Environmental Impact of Landslides

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Marten Geertsema, Lynn Highland and Laura Vaugeouis

Abstract Landslides affect the following elements of the environment: (1) the topography of the earth's surface; (2) the character and quality of rivers and streams and groundwater flow; (3) the forests that cover much of the earth's surface; and (4) the habitats of natural wildlife that exist on the earth's surface, including its rivers, lakes, and oceans. Large amounts of earth and organic materials enter streams as sediment as a result of this landslide and erosion activity, thus reducing the potability of the water and quality of habitat for fish and wildlife. Biotic destruction by landslides is also common; widespread stripping of forest cover by mass movements has been noted in many parts of the world. Removal of forest cover impacts wildlife habitat.

The ecological role that landslides play is often overlooked. Landslides contribute to aquatic and terrestrial biodiversity. Debris flows and other mass movement play an important role in supplying sediment and coarse woody debris to maintain pool/riffle habitat in streams. As disturbance agents landslides engender a mosaic of seral stages, soils, and sites (from ponds to dry ridges) to forested landscapes.

Keywords: Landslide • Environmental impact • Ecology • Biodiversity • Natural disturbance agent

31.1 Introduction and Scope

Landslides occur throughout the world, and especially in certain hotspots (Nadim et al., 2006). Much has been written about landslide impacts on human lives, and on infrastructure. Little attention, however, has been paid to landslide impacts on the natural environment (Schuster and Highland, 2007). Even less consideration has been given to the role that landslides play in disturbance ecology (Geertsema and Pojar, 2007).

Landslides are destructive agents. They change and modify the landscape – they disturb it. Destruction and disturbance is costly for the built

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* We dedicate this chapter to Laura Vaugeois who was to be one of the conveners of this session. Laura was a landslide specialist with the Washington State Department of Natural Resources. She died on the 30th of April 2008 after a brief and sudden illness.

Marten Geertsema (✉)
British Columbia Forest Service, British Columbia, Canada
e-mail: marten.geertsema@gov.bc.ca

Lynn Highland
U.S. Geological Survey, Denver Federal Center, Denver,
CO 80225, USA

Laura Vaugeouis
Washington State Department of Natural Resources,
Olympia, WA 98504-7012, USA

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environment, it is costly for natural resources, and yet it is essential for ecosystem cycling in the natural environment.

The purpose of this paper is to provide a background and frame work for Session 8, on the environmental impact of landslides at the First World Landslide Forum in Tokyo Japan, November 2008. The paper is organized into two main parts, discussing: 1. the environmental costs of landslides; and 2. the ecological role of landslides.

31.2 A Brief Overview of Landslide Types

All solid materials on Earth are subject to deformation and failure. Landslide is a generic term for the mass movement of earth materials. Landslides occur in a variety of materials (earth, debris, rock, organics) move at varying rates (mm/year to tens of m/second), and can involve various styles of movements (topple, fall, flow, slide, spread). Landslides can have a variety of stages of activity ranging from relict to dormant to active. They can be retrogressive, progressive, advancing or enlarging, move along planar or curved surfaces, and be shallow or deep. In addition to this, they are often complex involving more than one type of material and style of movement.

Different types of landslides behave differently, have different associated hazards, and have different effects on the environment. Managing landslides and landslide-prone terrain necessitated their classification to enable intelligent and efficient communication. The main classifications used today are those of Cruden and Varnes (1996) and of Hungr et al. (2001).

31.3 Environmental Costs of Landslides

Landslides are destructive. They can have long-lasting effects on the environment. At the extreme range, topographic changes caused by some large rock slides can persist for many thousands of years. Landslides can overwhelm, and even pollute streams and waterbodies with excess sediment. In extreme cases they can dam streams and rivers, impacting both water quality and fish habitat. Landslides can wipe out large tracts of forest, destroy wildlife habitat, and remove productive soils from slopes. In some cases landslides cause tsunami, seiches, or outburst floods.

There is a continuum between the socioeconomic costs of landslides (session 6) and the environmental costs of landslides. This is because a healthy environment is important for sustaining human populations. Where a landslide causes a loss of resources by destroying farmland or forest, deposits sediment into a stream, or pollutes a drinking water source, the environmental impacts have attained a socioeconomic dimension.

31.3.1 Landslide Impacts on Forests

Forest destruction by landslides (Fig. 31.1) is common in many parts of the world, but particularly in tropical areas as a result of the combination of intense rainfall and earthquakes.

