: (1) deforestation, (2) instability of loess and volcanic ash	Eyles, 1971
Cayaguás River drainage, SE Puerto Rico	Highly weathered granodiorite	Tropical	Steep	3.8	Severe denudation because area is deforested (subsistence cropping and plantations)	Larsen and Santiago Román, 2001
Hadleigh, Essex, England, U.K.	London Clay	Temperate maritime	Very steep	3.9-10	Recession of a steep inland cliff in London Clay. Based on historic records.	Hutchinson and Gostelow, 1976

There have been attempts to quantify losses of soil resources due to rainfall-triggered landslide activity in hilly regions in Tanzania. Rapp et al. (1972) estimated that soil losses in the Mogoro River valley averaged between 5000 and 10,000 m^3/yr, while Temple and Rapp (1972) noted that an approximately equal catchment in the Mgeta area of the western Uluguru Mountains lost approximately 270,000 m^3 in less than 3 hrs in February 1970.

It should be noted that some of the soil lost from hill slopes because of landslide activity with the passage of time may be reconstituted as usable agricultural soil in the valleys below. This is especially true in the case of debris-flow deposits in the form of debris fans or terraces, which with time may provide excellent agricultural conditions, either for pastureland or for crop production.

2.1.4. Coastal Cliff Retreat

With wave action serving as the primary trigger, landslide activity is the main process in the retreat of coastal cliffs. The most common landslide types in the failure of coastal cliffs are rock-and-soil fall, slides, and avalanches. However; topples and flows also occur occasionally. Many examples of coastal cliff retreat have been documented in the literature. Table 2 presents several of the best-documented examples in terms of quantitative measurement of retreat, with values being given in meters per year of cliff recession. The amount of cliff retreat is based primarily on the type of geologic material from which the cliff is composed and the strength of wave action. The values in Table 2 range from approximately zero to about 2 m/yr, with the low values generally being for cliffs composed of resistant rock, and the higher values for cliffs formed of very soft rocks or soils (mostly glacial drift). The higher values result in significant changes in coastal morphology over relatively short spans of geologic time. Note that, locally, cliff-retreat values have been recorded that considerably exceed the highest presented in Table 2. For example, the rate of erosion of the clay coast of Primorsko-Akhtarsk on the Sea of Azov, Russia, has been reported by Zenkovich (1967) to have been 12 m/yr. An even more extreme example was provided by the southeast coast of the Island of Surtsey (Iceland) during the winter of 1967-68. During the harsh winter, this coastline, which consists of 12-24-m high lava cliffs underlain by easily-eroded tephra, retreated an average of 75 m, with a maximum of 140 m (Norrman, 1970). A shoreline about one half kilometer long lost an estimated 2 million m^3 of volcanic material. However, such extremes are considered to be local and of relatively short term.

2.2 Submarine Landslides

Submarine landslide is a general term to describe a downslope mass movement of geologic material from shallower to deeper regions of the ocean floor. In doing so, the submarine-landslide process affects major changes in offshore topography. The recent development of well-integrated surveying techniques of the seafloor has enabled study of many previously undiscovered submarine-landslide masses worldwide. These studies have found that the compositions, mechanics, and morphologies of mass movements above and beneath the surface of the sea have many similarities, as well as significant differences (Hampton et al., 1996). Materials involved in submarine mass movements are as diverse as those on land, i.e., rock, soil, mud, and mixtures of all three (Locat and Lee, 2002). In addition, as shown in Fig. 8, classification of submarine landslides by types is similar to the common classifications of subaerial landslides. Enormous size is one way that submarine landslides can differ from those above sea level. The largest submarine landslide yet discovered, the prehistoric Agulhas slump off the coast of South Africa, is 750 km long and 106 km wide (Dingle, 1977). It has an estimated volume of 20,000 km^3 – about 150 times as large as the aforementioned subaerial Samar Island landslide and about 700 times as large as the Mount Shasta debris avalanche. A seismic triggering mechanism has been proposed for this post-Pliocene slumped mass.

Table 2. Representative examples of coastal cliff retreat from the geologic literature.

Location	Geology	Retreat, m/yr	Comments	References
Caucasus Mts., Black Sea Coast, Russia	Flysch	0.01-0.02	"….coast is subject to occasional landslips in beds of steeply dipping rocks…."	Zenkovich, 1967, p. 164
Odessa Coast, Black Sea, Ukraine	Limestone	<0.03	"….outcrops of Pontic limestones at the water's edge…."	Zenkovich, 1967, p. 165
Gotland, Sweden	Limestone, marl	0.04-0.06 (minimum values)	Cliffs 20-30 m high with 100-200 m wide wave-cut platform. Failure processes are rock falls and mud flows. Measurements: 1955-1966.	Rudberg, 1967
Winthrop Head, Boston Harbor, Massachusetts, USA	Unconsolidated glacial debris	0.23	Based on 48 yrs of record (1860-1908).	Johnson, 1925, p. 400
Illinois shore (bluffs), Lake Michigan, USA	Mainly glacial till	0.25 (average)	Using historical airphotos and maps, bluff-top retreat was measured along 30 km of Lake Michigan shoreline for the period 1872-1937.	Jibson, and Staude, 1992
Sussex Coast, southern England, United Kingdom	Chalk	0.42 (average)	"….an area of generally rapid cliff retreat."	May, 1971
Cape Breton, New Brunswick, Canada	Sedimentary rocks	0.45	Weak Carboniferous sediments easily eroded.	Johnson, 1925, p. 319
Joban Coast, eastern Honshu Island, Japan	Sandstone, siltstone, mudstone	0.3-0.7	Based on map and airphoto comparisons by coastal geographers.	Horikawa and Sunamura, 1967
Norfolk Cliffs, eastern England, United Kingdom	Till, sand/ gravel on chalk base	0.03-1.45 (avg,: 0.9)	Based on map comparisons and airphotos from 1880-1967.	Cambers, 1976
Walton-on-the-Naze, Essex, SE England, United Kingdom	London Clay and sands	0-2	1872-1923 (wooden groins): 0.2-1.0 m/yr; 1823-1956: (rock groins): 0-0.8 m/yr; 1970-1996 (no groins): 0.9-2.0 m/yr.	Flory et al., 2002
Fairlight Cove, East Sussex, SE England, United Kingdom	Clay, clay-stone, silt-stone, and sandstone	~1	Rate of retreat of cliffs in these soft sediments has been ~1 m/yr since 1873.	Palmer (2002)
Baltic Sea Coast, Poland	Unconsolidated glacial deposits	~1	Wave conditions in the Baltic Sea are moderate.	Zenkovich, 1967, p. 164
Holderness Cliffs, Humberside, eastern England, United Kingdom	Till, sand/ gravel on chalk base	0.29-1.75 (avg.: 1.2)	Based on map comparisons from 1852-1952.	Valentin, 1954
Holderness Cliffs, Humberside, eastern England, United Kingdom	Till, sand/ gravel on chalk base	~2	"….the Holderness coast has retreated by around 2 km over the last 1000 years, including at least 26 villages listed in the Domesday survey of 1086,…."	Lee et al., 2000
Northern coast, Kunisaki Peninsula, NE Kyushu Island, Japan	Unconsolidated volcanic breccia	2.2	Based on airphoto and map comparisons by coastal geographers.	Horikawa and Sunamura, 1967

The Storegga ('Great Edge') landslide, off the Norwegian coast, has a volume of about 5,700 km^3 (Kenyon, 1987; Bugge, et al., 1988). This slide, which has a 290-km-long main scarp, extends downslope for at least 400 km, and probably more than 800 km. Available data suggest that the Storegga slide consisted of three separate main events. The first slide (some 30,000-50,000 yrs B.P.) involved approximately 4,000 km^3 of relatively soft, clayey Plio-Quaternary sediments. The second and third events occurred some 6,000-8,000 yrs B.P. in sediments that were more consolidated; the volume displaced was about 1,700 km^3. Earthquake loading and gas hydrates probably caused liquefaction of the sediments, thus triggering the slides (Kenyon, 1987).

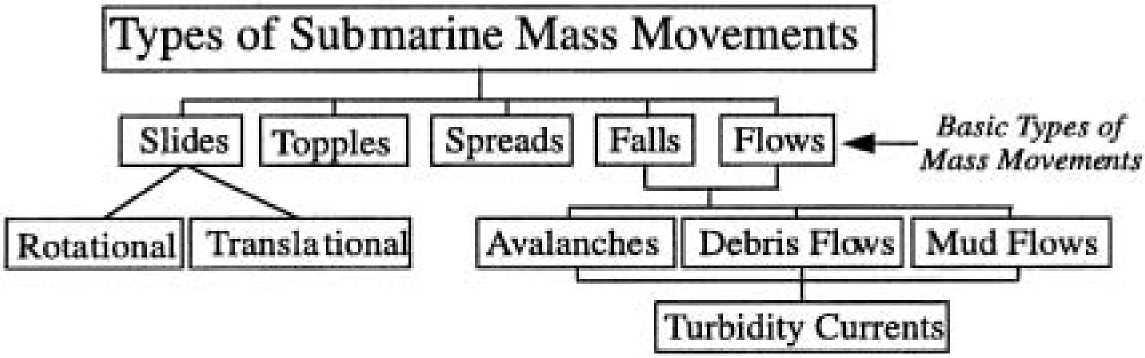


Fig. 8. Classification of submarine mass movements (Locat and Lee, 2002).

A large-volume submarine slope failure known as a ‘megaturbidite” has recently been discovered in the Balearic Basin of the western Mediterranean Sea. This large landslide (volume: ~500 km^3) occurred about 22,000 yrs B.P., at a time when sea level stood at its lowest level during the Last Glacial Maximum (Rothwell et al., 1998). Today’s deposit covers an area of some 60,000 km^2 of the basin with 8-10 m of sediment, forming the Balearic Abyssal Plain. The source of the megaturbidite most probably was the continental slope seaward of the mouth of a large river (such as the Rhône or Ebro) draining glaciated Europe.

Volcanic islands can be the sources of huge submarine landslides. Major rock and debris avalanches are reported around many volcanic islands (e.g., Elsworth and Voight, 1995; Voight and Ellsworth, 1997). An excellent example is provided by El Hierro, a small island in the volcanic Canary Island group, which served as the source of two major Pleistocene submarine landslides: the El Golfo debris avalanche and the Canary debris flow (Urgeles et al., 1997). The El Golfo debris avalanche originated subaerially on the western flank of the island of El Hierro and has an associated 150-km^3 rock-debris deposit with an area of 2,600 km^2 in the sea at the base of the volcanic slope (Fig. 9). The Canary debris flow, which dislocated some 400 km^3 of volcanic material, resulted from a separate failure that originated at a depth between 3200 and 3700 m on the submarine slope of El Hierro island.