Schuster and Highland (2007) summarize a number of case studies. A large earthquake in Chile in 1960 triggered landslides that destroyed more than 250 km^2 of forest. After the 1976 Panama earthquakes (M6.7 and 7.0) 54 km^2 of tropical forest was wiped out by landslides (12% of the impacted area) (Garwood et al., 1979). Similarly, heavy rains and earthquakes removed 25% of the forest from the Reventador Volcano (Ecuador) in 1987, and

Fig. 31.1 Debris avalanches strip forests from the hillslope in coastal British Columbia

denuded 250 km^2 of forest and soil in Paez, Colombia in 1994 (Martinez et al., 1995).

Several studies have been made of coniferous forest damage due to landslides in southwestern Canada and the northwestern United States. Especially noteworthy have been studies of forest damage due to landslides on the Queen Charlotte Islands off the British Columbia coast. 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., Megahan et al., 1978); most of these studies have dealt with the effects of logging operations in causing destructive landslides.

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).

31.3.2 Landslide Impacts on Streams

Schuster and Highland (2007) summarize a number of landslide impacts on streams. The main types of landslides that impact streams are debris flows, which may fill and/or erode the stream channel for great distances (occasionally 100 km or more). Debris flows provide important sediment transport links between hillslopes and alluvial channels (Butler, 2001), and thus are an important factor in drainage-basin sediment budgets. 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).

Landslide size and type play a role in impacts on streams. Obviously the size of the landslide in relation to the size of the stream is important. Earth flows along tributaries of Buckinghorse River in northeastern British Columbia overwhelm the sediment budget in streams, with dams persisting for decades (Geertsema et al., 2006). Dams from flows in the main river are extremely short-lived. Rockslide dams can persist for millennia (Costa and Schuster, 1988). Swanston (1991) noted variable impacts to streams 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. In contrast, 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.

Landslide deposits, although important for stream morphology in the long term, can destroy fish habitat in the short term. Recovery rates depend on a wide range of factors.

An exceptional example of a recent lahar (volcanic debris flow) occurred as a result of the 1980 Mt. St. Helens, USA eruption (Schuster and Highland, 2007). A debris avalanche transformed into a 100 km long debris/mud flow (Fig. 31.2), filling and permanently modifying the channels of the Toutle and Cowlitz Rivers and continued into the

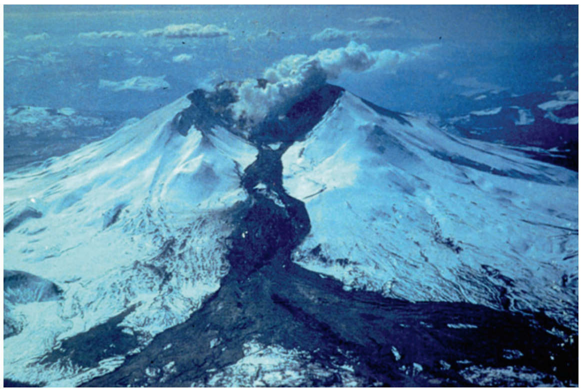

Fig. 31.2 Photo of a lahar, caused by the 1982 eruption of Mount St. Helens, Washington, USA (Photo by Tom Casadevall, U.S. Geological Survey)

much larger Columbia River, which was partially blocked by the sediment. Between June 1980 and May 1981, 45 million m^3 of sediment was dredged from the Cowlitz and lower Toutle Rivers to restore their original channels. The mud flow deposited more than 30 million m^3 of sediment in the Columbia River.

Today, nearly 30 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. Sediment levels in the Toutle River range from 10 times to more than 100 times the amount before the eruption. Sediment levels will likey 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.

31.3.3 Landslide Impacts on Drinking Water Quality and Environmental Health

Landslides can negatively impact drinking water sources by introducing suspended sediment and organic materials. In 2006 the Greater Vancouver Regional District introduced the longest water boiling advisory in its history. Poor water quality is thought to be linked to landslide activity in watersheds above drinking water reservoirs. In Washington State, USA, a bedrock landslide in the headwaters of Sumas River exposed natural asbestos. Elevated levels of nickel and chromium were found in sediments downstream of the landslide.

An unusual outbreak of coccidiomycosis occurred after the January 1994 Southern California earthquakev caused numerous landslides. The infection was caused by the fungus *Coccidioides immitis*, which is found in soil in certain semiarid areas of North and South America. The outbreak was associated with exposure to increased levels of airborne dust from exposed landslide surfaces in the aftermath of the earthquake.

31.3.4 Landslide Generated Tsunami

Landslide-generated tsunami occur in water bodies around the world (Locat and Lee, 2002). The 8000 year old Storegga submarine landslide off the coast of Norway is one of the most famous examples. Its tsunami inundated coastlines as far away as Greenland. Fan-delta collapse and translational sliding associated with the 1964 Alaska earthquake resulted in ~ 75 M m^3 of shoreline in Valdez Harbour, Alaska (Schuster and Highland, 2007). The highest displacement wave in historic time, occurred from a rock slide generated tsunami in Lituya Bay, Alaska in 1958 (Pararas-Carayannis, 1999). The rock slide created a large crater on the floor of the inlet. The wave removed the forest from the mountainside up to a height of more than 500 m.

On December 4, 2007 a 3 M m^3 rock slide entered Chehalis Lake near Vancouver, Canada. The resultant tsunami removed trees from the shoreline to a maximum height of 18 m. In addition to trees growing on the hillslope, several ha of shoreline forest were destroyed (Fig. 31.3). Trees

Fig. 31.3 The 4 December 2007 Chehalis Lake rock slide and tsunami damage near Vancouver, Canada. Photos courtesy Frank Ullmann, BC Government

traveled beyond the lake and up to 14 km down a river (Tom Millard, BC Forest Service, personal communication).

31.3.5 Landslide Dams

Landslide dams can cause two main problems. (1) They flood valleys. (2) Sometimes the dams fail catastrophically resulting in outburst floods. The dams introduce a tremendous amount of new sediment load to streams. The dams themselves may either trap or deliver sediment.

Landslide dams may persist from several minutes to millennia (Costa and Schuster, 1988). Drowned forests may survive flooding if the dam is short-lived. Otherwise the submerged vegetation dies. In some instances additional landslides occur above the landslide dam, likely due to rapid drawdown, from falling water levels.

While most landslide dams do not fail catastrophically, enough do to warrant mention. The most devastating losses occur where human lives are lost, but there are also environmental consequences. Flood waves can destroy downstream forests and farmland. Sometimes the outburst floods trigger other landslides such as debris flows.

31.3.6 Landslides Impacts on Scenery in Parks

Landslides in parks can damage infrastructure, change topography, wipe out forests and add sediment to streams. But they can also become awe-inspiring testimonies to natural processes. Some major landslides have become tourist attractions. Both the 1903 Frank and 1983 Thistle landslides in Alberta, Canada, and Utah, USA, respectively, have highway pullouts with interpretative signs.

The most recent example of destruction in a major site occurred at a UNESCO world heritage site, the Valley of Geysers, Kamchatka, Russia. On 3 June, 2007 a massive landslide covered the geysers (Fig. 31.4). It certainly changed the valley. Yulia Kugaenko (see below) considers the Valley of Geysers a huge natural museum with both volcanic processes and landslides. She stresses the landslide was not a catastrophe, but a natural process on display.

31.4 The Ecological Role of Landslides

Natural disturbance is an important process of rejuvenation in ecology. There are many abiotic disturbance types including volcanic eruptions,

Fig. 31.4 Valley of Geysers before and after the 2007 landslide. Note the new lake formed by the landslide dam. Photos contributed by Yulia Kugaenko. Photo 1 by I.Shpilenok and V.Droznin. Photo 2 by Y. Muraviev

earthquakes, tsunami, wildfire, violent windstorms, floods, and landslides. These, in addition to biotic disturbances, such as insect outbreaks and tree diseases, contribute to natural cycling of both aquatic and terrestrial ecosystems. There is often a synergy between disturbance agents. For example, insect oubreaks or wildfire may predispose slopes to landslides (Fig. 31.5). Here we consider the ecological role of landslides as disturbance agents in the natural environment.

Episodic erosion and sedimentation events are essential to the long term structure, function and integrity of aquatic ecosystems (Keller and Swanson, 1979; Swanson, 1980; Swanson et al., 1982, 1988; Hogan, 1986; Naiman et al., 1992; Benda and Dunne, 1997; Nakamura et al., 2000; Montgomery et al., 2003).

The structure and function of fish-bearing streams depends in large part on the periodic input of sediment and woody debris. Much of this input comes from landslides. Log jams in particular are important for creating pool/riffle habitat.

Geertsema and Pojar (2007) argue that landslides contribute to biodiversity in three main ways: by changing site, soil, and vegetation (habitat). Landslides usually change the site conditions at a given location, for example, making conditions drier or wetter, or stonier or muddier, more pervious or less pervious, sunnier, more exposed, etc. Changes to site conditions then also lead to changes in soils developing on those sites. Changes to site and soil, and the resultant changes in vegetation, contribute to increased habitat diversity, which is expressed at the landscape scale. The following sections are derived largely from Geertsema and Pojar (2007).