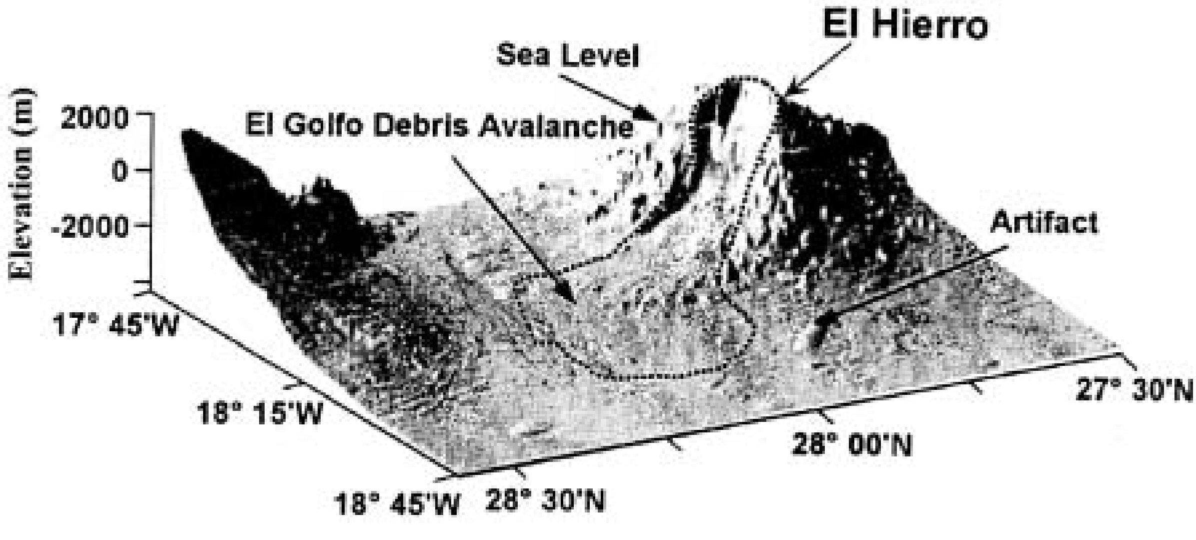


Fig. 9. El Golfo subaerial and submarine debris avalanche from El Hierro Island, Canary Islands, Spain. (From Locat and Lee (2002) after Urgeles et al. (1997).)

In the State of Hawaii, U.S.A., huge prehistoric submarine landslides are exposed over about 100,000 km^2 of the submarine ridge and adjacent seafloor between the islands of Kauai and Hawaii, covering an area more than five times the land area of the islands (Moore et al., 1989). Some individual debris avalanches are more than 200 km long and about 5,000 km^3 in volume. The slope failures that produced these huge landslides began early in the history of individual Hawaiian volcanoes when they were small submarine seamounts, culminated near the end of subaerial shield building, and apparently continued long after volcanic dormancy. The landslides are of two general types: slumps and debris avalanches. The slumps were slow-moving, wide (up to 110 km), and thick (about 10 km), with transverse blocky ridges and steep toes (Moore et al., 1989). The debris avalanches were fast-moving, long (up to 230 km) compared to their widths, and much thinner (0.05-2 km).

The size and displacements of individual submarine landslide blocks also are impressive. For example, the Tuscaloosa Seamount, which is a detached block from the Nuuanu debris avalanche, off the Hawaiian island of Oahu, is 30 km long, 17 km wide, and 1.8 km thick; it rests 90 km from its source (Normark et al., 1993).

Although not as large as the above prehistoric examples, a few historic submarine landslides have been documented (Hampton et al., 1996). For example, the 1964 Alaska earthquake resulted in catastrophic failure of the steep submerged shore of the town of Valdez, Alaska (Coulter and Migliaccio, 1966). The submarine landslide then retrogressed beyond the shoreline, submerging areas of coastal land and harbor facilities. Almost 75 million m^3 of the shoreline of Valdez Harbor disappeared into the sea (Fig. 10). Accompanying these and similar submarine landslides are the dangerous tsunamis, or giant ocean waves, that spread outward from the landslide area and travel at high speeds for great distances. These waves strike coastal areas with disastrous results to mankind, flora, and fauna, alike. A submarine landslide in 1888 in the harbor of Trondheim, Norway (Andresen and Bjerrum, 1967), and a 1975 landslide in Kitimat Arm, British Columbia, Canada (Prior et al., 1982), exhibited similar sequences of offshore initiation, retrogression inland, and tsunami generation.

Submarine canyons incise many of the world's continental slopes, and the presence of large submarine fans at their mouths attests to their importance as conduits of sediment transport (Hampton et al., 1996), much of which occurs as landslides, particularly flows and avalanches. Slope failure 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 of Alaska originated from submarine landsliding during the period of low sea level caused by the existence of Pleistocene glaciers.

2.3 Valley Morphology

Both subaerial and submarine landslides have major long-term effects on valleys (and canyons) in which they occur. While gravitational mass movements tend to lower the surface of the Earth, landslide deposits in mountain valleys often have the opposite effect on the valley bottoms, particularly when the streams are dammed by the landslides.

2.3.1. Effects of Landslide Damming

Large landslides often completely block river valleys, impounding lakes. Most landslide "dams" fail by overtopping and breaching due to erosion. However, if they don't fail, the geologic "short-term" effect on morphology is the impoundment of a lake. Landslide dams can affect valley morphology in the following ways:

- Deposition of lacustrine and deltaic sediments in the lake impounded by the dam, resulting in changes of stream gradient, surface morphology, and surficial geology upstream from the dam.
- Formation of avulsively-shifting channels downstream from the dam by the introduction of high sediment loads from erosion of the landslide deposits.

Fig. 10. Destruction of shoreline and port facilities at Valdez, Alaska, by a submarine landslide triggered by the March 1964 Alaska earthquake (Coulter and Migliaccio, 1966). Dashed lines indicate dock area destroyed by the slide. (Drawing by David Laneville, U.S. Geological Survey.)

- Secondary landsliding along the shore of the impounded lake due to reservoir filling or to rapid drawdown if the natural dam fails (Schuster, 1995).

Most landslide dams fail within relatively short periods of time (Schuster and Costa, 1986; Costa and Schuster, 1988). However, many of today's large landslide dams and their impounded lakes have existed for hundreds or even thousands of years. Especially noteworthy are the following: (1) 2,200-yr-old Waikaremoana landslide dam and lake, New Zealand, (2) Simareh (Seimarreh, Saidmarreh) landslide dam in southwest Iran, which about 10,000 yrs ago impounded a huge lake that later filled with sediment to become a lacustrine plain, and (3) 20^{th} century Usoi landslide dam and Lake Sarez, southeastern Tajikistan.

An outstanding example of a landslide-dammed lake that exists as a long-term geologic feature is Lake Waikaremoana on the North Island of New Zealand (Fig. 11). This 250-m-deep lake with an area of 56 km^2 is a remarkable natural feature that owes its survival to the erosion-resistant nature of the Tertiary sandstones and siltstones in the landslide dam (Read et al., 1992; Riley and Read, 1992). The lake has reduced the upstream gradient of the Waikaretaheke River to zero for about 15 km. Because the incoming river carries little sediment, Lake Waikaremoana has not been noticeably reduced in size or volume by sediment deposition.

Fig. 11. Oblique aerial view of landslide-dammed, 56-km^2 Lake Waikaremoana, New Zealand. The outlet of the lake is at the center of the photo. (Photo by Lloyd Homer, Institute of Geological and Nuclear Sciences, Ltd., New Zealand.)

Probably the world's outstanding example of a long-term landslide dam that still exists, although there is no longer a lake behind it, is the previously mentioned Simareh landslide in southwest Iran (Harrison and Falcon, 1938; Watson and Wright, 1969). This limestone mass dammed the Simareh and Kashkan Rivers, forming a blockage as much as 400 m thick. Two major lakes, now filled with sediment, were impounded by the landslide (Watson and Wright, 1969). "Lake Simareh" extended 40 km up the Simareh River to cover an area of 200 km^2 (Fig.

2). The lake eventually filled with as much as 125 m of sediment (Harrison and Falcon, 1937). Smaller "Jaidar Lake" (Fig. 2) covered an area of 90 km^2 north of the landslide debris at the mouth of the Kashkan River. Its lake deposits consist of thinly bedded, marly, clayey silt (Watson and Wright, 1969). Today these lakes exist as long-term dissected lacustrine plains.

The world's largest and highest historic landslide dam was formed by the earthquake-triggered Usoi rock slide–rock avalanche, which dammed the Murgab River in the Pamir Mountains of southeastern Tajikistan in 1911 (Gaziev, 1984; Alford and Schuster, 2000; Hanisch, 2002; Schuster, 2002). The resulting 600-m-high dam impounds 53-km-long, 550-m deep Lake Sarez (Fig. 12). This natural dam is twice as high as Nurek Dam (also in Tajikistan), the world's highest man-made dam. The dam has not been overtopped; inflow from the Murgab River and outflow (seepage) through the dam, in the form of several large outlet springs, appear to be in equilibrium. Thus, this landslide dam will continue to have a major effect on the long-term gradient of the Murgab River.

Fig. 12. View of Usoi landslide dam (foreground) and downstream (west) end of Lake Sarez., southeastern Tajikistan. Source area of the landslide is in the distance at the far left. (Photo by S. F. Cunha, Humboldt State University, Humboldt, California.)

Other examples of very large historic landslide dams are the 1933 earthquake-triggered Deixi blockage (255 m high) of the Min River in central China (Li et al., 1986) ; the 1974 Mayunmarca landslide dam (170 m high) on the Mantaro River, Peru (Kojan and Hutchinson, 1978); and the 1985 Bairaman River landslide dam (200 m high) on the island of New Britain, Papua New Guinea (King et al., 1989). Unlike the Usoi and Waikaremoana landslide dams, all of these natural dams failed catastrophically, sending major outburst debris flows/floods downstream, thus having significant effects on downstream morphology.

Landslide dams may last for several minutes or for several thousand years, depending on many factors, including:

1) Volume and rate of water and sediment inflow into the newly formed lake.
2) Size and shape of the dam.

3) Character of the geologic materials comprising the dam.
4) Rates of seepage through the dam.

Dams that fail quickly commonly have little upstream effect on valley morphology; however, downstream effects of debris flows and/or flooding may be significant. The world's worst landslide-dam disaster occurred in 1786 when the Kangding-Louding earthquake in Sichuan Province, China, triggered a huge landslide that dammed the Dadu River (Li, 1989). After 10 days, the blockage was overtopped and failed; the resulting debris flow and flood extended 1,400 km downstream, drowning about 100,000 people.

The aforementioned Simareh landslide in Iran provides the world's outstanding example of large-scale deposition of lacustrine sediment behind a landslide dam. Another excellent example was provided by the 1941 Tsao-Ling landslide dam on the Chin-Shui-Chi (river), central Taiwan, where 50 m of lacustrine sediments deposited in the impoundment caused severe siting problems for a proposed hydroelectric project planned for the bed of the lake after failure of the natural dam (Chang, 1984). The 1941 Tsao-Ling landslide also changed the gradient of the Chin-Shui-Chi. After failure of the natural dam, the gradient of the river bed upstream from the knickpoint was 1.1 percent, whereas downstream it was 7.6 percent. Interestingly, another major landslide formed a new natural dam at the site in 1999. Man-made remedial measures preserved this dam so that there now is a permanent impoundment at the site (Schuster and Throner, 2000).