Fig. 31.5 There is often an interplay between disturbance agents. Here, in the Northwest Territories, Canada, wildfire has likely contributed to retrogressive thaw flowing by reduction of an insulating moss layer, resulting in the thickening of the active layer, thawing permafrost

31.4.1 Site Diversity

Geertsema and Pojar (2007) define site as a segment of landscape that is relatively uniform in local climate, topography and soil. Landslides increase site diversity. One of the main ways that landslides impact site is by changing topography. Landslides create, at the same time, erosional and depositional landforms with zones of depletion and zones of accumulation (Cruden and Varnes, 1996). Within landslides a range of positive and negative microtopography is possible at various scales.

Examples of positive microtopography in landslides include hummocks and ridges that rise up from the main ground surface (Fig. 31.6). Hummocks and ridges are often drier and warmer than surrounding terrain. Rubble deposits resulting from rock slides tend to be very rapidly drained, often in extreme contrast to adjacent terrain. The complex microtopography in landslides contributes to a redistribution of sites, usually with a greater number of very wet and very dry microsites (Fig. 31.7).

Fig. 31.6 Dry ridges and wet depressions in a translational landslide near Fort St. John, Canada contribute to the biodiversity of the local landscape. Photo courtesy Ake Nauta

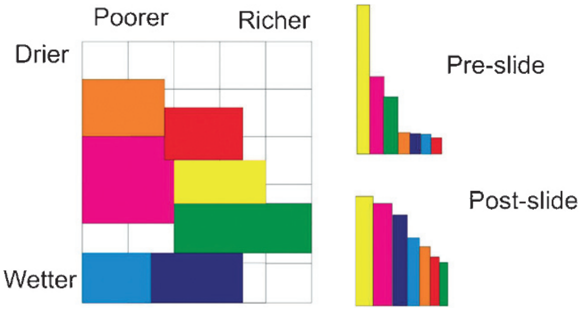

Fig. 31.7 Edatopic grid on right shows the distribution of site series (ecosystems) based on site moisture and richness. The distribution of various site series changes after a landslide has happened

Examples of negative microtopography include sag ponds below the main scarps of rotational landslides (Cruden et al., 1997). Other ponds result from variable topography in the zone of accumulation in earth flow deposits, or from the impoundment of streams (Cruden et al., 1993; Geertsema and Pojar, 2007).

Landslides also create open, at least temporarily exposed sites, often with more extreme microclimates than the surrounding landscape matrix—especially in forested terrain. Scarps created by landslides are steeper than the pre-slide slopes, and commonly form cliffs.

Repeated debris flows and slides tend to deepen channels in hillslopes, resulting in a gully-interfluve topography, often with deposits on terraces (Fig. 31.8) or in streams. This is especially the case in fine-textured tills and glaciolacustrine deposits and in soft, fine-grained bedrock.

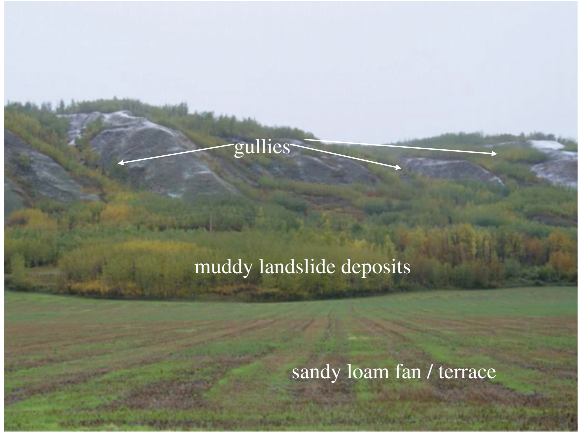

Fig. 31.8 Landslides play an important role in the formation of gullies and lobate deposits that are different from the terrace in the foreground. Modified from Geertsema and Pojar (2007)

31.4.2 Soil Diversity

Landslides change soil properties primarily by exposing parent material (the C horizon) by removing organic mats and A horizons. This can result in a mosaic of pedogenic stages in a landscape unit. At a given site, a Podzol (FAO Soil Classification) may be removed, exposing a Regosol, thus resetting the pedogenic clock to the initial stages of a Regosol Podzol sequence. Landslides that have translational movement typically raft intact mats of soil, and in the extreme case, large portions of forest may move as coherent units, maintaining both the forest and soil. The most thorough mixing occurs in flows.

If both site and soil change, soil changes may persist much longer and have greater ecological effects. For example, when a landslide exposes a phreatic surface, the site hydrology could change, and in the extreme case, lakes or wetlands can develop in the zone of depletion. Thus we could expect Gleysols, or perhaps Histosols to replace the original Podzol. At the other extreme, a landslide deposit may fill in a moist valley, replacing a wet Histosol with a soil that will develop on the new, drier site. In both instances, changes to site also bring about changes in soil.