Similar long-term effects on stream gradient of lacustrine deposition behind a landslide dam can be noted for the North Fork of the Virgin River in Zion National Park Utah, where a large slide mass that formed "*several thousand years ago*" impounded a lake 5 km long and nearly 1 km wide (Grater, 1945, p. 116). The impoundment lasted long enough before the natural dam failed to allow deposition of a large amount of lacustrine sediment, much of which still exists (Fig. 13).

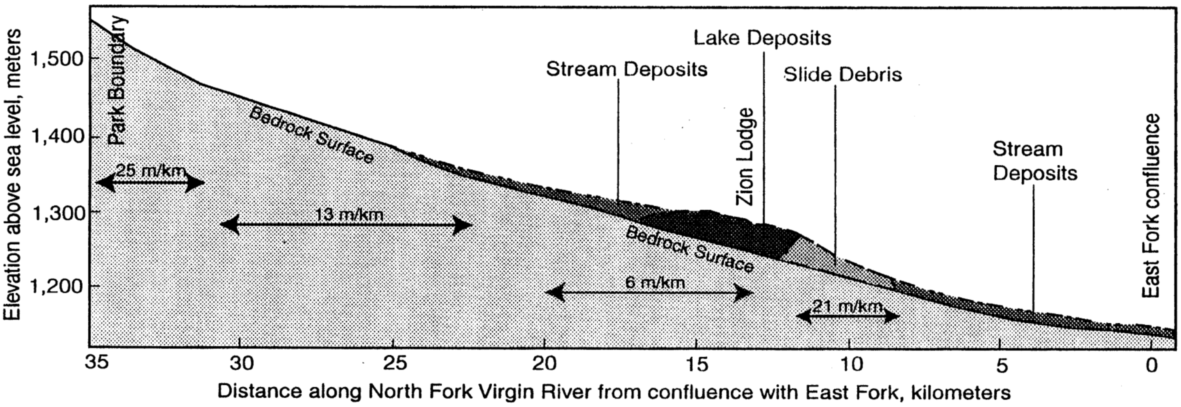


Fig. 13. Profile of the North Fork of the Virgin River, Zion National Park, Utah, U.S.A., showing the long-term effect of landslide damming on the stream gradient (after Hamilton, 1992).

The channel downstream from a landslide dam can be affected by either erosion or deposition. Leopold et al. (1964, pp. 454-455) noted that man-made dams trap 95-99 percent of the sediment that passed downstream before the dams were built. Clear water is released from the impoundment instead of the sediment-laden flows that existed prior to construction. The combination of clear water and changing flow regimen leads to erosion of the channel and lowering or degradation of the bed of the channel downstream from the dam. The same process occurs downstream from long-term natural dams.

If a landslide dam fails, downstream deposition of sediment derived from the dam itself will probably occur. At certain stretches of the stream, erosion also may occur. As an example of downstream deposition of sediment derived from the dam, the partial failure in 1992 of a 100-

m-high landslide dam on the Toro River in Costa Rica deposited 10 m of sediment at the site of a proposed powerplant 700 m downstream from the landslide dam (Mora et al., 1993).

Failure of a landslide dam often causes secondary landslide activity along the lake shore due to rapid drawdown. An example of this phenomenon occurred along the shore of the 30-km-long lake that was impounded by the 1974 Mayunmarca landslide dam on the Mantaro River in Peru (Kojan and Hutchinson, 1978). These secondary landslides, which were mostly thin debris slides, had only minor effects on the morphology of the Mantaro Valley, but did major damage to the highway along the lower valley wall.

2.3.2. Effects on Streams of Sediment Derived from Landslides

Sediment liberated from mountain slopes by mass movements is stored on the lower slopes, on the valley bottoms, or in stream channels. Numerous studies have been conducted to determine the amounts of sediment that actually enter streams from landslides. In some cases, this material is in the form of landslide-derived sediment that dams, or partially dams, the streams. In other cases, the sediment is derived by erosion from landslides located near the streams.

Sediment delivery to stream channels from landslides can be significant. Based on studies of 19 debris flows that entered the Van Duzen River basin in northern California, Kelsey (1978) estimated that the annual yield of sediment to the river by debris-flow activity was ~41,000 m^3, or ~2,200 m^3 per event.

Studies of sediment production in streams in the Rocky Mountains of northern Idaho, U.S.A., have indicated that the amount of sediment reaching stream bottoms is derived from the following sources: 40 percent from rotational landslides, 40 percent from debris avalanches, and 20 percent from overland flow erosion (Wilson et al., 1982). In a similar study in Puerto Rico, Larsen and Torres Sanchez (1992) found that 81 percent of the 300 t/km^2 of sediment transported out of the Mameyes River basin was contributed by mass wasting.

Swanston (1991) has noted the types of channel changes that occur by introduction of materials from the following types of mass movements:

1) *Debris avalanches and debris flows* – Large, short-term increases in sediment and woody debris; channel scour; large-scale movement and redistribution of bed-load gravels and woody debris; damming and obstruction of channels; accelerated channel bank erosion and undercutting; and alteration of channel shape by flow obstruction.
2) *Slumps and earthflows* – Low-level, long-term contributions of sediment and large woody debris to channels; partial channel blockage; local channel constriction below point of entry; and shifts in channel configuration.

Debris flows, which often follow the stream channels for great distances, are the main landslide types that affect streams. Debris flows provide important sediment-transport links between hillslopes and stream 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 themselves provide sources for enhanced transport of sediment farther downstream (Benda, 1990).

As an outstanding example, remobilization of the already-saturated surface of the 1980 Mount St. Helens debris avalanche formed large debris/mud flows, which continued downstream 95 km beyond the distal margin of the debris avalanche (Janda et al., 1981; Schuster, 1981, 1989). The huge flows filled and permanently modified the channels of the Toutle and Cowlitz Rivers, and continued into the much larger Columbia River, which was partially dammed by the sediment (Fig. 14). Between June 1980 and May 1981, ~45 million m^3 of sediment were dredged from the Cowlitz and lower Toutle Rivers to restore the original stream channel (U.S. Army Corps of Engineers, 1984). An additional 34 million m^3 of

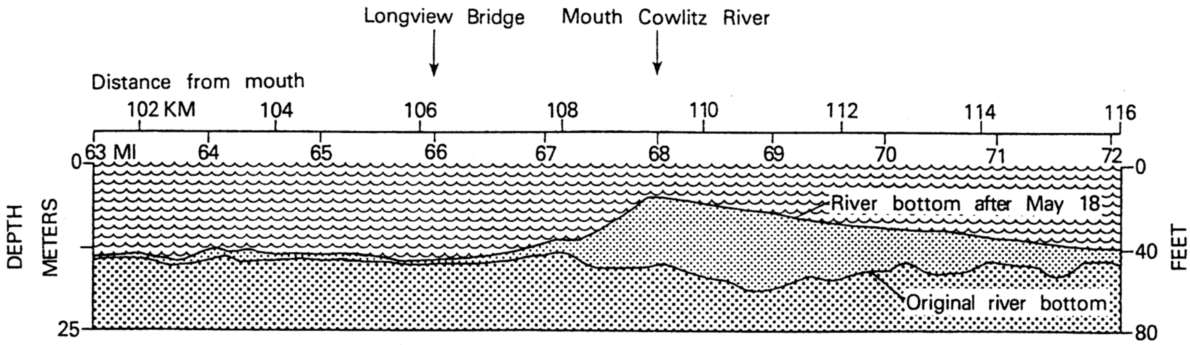


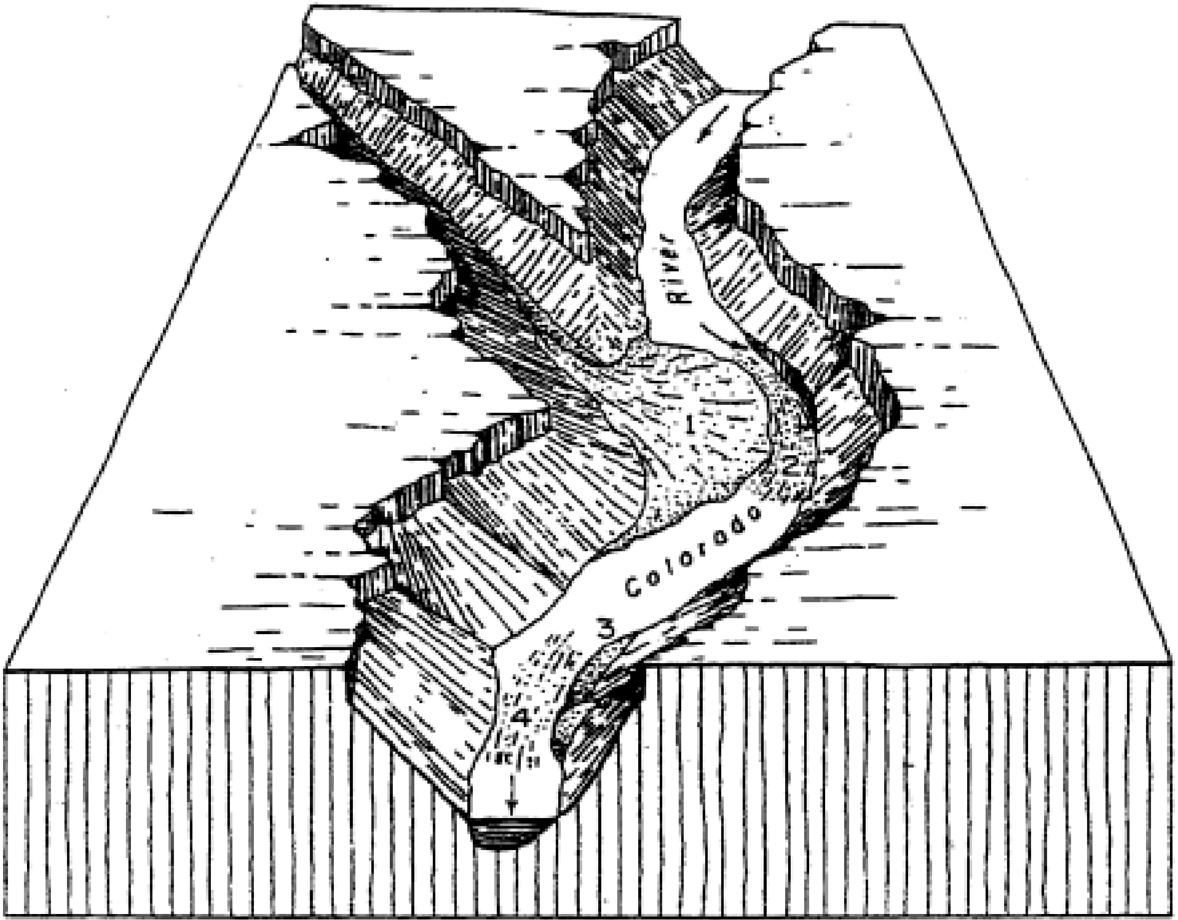
Fig. 14. Longitudinal profile of the bottom of the Columbia River where sediment resulting from the 18 May 1980 mudflows entered from the Cowlitz River. Note that most of the sediment was deflected upstream (Schuster, 1989; modified from Bechly, 1980).

sediment was deposited in the Columbia River about 100-120 km upstream from where the Columbia enters the Pacific Ocean (Schuster, 1989).

Similar large/long debris flows were deposited in river channels as the result of landslide activity caused by the aforementioned 1987 Reventador (Ecuador) and 1994 Paez (Colombia) earthquakes. In both cases, thin earthquake-triggered slides on steep slopes covered with saturated residual soils were rapidly transformed into debris flows, which followed lower-order tributaries to the flood plains of major rivers, where they continued onward before being dissipated dozens of kilometers downstream. In the Reventador case, the channels of the Coca and Aguarico Rivers, tributaries of the upper Amazon, received depths of as much as 20 m of sediment (Nieto et al., 1991; Schuster et al., 1996). Debris flows triggered by the Paez earthquake followed the Paez River and its major tributaries, the San Vicente (Fig. 4) and Moras Rivers, as far as the much larger Magdalena River and Betania Reservoir, some 120 km downstream (Martinez et al., 1995). The debris flow reached heights of as much as 40 m above pre-earthquake river levels.

In arid to semi-arid regions, debris flows commonly enter major rivers from their tributaries, impacting the morphologies of the major river channels. Debris flows into the Colorado River in the Grand Canyon, Arizona, U.S.A., provide an outstanding example of this process (Webb et al., 1989). These debris flows, triggered by slope failures on the canyon walls of the tributaries, are a major process by which sediment is transported to the bottom of the canyon. The main depositories for this sediment have been the many (about 60) alluvial fans that have formed at the mouths of the tributary canyons (Kieffer, 1985) (Fig. 15). Of the debris-flow material that has entered the river, the coarser materials have been deposited as cross-river bars that have formed major rapids; the sand-sized materials have formed beaches, and the silt- and clay-sized particles have been flushed downstream.

Some tributary debris flows have been large enough to have temporarily dammed the Colorado River in the Grand Canyon, resulting in long-term morphologic effects in the river channel. An example is the fan at the mouth of the tributary Prospect Canyon, which dammed the river about 3,000 yrs ago, and has partially dammed it twice since (Fig. 16) (Webb et al., 1996). The Colorado River in the Grand Canyon was also dammed by large, prehistoric, rotational landslides that were as much as 600 m high and covered a surface area of as much as 16 km^2 (Savage et al., 2003). The river was forced to reroute around the landslide debris and excavate new channels.



(Modified from Hamblin and Rigby, 1968)

EXPLANATION

1 Tributary debris fan
2 Rapid controlled by large immobile boulders
3 Debris bar (synonymous with "island" or "rock garden")
4 Riffle or rapid caused by debris bar

Fig. 15. Morphology of a typical debris fan and rapid on the Colorado River in the Grand Canyon, Arizona, U.S.A. (Webb et al, 1989).

3. Effects of Landslides on Forests and Grasslands

3.1 Forest Destruction

Widespread stripping of natural forests and jungle cover by mass movements has been noted in many parts of the world, but especially in tropical areas as the result of large-scale, earthquake-induced landslide activity. In September 1935, two shallow earthquakes (M=7.9 and 7.0) in the Torricelli Range, north coast of Papua New Guinea, caused "*hillsides to slide away, carrying with them millions of tons of earth and timber, revealing bare rocky ridges completely void of vegetation*" (Marshall, 1937). Approximately 130 km^2 (8 percent of the region affected) was denuded by the landslides (Simonett, 1967; Garwood et al., 1979). On the south slope of the Torricelli Range, Montgomery and Eve (1935, p. 14) reported: "*Soil and sub-soil with their covering of tropical jungle had disappeared from 60% of the slopes, baring the underlying bedrock.*" In November 1970, a M=7.9 earthquake triggered landslides along the north coast of Papua New Guinea that removed shallow soils and tropical forest vegetation from steep slopes in the Adelbert Range (Pain and Bowler, 1973). Vegetation was stripped from about 25 percent of the slope surfaces in the 240-km^2 area that was affected by landsliding. Similarly, in 1976 two shallow earthquakes (M=6.7 and 7.0) struck the sparsely populated, jungle-covered, southeast coast of Panama, causing huge areas of landsliding. Garwood et al. (1979) estimated that the slides removed approximately 54 km^2 of jungle cover (12 percent of the affected region of 450 km^2).

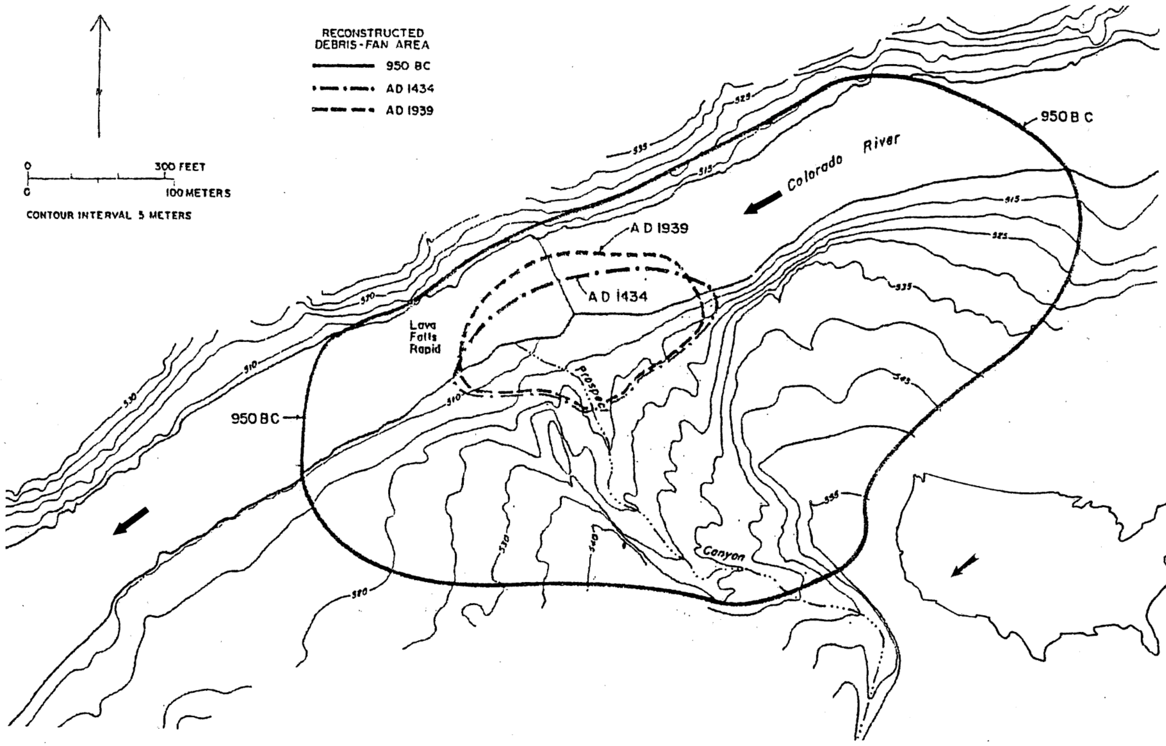


Fig. 16. Debris fans deposited by Holocene debris flows from Prospect Canyon into the Grand Canyon of the Colorado River, Arizona (Webb et al., 1996).

Similar sub-tropical forest devastation due to earthquake-induced landslides occurred in the previously mentioned 1987 Reventador and 1994 Paez events in Ecuador and Colombia, respectively. In both cases, the earthquakes occurred after long periods of rainfall, and the saturated residual soils on steep slopes failed as thin slides that rapidly transformed into debris flows. The Reventador landslides (Fig. 17) removed the subtropical jungle from more than 75 percent of the southwestern slopes of Reventador volcano (Nieto et al., 1991; Schuster et al., 1996). Figueroa et al. (1987) estimated that 230 km^2 of natural forest were lost in the region. The Paez landslides (Fig. 4) stripped soil and vegetation (mostly second-growth sub-tropical brush and forest) from 250 km^2 of steep valley walls (Martinez et al., 1995).

In Puerto Rico, landslides are triggered by heavy rainstorms, including hurricanes. In the Luquillo Mountains of Puerto Rico, which are especially hard-hit by landslides, Brokaw (2003) has reported that landslides denude between 0.08% and 1.1% of the forest area per century.

The destruction of temperate forests by landslides has also been studied extensively. In their study of the influence of landslides on forest vegetation in the Valdivian Andes due to the 1960 M=9.2 Chilean earthquake, Veblen and Ashton (1978, p. 165) have noted that: "*Catastrophic mass movements associated with seismic activity have affected the Andes of south-central Chile several times in the past 400 years and have profoundly influenced the* *regional vegetation.*" They further noted that more than 250 km^2 of temperate forest slopes were denuded in the 1960 event.

Many forest areas in New Zealand have been damaged by landslides. Studies of forest losses in the upper drainage basin of the Pohangina River on the North Island by James (1973) noted

Fig. 17. Aerial view of the northeast valley wall of the Malo River, northeast Ecuador, showing extreme denudation of slopes due to slips/avalanches/flows triggered by the 1987 Reventador earthquakes.

that in 1946 the erosion surface exposed by mass movements in a red beech forest was 1.7 percent of the drainage area. By 1963, the denuded area was 2.7 percent, an increase of 60 percent in 17 years. In another study on the North Island, Eyles (1971, p. 91) found that: "*The initiation of rapid hillside erosion was probably connected with the vegetational change from forest to scrub and it may have been enhanced by further change to grass.*"

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 landslide-caused forest damage on the Queen Charlotte Islands off the coast of British Columbia (e.g., Wilford and Schwab, 1982; Smith et al., 1986). The Queen Charlotte Islands include vast tracts of valuable commercial timber. The coniferous forests of the islands consist primarily of western hemlock, Sitka spruce, Douglas fir, and western red cedar. Gimbarzevsky (1988) has inventoried more than 9,000 rainfall-caused landslides in these forest areas.

In the northwestern United States, numerous studies on the effects of landslides on forests 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 practices on landslide activity.

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

3.2 Destruction of Grasslands

There are few references in the literature devoted specifically to the destruction of grassland or non-forested areas by landslides. Noteworthy was the study by Langenheim (1956) of the effects of the 1923 Gothic earth flow in Colorado, U.S.A., on subalpine vegetation. In another study in the western United States, Beatty (1988) noted the effects of mass wasting on natural grasslands on Santa Cruz Island, California.

In a New Zealand study of mass movements that destroyed grasslands in the Tangoio Conservation Reserve, northern Hawkes Bay, Eyles (1971) noted that landslide activity was significant in areas that had originally been forested, but had been converted to grassland. In another study of landslides on grasslands of the North Island of New Zealand, Trustrum et al. (1984) studied the relationship between landslide activity and pastureland productivity in the landslide-prone Wairarapa hill country.

3.3 Destruction of Marine Plant Life

Although less is known about destruction of marine plant life by landslides than that which occurs subaerially, current studies of California's Big Sur Coast indicate that coastal landslides can harm habitats for marine plants ranging from macroalgae to kelp forests and other varieties of seaweed (Moss Landing Marine Laboratories, 1998; Oliver et al., 1999). In the Monterey Bay National Marine Sanctuary (MBNMS) (Fig. 18), coastal plant life continually is affected by landslides, especially those that are triggered by the effects of California State Highway 1. Disposal of debris from these landslides without harming the habitats of plants and wildlife along this pristeen coastline poses a continual problem to the California Department of Transportation (Caltrans). Although not so well-reported, landslides on other coastlines worldwide undoubtedly have similar harmful effects on marine plant life.

3.4 Revegetation of Forests and Grasslands

Landslides are among the most severe disturbances of the tropical rainforests of Puerto Rico. Revegetation of the forested landslide areas of the tropical, wet Luquillos Mountains of northeastern Puerto Rico has received a greater concentration of study than any other landslide area in the world. The following recent ecological papers having been devoted to this study: Guariguata (1990), Walker and Neris (1993), Walker (1994), Fernandez and Myster (1995), Walker and Boneta (1995), Fetcher et al. (1996), Walker et al. (1996), Myster (1997), Myster and Walker (1997), Myster et al. (1997), Myster and Everham (1999), Brokaw (2003), Walker (2003), and Shiels and Walker (in press). As noted by Walker (2003, p. 1):

> "*Tropical landslides, including those in Puerto Rico, revegetate within a remarkably short time, provided there exists a stable substrate* [Fig. 19]. *When ample nutrients are also available* [landslide] *forests recover most characteristics of pre-disturbance forests within 100 yr. Plant succession is governed by slope stability and nutrient availability…Biological processes that lead to succession and stabilization include inputs of seeds by wind, gravity and birds, vegetative expansion of neighboring plants; and the competitive and facilitative interactions of colonizing plants…Attempts to stabilize landslides include physical barriers to slow erosion, plantings to stabilize soil surfaces, fertilization to promote plant growth, and artificial perches to encourage bird dispersal of seeds.*"

Similarly, in a study of 46 landslides in the Luquillos Mountains, Guariguata (1990, p. 828) noted that post-landslide forest succession "*seems to require at least fifty years before regrowth begins to resemble mature-forest basal area.*"

Other studies of revegetation of landslide areas in tropical forests have been carried out for the following countries/areas: Jamaica (Dalling, 1994); the Caribbean (Walker et al., 1996); Costa Rica (Walker, 1994; Myster, 1997); and Panama (Garwood, 1985).

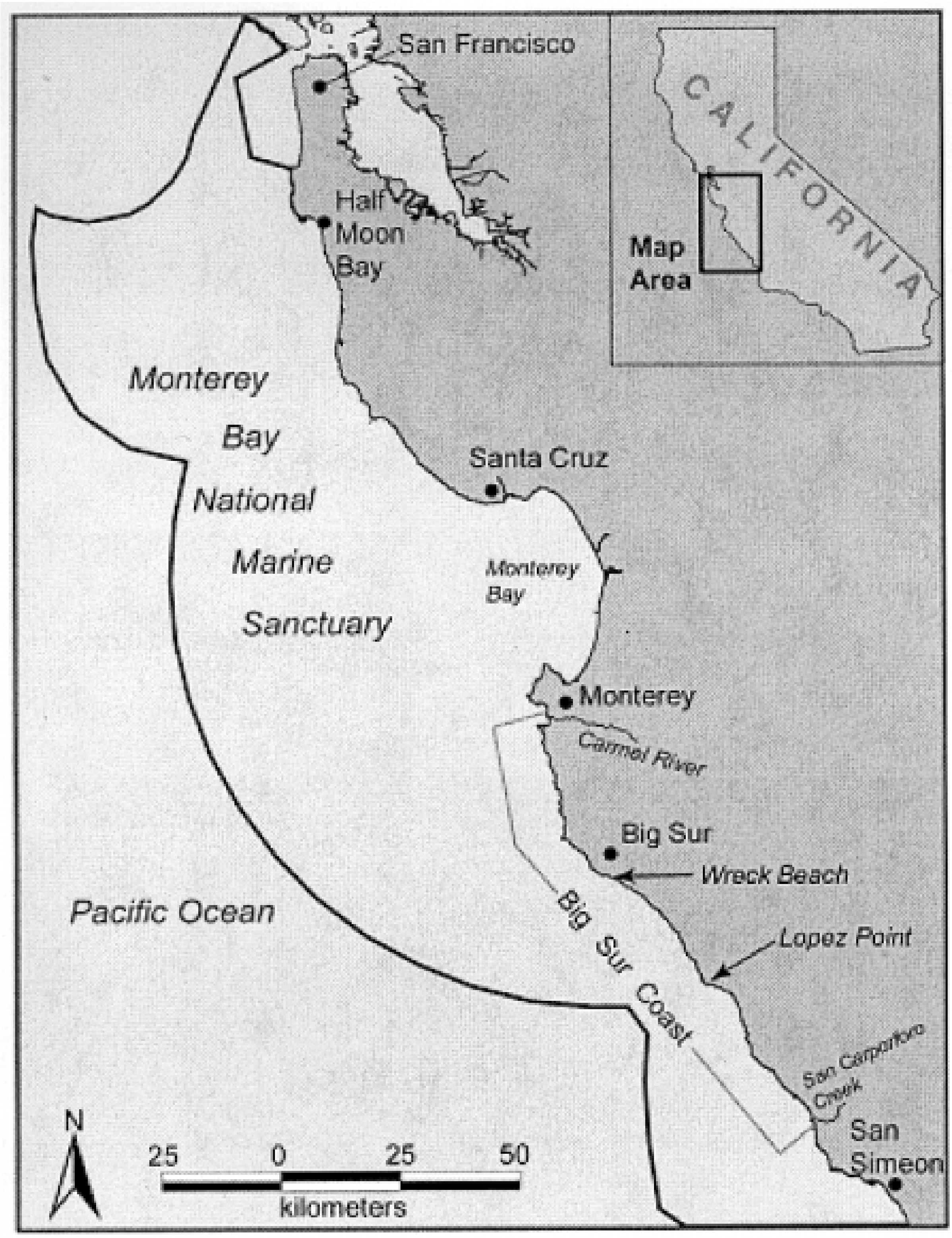


Fig. 18. Map showing locations of the Big Sur Coast and the Monterey Bay National Marine Sanctuary, California (Hapke and Griggs, 2002).

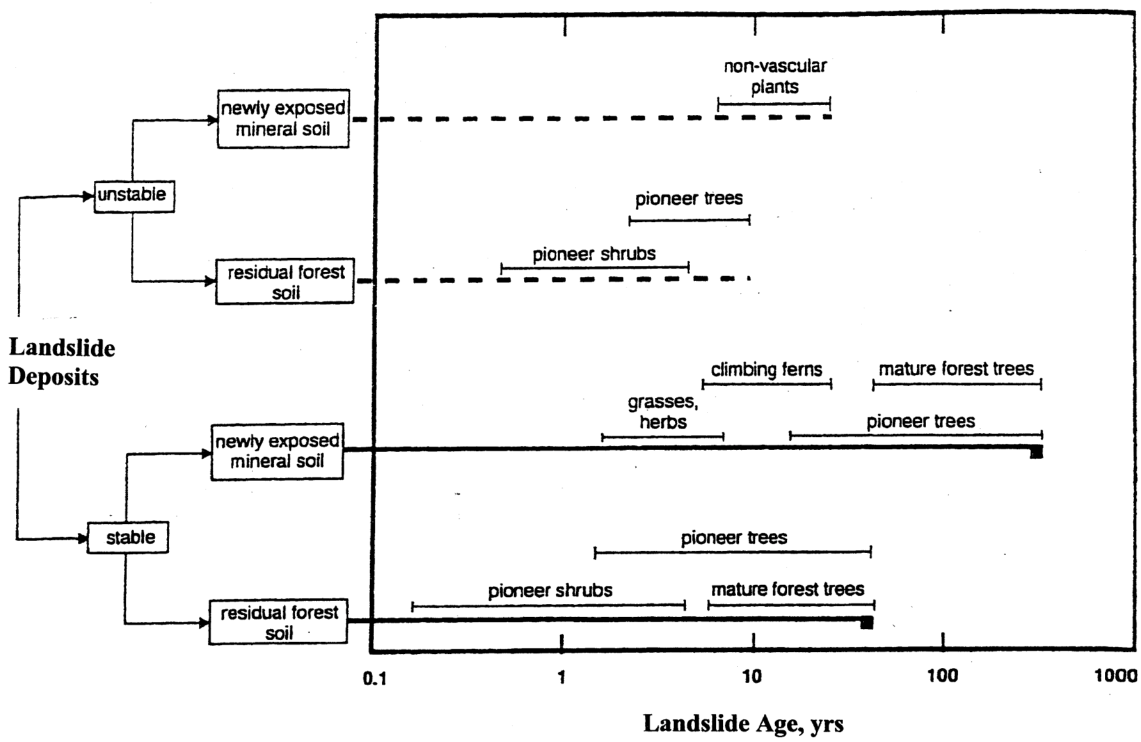


Fig. 19. Proposed plant succession on landslides in the Luquillo Mountains, Puerto Rico (Walker et al., 1996). On unstable soils, erosion constantly resets succession (dashed lines). On stable soils, filled squares indicate ages at which pre-landslide vegetation may re-establish.

Studies of revegetation of landslide areas in subtropical montane forests have been conducted in Ecuador (Stern,1995; Myster and Sarmiento, 1998; and Ohl, 2000), Bolivia (Kessler, 1999), and Tanzania (Lundgren, 1978). Stern (1995) and Kessler (1999) have suggested that landslides are important in tropical mountains for maintaining forest species diversity, particularly in areas with steep topography and humid climate. In her study of revegetation of landslides triggered by the 1987 Reventador earthquakes in northeastern Ecuador, Stern (1995, p. 219) noted that landslides "*likely contributed to the large portion of forest dominated by colonizing species that are not able to establish or survive under mature, closed-canopy forests.*" In tropical mountain areas of southern Ecuador, Ohl (2000) has noted that landslides are an important factor in regeneration and diversity of the forest ecosystem. Where landslides occur, diversity of the forest increases dramatically as shown by the fact that most species found on landslides during succession are not elements of the mature forest.

Numerous studies of revegetation of landslide areas have also been conducted in temperate areas. In the United States, Moss and Rosenfeld (1978) have described local destruction of the temperate forest community in a valley in the Niagara escarpment of New York State by "catastrophic" mass wasting. They found that forest and grassland areas destroyed by landslides do not remain permanently blighted. Instead, mass movement is just one of several environmental factors that give rise to "*random perturbations*" that trigger essential recycling and rejuvenation of biotic systems. They found that "*...a whole new series of small isolated communities has been brought into being as a result of mass movements opening up the forest cover enabling enrichment of the flora by providing additional, diverse habitats where the adjacent dominant and subdominant species compete with species from outside the valley.*" (Moss and Rosenfeld, 1978, p. 172).

Flaccus (1959) discussed rates of revegetation of important "*pioneer*" tree species – paper and yellow birch, pin cherry, and trembling aspen – on landslide scars and deposits in the White Mountains of New Hampshire, U.S.A. He found that for the harsh climates of New Hampshire, steep scarps, bare till, and talus may remain largely free of forest cover for more than 100 yrs after landslide activity, but that all such areas recover over sufficient time if the the slopes do not continue to be disturbed. Less-steep, more-protected habitats on landslides, and especially landslide deposit areas, may revegetate much more rapidly, commonly within 50 years. Local hardwoods are the first to return, followed by conifers. [Note that the authors have observed thick, immature stands of the common native hardwood, red alder, on landslides in the U.S. Pacific Northwest within 10 yrs of landslide occurrence.]

Forest recovery following landslide activity has received considerable attention in Fiordland on the South Island of New Zealand (e.g., Poole, 1951; Holloway, 1954: Mark et al., 1964; Stewart, 1986). Poole (1951) mentioned the importance of landslides in determining plant succession for valley-slope forests in Fiordland. Holloway (1954, p. 399) noted that "*communities of kamahi, broadleaf, and mountain ribbonwood occupy temporarily the debris of past landslides.*" Mark et al. (1964) suggested that forest species return more quickly to landslide debris deposits than to the denuded main-scarp surface. On the denuded main scarp and slide face, brush species become established soon after the landslide and retain an important place in the canopy for about 50 yrs, after which they are increasingly suppressed by the emerging forest trees.

In the 1980's, Smith et al. (1986) conducted a detailed study of revegetation patterns of landslide-destroyed forests in the Queen Charlotte Islands, British Columbia, Canada. The upper portions of the landslides were partially scoured to bedrock or compact glacial till, whereas the lower parts consisted mainly of chaotic mixtures of logs, rocks, and soil

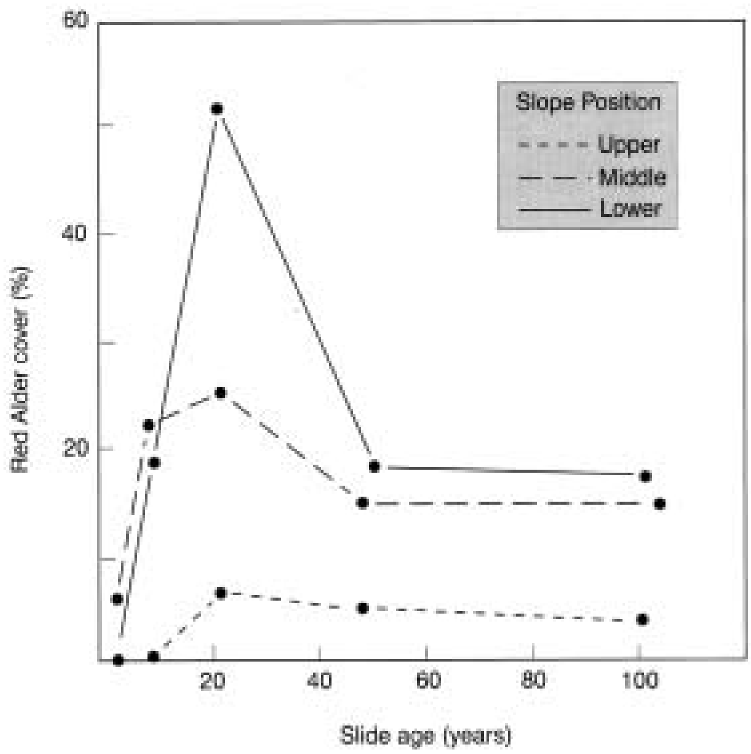


Fig. 20. Cover of landslide-damaged land by red alder as a function of landslide age and slope position, Queen Charlotte Islands, British Columbia, Canada (after Smith et al., 1986).

deposited on, or mixed with, the original soil. Two major trends in vegetative development on slide surfaces were observed, one dominated by red alder (Fig. 20) and one by conifers (Fig. 21). The alder was dominant on the lower parts of the slides, while conifers dominated on the middle and upper parts.

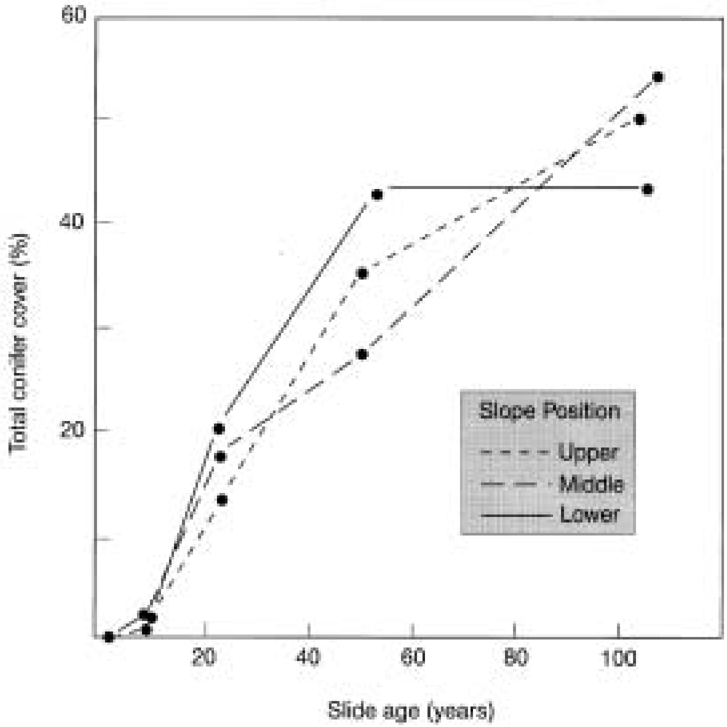


Fig. 21. Cover of landslide-damaged land by coniferous trees as a function of landslide age and slope position, Queen Charlotte Islands, British Columbia, Canada (after Smith et al., 1986).

As indicated in Fig. 22, forest cover on the Queen Charlotte Islands, in general, returns to slide areas more slowly than to logged areas. Smith et al. (1986) found that forest productivity of landslide areas is reduced by about 70 percent as compared to logged areas of similar age.

McCune (1977) conducted a study in the Rocky Mountains of Montana, U.S.A., of the rate of revegetation of rockfall talus deposits. He noted that talus slopes are common in mountainous areas, but little attention has been given to primary plant succession occurring on these slopes. He found that both slow (talus-creep) and fast (debris-slide) movements occur on talus slopes, and that fast movements are relatively important as a negative habitat factor for vegetation. As would be expected, vegetation patterns on talus appear to be closely related to patterns of rockfall accumulation and movement, successful plant invasion occurring primarily where there is little rockfall accumulation or movement. Sheltered areas usually occur downslope of bedrock outcrops. Plant succession commonly follows establishment of mats of moss on the talus surface.

Beatty (1988) studied recolonization of non-forest plant species in grassland areas on Santa Cruz Island off the coast of California. She expected the responses of plant species to conform to predictions that heterogeneity of habitat would foster greater species richness. Instead, she found that overall richness of species on landslides was lower than in non-slide areas.

Three years of study by Trustrum et al. (1984) in the landslide-prone Wairarapa hill country of the North Island of New Zealand found that 18 percent of these grassland areas had been impacted by erosion and mass movement. Although the affected areas had revegetated rapidly over the first 20 yrs to within 70-80 percent of their uneroded productivity, further recovery was slow. The evidence suggested that these man-modified soils, once subjected to erosion and landslides, may never regain their potential for agriculture under a pasture regime.

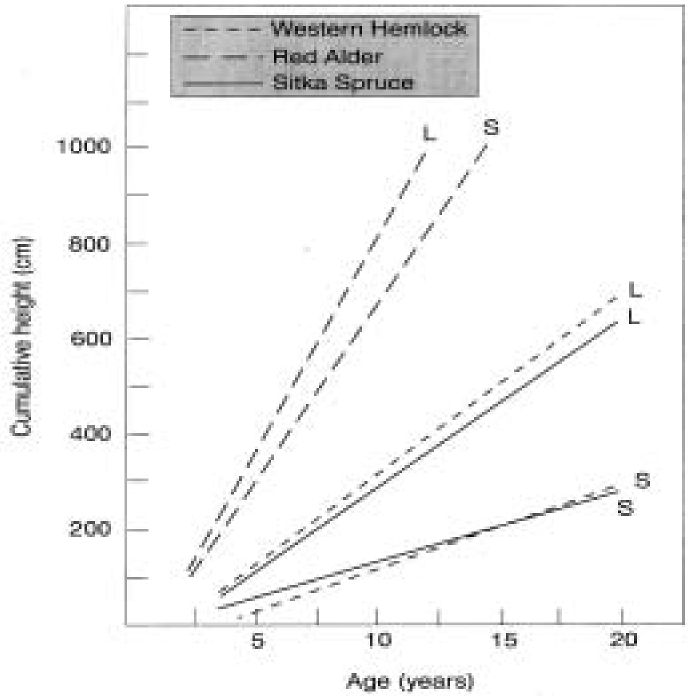


Fig. 22. Early height growth of red alder, western hemlock, and Sitka spruce in landslide (S) and logged (L) areas, Queen Charlotte Islands, British Columbia, Canada (after Smith et al., 1986).

4. Effects on Fish and Wildlife

4.1 Effects on Fish Populations

Although most kinds of wildlife are able to retreat fast enough to prevent direct injury from all but the fastest-moving landslides, all wild creatures are subject to habitat damage and destruction. Fish are probably most affected because they depend on stream access and water quality for their livelihood, both of which are commonly influenced in the short term by landslides. However, "S*urvival of fish over long periods (10^2 – 10^3 yrs) and over large land areas (10^2 – 10^5 km^2) is framed in the context of environmental risks, refugia, and biological adaptations.*" (Benda et al., 1997). Thus, although landslides, on one hand, create a hostile stream environment for fish, on the other they may provide long-term stream refuges that aid survival.

From the hostile environment point of view, Swanston (1991) noted that storm flows and landslides are the dominant random events that cause physical habitat deterioration in streams. Especially susceptible to stream environment changes are anadromous fish (primarily salmonids, such as salmon or steelhead trout), which live in the oceans but return to their native streams to spawn. Their passages to spawn can be blocked by landslide dams, or their spawning grounds can be damaged or destroyed directly by landslide deposits or by sediment washed into the streams by landslides.

Stream sediment, from landslides or other sources, contributes to the deterioration of fish habitat and affects downstream water quality (Sidle et al., 1985, p. 9). When sediment is suspended: (1) it blocks the transmission of light, thus reducing algae production, and (2) it damages the gill membranes of the fish, causing death where concentrations are high and exposure is prolonged (Phillips, 1971). When sediment settles onto gravel beds, it is harmful in the following ways: (1) it fills the gravel interstices, reducing the supply of dissolved oxygen to the fish eggs; (2) it forms a barrier to fry emergence; and (3) survival after fry emergence is impaired because of loss of escape cover and reduction of aquatic organisms that are food for the fry. Excess sediment can also damage rearing habitat, areas where young fish feed and grow, by creating unfavorable conditions for growth of aquatic insects (Meehan, 1974).

Much has been written on the effects of landslides on the lives of anadromous fish that spawn along the West Coast of North America. Freshwater habitats for salmonids are the:

> "*products of interactions among climate, hydrologic responses of watersheds and hillslope and erosion processes... Major disruption of these interactions* [by a disturbing process, such as a landslide] *can drastically alter habitat conditions. The result may be movement and redistribution of spawning gravels, addition of new sediment and woody debris to the channel system, changes in accessibility to fish of viable spawning habitats, changes in availability of food organisms, and changes in seasonal and diurnal water temperatures.*" (Swanston, 1991, p. 139).

As an example of habitat deterioration, in their study of irrigation-induced landslides in South-central Washington State, Schuster et al. (1989) noted the direct destruction of spawning beds by landslides that had entered the last free-flowing stretch of the Columbia River in the United States (Fig. 23). In addition, the beds and stream quality were further impaired by silt washed from the landslides.

Tripp and Poulin (1986a,b) reported on the effects of mass wasting on salmonid-rearing habitats in the Queen Charlotte Islands. They found that mass wasting increased sediment levels in spawning habitats, but not to the degree of sedimentation caused by logging. Substantial reductions in both quantity and quality of fish-rearing habitat were found in perennial streams affected by debris flows.

Major debris flows, such as those in the Toutle and Cowlitz Rivers from the 1980 Mount St. Helens eruption (Janda et al., 1981; Schuster, 1989); in the Bairaman River, Papua New Guinea, from the catastrophic failure of the Bairaman landslide dam in 1986 (King et al., 1989); in the Coca River, Ecuador, from the 1987 Reventador earthquakes (Schuster et al., 1996); and in the Paez River, Colombia, from the 1994 Paez earthquake (Martinez et al., 1995) must have directly killed large percentages of the fish populations in these rivers and their tributaries. However, within a few years stream regimens would have improved, and some species would have moved upstream into the formerly barren river reaches.

Another major cause of changes in stream habitat for fish is the long-term existence of landslide dams, which, if not overtopped, commonly do not allow passage for migrating fish, thus isolating the upstream populations. For example, Logan and Schuster (1991) noted development of a new species of cutthroat trout in Lake Crescent, a still existing, prehistoric landslide-dammed lake on the Olympic Peninsula of the State of Washington, U.S.A. For several thousand years, the trout in this lake have been isolated by its natural dam, which has never overtopped.

Wild fires in mountain areas often result in runoff conditions that lead to debris-flow activity during ensuing rainy seasons. These debris flows can have disastrous effects on fish populations in mountain streams. Two examples occurred in Colorado, U.S.A., following fires that occurred during the summer of 2002. In August 2002, heavy rains in the San Juan Range of southwestern Colorado sent mud, ash, and rocks down a burned hillside above Million Reservoir, partially filling the reservoir and killing much of its fish population (Rocky

Fig. 23. Irrigation-caused landslides have badly damaged salmonid spawning grounds in the last free-flowing stretch of the Columbia River in the United States (Schuster, 1989).

Mountain News, 2002). In a similar event, heavy rain in late May 2003 caused debris-flow/flood runoff from the huge Hayman burn area of the previous summer. A torrent of mud and debris from the vulnerable burn area flowed into the South Platte River, killing an estimated 50-75 percent of the trout in this popular Rocky Mountain fishing stream (Ingold and Wallace, 2003). Following a large wildfire near Tucson, Arizona, in June 2003, endangered varieties of fish were captured and moved from streams in the burn area as a precautionary measure because harmful debris flows/floods were expected to occur later in the summer due to anticipated heavy rains (Rotstein, 2003).

Although there is general agreement that landslides result in short-term deterioration of mountain-stream fish habitat, there is a growing feeling among ecologists that landslides may increase the quality of fish habitat in the long-term by breaking up stream flow. For example, landslides may deliver large boulders to a stream, thus forming downstream pools that provide quality habitat (Sedell et al, 1990). As noted by Reeves et al. (1995, p. 717):

> "*When intense rainstorms saturate soils during periods of low root strength, concentrated landsliding into channels and debris flows may result. Such naturally occurring disturbances in stream channels can have both immediate impacts on and long-term implications for anadromous salmonids. Immediate impacts include direct mortality, habitat destruction, elimination to access to spawning and rearing sites, and temporary reduction or elimination of food resources. Longer-term effects may be positive, however; landslides and debris flows introduce essential habitat elements, such as large wood and sediment, into channels and affect storage of these materials. The configuration of channel networks, the delivery, storage, and transport of sediment and wood, and the decomposition of woody debris interact to create, maintain, and distribute fish habitat over the long term."*

Montgomery et al. (2003) generally agree with the surmise that landslides can improve fish habitat in streams over the long term. However, in the Pacific Northwest of the United States, they have noted differences in the formation of fish refugia on streams between areas of old-growth forests and "industrial" (i.e., logged) forests (Montgomery et al., 2003, p. 87):

> "*We suspect that historic reduction in the size and abundance of wood debris in Pacific Northwest channels has changed the nature of debris-flow influences on the structure and dynamics of salmon habitat. In primeval forests, locally derived log jams primarily controlled habitat abundance through recruitment of large key-member-size logs from streamside and valleywall forests. In contrast, the dearth of such large logs recruited to channels from contemporary industrial forests results in a greater direct influence of debris flows on habitat availability.*"

4.2. Effects on Wild-animal Populations

In general, the short-term effects of landslides on wild-animal habitat are negative through direct destruction of habitat. An excellent example is provided by much of the coast of California: of the 1750 km of California coastline, 86 percent, or 1500 km, is undergoing erosion (Oliver et al., 1999). Especially hard-hit by landslides is the aforementioned Big Sur Coast of central California, the site of the Monterey Bay National Marine Sanctuary (MBNMS) (Fig. 18), a protected area of coastal waters and home to a variety of protected species, ranging from barnacles and corals to clams and crabs, and even to sea otters. In this coastal area, weak rocks and steep topography provide ideal conditions for frequent large landslides (Fig. 24) that contribute to the littoral sediment budget, and thus affect the coastal habitat. Contributing to the problem is the existence of California State Highway 1, which is subject to frequent large-scale landslide activity. A continuing problem has been disposal of materials from landslides along the highway. In the past, landslide disposal practices utilized by the California Department of Transportation (Caltrans) had the potential to alter nearshore zone habitat by converting marine habitats from rock substrate to soft bottom (Hapke et al., 2003). Anthropogenic disposal of landslide material (from highway maintenance) have the potential to upset the equilibrium of the system through burial of organisms and/or alteration of bottom type (e.g., conversion of rocky substrate to soft bottom). As noted by Hapke and Griggs (2002, p. 654):

> *"MBNMS staff became concerned with the Caltrans landslide disposal practices for three reasons: 1) National Marine Sanctuary regulations prohibit disposal of material within a Sanctuary or where it will enter a sanctuary; 2) landslide disposal practices have the potential to bury shoreline habitat, converting marine habitats from rocky substrate to soft bottom; and 3) the disposal practices have the potential to increase nearshore suspended sediment concentrations, possibly impacting biological communities. On the other hand, coastal landslides and*

streams naturally deliver sediment to the coast providing nutrients to the water as well as material for beaches."

Fig. 24. Aerial view of the 1983 McWay landslide, Big Sur Coast, California. By reaching tidewater, this slide impacted marine organisms, both flora and fauna. (Photo by Lynn Harrison, California Department of Transportation.)

Generally, marine organisms along this coast are impacted by a triad of sediment inputs from landslide activity: *direct burial*, *sediment scouring,* and *suspended sediment plumes* that clog organism functions or impair light penetration (Oliver et al, 1999). The MBNMS is home to one of the most diverse marine ecosystems in the world, including 33 species of marine mammals, 94 species of seabirds, 345 species of fishes, and numerous invertebrates and plants (Monterey Bay National Marine Sanctuary, 2003). Because of this threat to wildlife (as well as coastal vegetation), Caltrans is currently making every effort to prevent landslides on Highway 1, and to dispose of landslide debris in an "environmental-friendly" manner. Selection of geotechnically suitable and environmentally acceptable disposal sites for landslide debris has become a major component of the environmental element of California's coastal highway landslide program (Van Velsor and Walkinshaw, 1992).

Birds also suffer from direct habitat loss due to landslides. As an extreme example, the senior author noted a sad case of the landslide-caused deaths of birds during his study of irrigation-induced landslides in fluvial lacustrine sediments along the Columbia River in south-central Washington State, U.S.A., in the early 1980's. In the spring of 1981, he noted hundreds of nests that cliff swallows had excavated in the 25-m-high silt/sand main scarp of a major landslide that had occurred in 1980. At that time, the eggs were newly hatched. When he returned to the site one week later, the scarp had retrogressed catastrophically (Fig. 25). Undoubtedly, most of the newly hatched swallows were killed by the sudden habitat destruction.

Fig. 25. April 1981 aerial oblique view of the 12-million-m^3, irrigation-induced Savage Island landslide on the Columbia River, south-central Washington State, U.S.A. In the spring of 1981, hundreds of baby cliff swallows were killed when their nests in the 25-m-high main scarp were destroyed because of catastrophic headward recession of the landslide to the location shown.

Although landslides undoubtedly cause short-term destruction of wild-animal habitat, evidence is accumulating that, at least for some types of landslides in some areas, in the longer term, these features may improve habitat quality. For example, as reported by Rozell (1998), it was found in a study of wolverine habitats in British Columbia, Canada, that wolverines frequently were found near (snow) avalanche chutes. The wolverines were rewarded with abundant food in the form of dead animals caught in the avalanches. It was also found in British Columbia and Montana (U.S.A.) that grizzly bears were attracted to avalanche chutes because of the abundance of vegetative food, such as avalanche lilies. And in Kenai Fjords National Park, Alaska, it was noted that black bears prefer avalanche tracks as habitat because of ease of travel as compared to virgin forest. It would be expected that similar habitat conditions would exist for rock and debris avalanches. As noted by Rozell (1998, p. 1) in regard to wildlife habitat: "*Avalanche chutes and landslide tracks are now viewed with such importance that the British Columbia Ministry of Forests has created buffer zones around them to prevent logging or other manmade disturbances that could interfere* *with animals' foraging and mating in open areas. Long seen as only terrifying and destructive, landslides and avalanches are now seen as essential."*

5. Effects on Fossil Beds—A Natural Resource Disturbance

A few landslides have caused damage to the habitats of what are now *fossil* animals. An excellent example is provided by irrigation-induced landslides at Hagerman Fossil Beds National Monument in southern Idaho, U.S.A. (Chleborad and Schuster, 1995). These active landslides threaten fossil beds that include 11 species of animals, including remains of the "Hagerman Horse," camels, beavers, muskrats, rabbits, and ducks, which *"are of major paleontological significance and are considered to be one of the most complete assemblages of Pliocene fauna in the world.*" (Lewis, 1987, p. 55). In another example of landslides in fossil-bearing strata, Atherton and Burbridge (2000) have reported on landslide activity during the 1990's in the Lower Lias Green Ammonite and Belemnite Beds on the Dorset Coast in southern England. The main failure surface lies along the contact between the two beds; thus the ammonite-bearing strata form the slide. In addition, fossil dinosaur tracks have recently been found in the Debeque landslide near Grand Junction in western Colorado, U.S.A. (D.C. Noe, Colorado Geological Survey, personal communication, 2003). At present the tracks are moving *en masse* in a landslide block, and thus far remain intact.

6. Biotechnical Slope Protection – An Introduction to Means of Reducing the Impact of Landslide-Mitigation Measures

When used for landslide remediation, conventional earth-retaining structures made of steel or concrete are usually not visually pleasing or environmentally friendly. "*…slope repairs often consist of a rock blanket, gabions, concrete walls, or other conventional erosion control and slope stability systems. These solutions are developed with more restricted views and less understanding of the broader opportunity or environmental picture and they appear to operate without a full appreciation for natural principles.*" (Sotir, 1994, p. 191). These traditional "hard" remedial measures are increasingly being supplanted by vegetated composite soil/structure bodies that are environmentally more friendly, i.e., a process that has come to be known as *biotechnical slope protection.* "*In such work, vegetation is used as surface protection and to augment the strength of soil in which it grows, usually combined with naturally occurring or recycled inert materials – timber, stone, iron and steel cables and meshes. These vegetated composite soil bodies or structures are 'soft' – flexible and multiredundant statically and visually attractive. They contrast with conventional 'hard' slope retention structures – rigid and discreet."* (Barker, 1995, p. 238). Common biotechnical systems are geonets anchored by soil nails that hold in place soil seeded with grass. Also common are geocells with seeded soils in the interstices.

Biotechnical slope protection consists of two elements: *biotechnical stabilization* and *soil bioengineering stabilization*, both of which entail the use of live materials – specifically vegetation (Gray and Sotir, 1996). Biotechnical stabilization utilizes mechanical elements (structures) in combination with biological elements (plants) to prevent and arrest slope failures and erosion (Gray and Leiser, 1982). Both mechanical and biological elements must function together in a complementary manner. Soil bioengineering stabilization, on the other hand, can be regarded as a specialized subset of biotechnical stabilization in which live plant parts, i.e., roots, stems and branches, serve as the main structural/mechanical elements in the slope protection system (Gray and Sotir, 1996).

Biotechnical slope-protection systems blend into the landscape. They emphasize the use of natural, locally available materials, such as soil, rock, timber, and vegetation, in contrast to man-made materials, such as steel and concrete. The structural or mechanical components do not visually intrude upon the environment as much as conventional earth retaining structures (Gray and Leiser, 1982). Examples of such structures, which commonly incorporate

Table 3. Classification of biotechnical slope-protection and erosion-control measures (after Gray and Sotir, 1992).

CATEGORY	EXAMPLES
1. Live Construction	
Conventional plantings	• Grass seeding • Sodding • Transplants
2. **Mixed Construction**	
Woody plants used as reinforcements and barriers to soil movement	• Live staking • Contour wattling • Brush layering • Soft gabions • Brush mattress
Plant/structure associations	• Breast walls with slope-face plantings • Revetments with slope-face plantings • Tiered structures with bench plantings
Woody plants grown in the frontal openings or interstices of retaining structures	• Live cribwalls • Vegetated rock gabions • Vegetated geogrid walls • Vegetated breast walls
Woody plants grown in the frontal openings or interstices of porous revetments	• Joint plantings • Staked gabion mattresses • Vegetated concrete-block revetments • Vegetated cellular grids • "Reinforced" grass
3. **Inert Construction**	
Conventional structures	• Concrete gravity walls • Cylinder-pile walls • Tie-back walls

vegetation into the structure itself, include log and timber cribs, gabion and rock-breast walls, welded wire walls, and reinforced earth. Internal, tensile reinforcements utilizing the principles of bioengineering permit construction of oversteepened fill slopes to as much as 70º (Gray and Sotir, 1992). A classification scheme or taxonomy of different bioengineering stabilization methods is presented in Table 3. An example of a steep highway cut slope that has been stabilized by a system of rock anchors that have been completely hidden by an environmentally-friendly grass-covered soil fill is shown in Figure 26.

As noted by Gray and Sotir (1995, p. 6), "*Biotechnical and soil bioengineering stabilization offer a cost-effective and attractive approach for stabilizing slopes against erosion and shallow mass movement. These approaches capitalize on the advantages and benefits that*

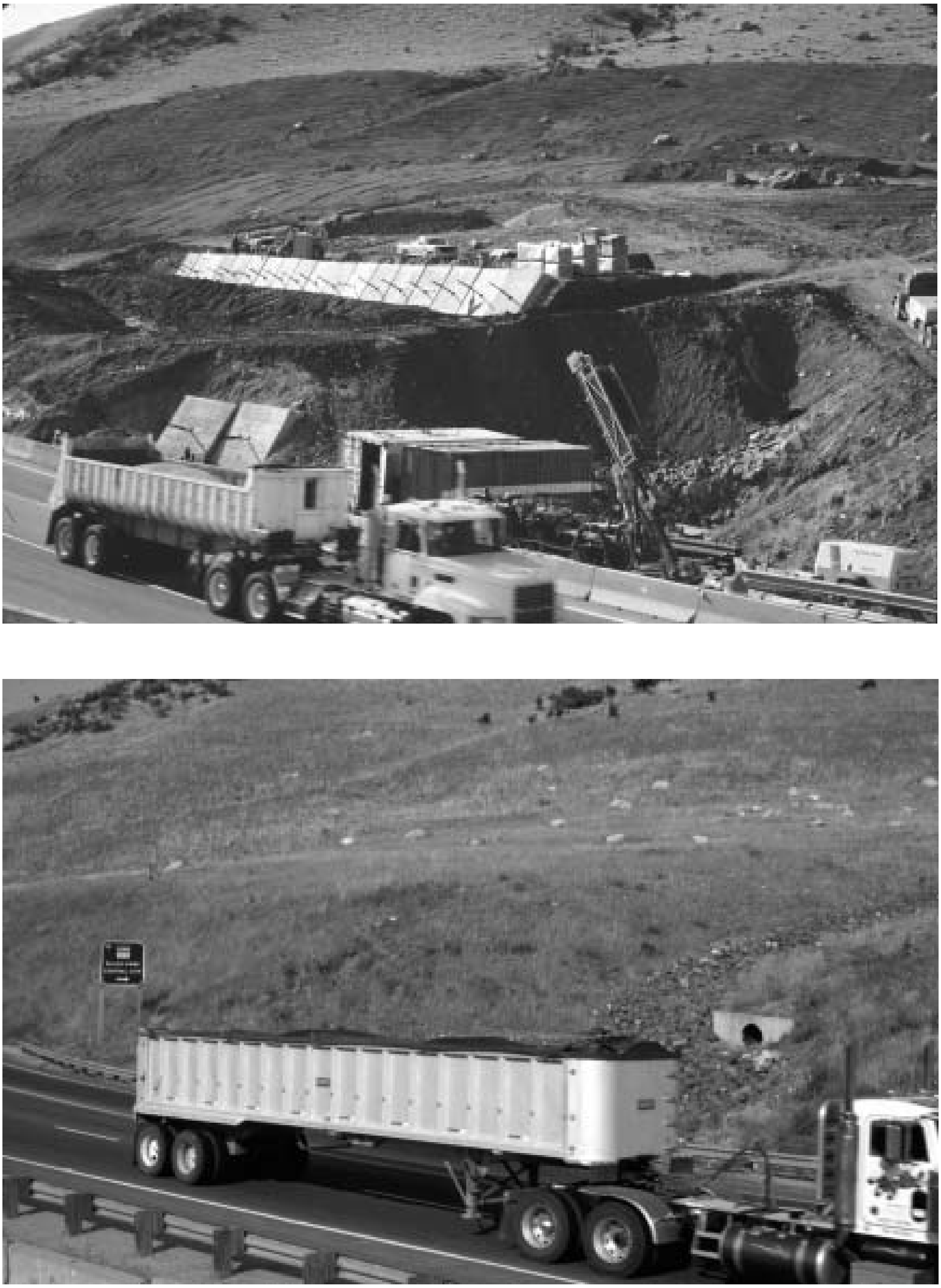


Fig. 26. Environmentally-friendly stabilization of a cut slope on Colorado State Highway 93 in Golden, Colorado, U.S.A. (A) Installation of 3m x 3m reinforced-concrete “face plates” tied to a system of rock anchors (photo: March 1994). The final rock-anchor system consisted of three rows of anchors with a total of 40 anchors and face plates. (B) Post-construction view of same site (photo: July 2003). Anchors and plates have been hidden by a soil fill, which has been planted with native grass.

vegetation offers for erosion control and slope protection." Soil bioengineering relies mainly on the use of native materials, such as plant stems or branches, rocks, wood, or soil. Appropriate vegetation can be obtained from local sources of willow, alder, and other native, easily-propagated varieties. In addition, soil bioengineering systems commonly are environmentally compatible during the construction process because they generally require minimal access for equipment and workers, and cause relatively minor disturbance. With time, the bioengineering systems are visually non-intrusive and blend into the natural surroundings. This is a favorable attribute in environmentally sensitive areas, such as parks, riparian areas, and scenic corridors, where aesthetic quality, wildlife habitat and ecological restoration are important (Gray and Sotir, 1996). As bioengineered structures that utilize tree species become older, they have the added benefit that they become more stable, and eventually assist in the natural succession and long-term colonization of forest species.

In most cases, native grasses, shrubs, and trees are used as the vegetation in bioengineering stabilization. Willow has been very successful in many parts of the world. In tropical and subtropical areas the use of *Vetiver* grass hedgerows (VGHR) for stabilization has become very popular because of the fast growth and deep root penetration of this grass (Yoon, 1995a,b). However, if exotic species of plants or trees are introduced, there is a real danger that they will conflict with native plant life (Brown, 1995).

While detailed slope stability assessments have normally been carried out by geotechnical engineers and engineering geologists, the organic interactions between vegetation, soil, and structures that must be evaluated in applying the technique of bioengineering stabilization are perhaps better understood by soil scientists, agriculturists, foresters, and hydrologists (Greenway, 1986). Thus the bioengineering approach to slope stabilization requires cooperation of geoscience and plant-science disciplines working in parallel and in unison.

7. Conclusions

Landslides, and especially large catastrophic landslides, cause significant changes in the Earth's natural environment. Mountain and valley morphologies are most significantly affected by downslope movement of large landslide masses. Forest, grasslands, and wildlife are often negatively affected by landslides, with forest and fish habitats being most easily damaged or temporarily destroyed. However, because landslides are relatively local events, both flora and fauna can recover with time. In addition, recent ecological studies have shown that, under certain conditions, in the medium-to-long term,, landslides can actually benefit fish and wildlife habitats, either directly or by improving the habitat for organisms that the fish and wildlife rely on for food.

Techniques in biotechnical slope stabilization are becoming popular for reducing the environmental impact of slope-protection measures. These so-called "soft" remedial measures not only are environmentally more "friendly" than steel and concrete retaining structures, but they often are more economical and provide better long-term stability.

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