An important influence of landslides on soil is the change in texture. Textural changes occur where landslides bring different material to, or remove material from, a given site. Material can be brought to the surface from below, as in mud volcanoes (Schwab et al., 2004) or sand blows resulting from liquefaction, but more commonly where landslide deposits cover a site. For example, both the mud of earth flows and the rubble of rock avalanches change the texure of surficial material on a gravelly terrace. Debris flows often impart a mixture of clasts and soil to a site with lateral sorting (e.g. Nakamura et al., 2000; Butler, 2001). In other cases landslides may remove sands and gravels or till, exposing fine-textured muds. Spreads that occur in marine clays overlain by sands, often result

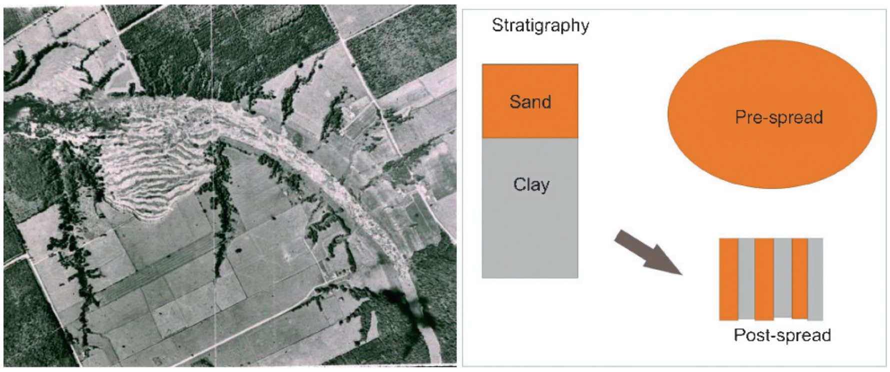

Fig. 31.9 Ribbons of sand and clay persist long after a spread has occurred in sensitive glaciomarine clays at the 1971 South Nation landslide, Ontario, Canada

in a thumbprint-like pattern of sand and clay ribbons 5–10 m wide (Eden et al., 1971; Mollard and Janes, 1984; Carson and Geertsema, 2002) (Fig. 31.9). Indeed, where various stratigraph units are involved in a landslide, textural sorting by the landslide process is common (Fig. 31.10). Post-landslide erosion also sorts surface deposits and thus changes soil texture. Landslides can also change local soil density and porosity.

Remoulding and liquefaction of clays and silts in earth flows, reduces structure and porosity, and increases soil density. In contrast, colluvial slopes in mountainous terrain generally have a looser structure and higher porosity than underlying tills. The mixing of wood with landslide debris can also increase the porosity of the soil. In general, landslide deposits occupy more volume than the original pre-movement source (Cruden and Varnes, 1996).

Landslides can also change soil chemistry at a site (Zarin and Johnson, 1995; Hugget, 1998). Deposition of foreign material can do this, but soil chemistry can also change due to the weathering of surficial materials and the exposure of material at depth. Geertsema and Schwab (1995) found that material exposed at depth in glaciomarine sediments had a pH of 8 and up to 5% carbonate as opposed to near-surface soil (pH <5) that had undergone leaching and acidic weathering in a coniferous temperate rainforest. Thus materials exposed in the surface of the landslide had soils highly variable in pH and soil chemistry, depending on whether surficial material or deeper material covered the ground surface. Smith et al. (1986) found that, on the Queen Charlotte Islands BC, pH of humus decreased with the age of landslides, and that organic carbon and total nitrogen increased with landslide age. Lambert (1972) found that the pH of tundra mudflow soils in the Northwest Territories ranged from 5.5 to 6.9 in comparison to 4.6 in the mineral soil of the surrounding climax vegetation. Burn and Friele (1989) also found that fresh to 43-year-old thaw slump soils near Mayo, Yukon had pH values of 7.3–7.4, compared to 6.2 in soils under mature spruce forest.

Fig. 31.10 Vertically stratified (preslide) units are often found adjacent to each other in landslide deposits

31.4.3 Habitat Diversity

Habitat diversity is a derivative of site and soil diversity, as expressed over landscapes (Geertsema and Pojar, 2007). Various combinations of microtopography, substrate, soil, nutrient and moisture regime, and vegetation, result in a variety of habitats for different species.

A landscape typically consists of a mosaic of patches and corridors in a background matrix (Parminter, 1998). Habitat diversity of landscapes is strongly related to patterns of disturbance and recovery. Landslides alter both site and soil, and thus contribute to landscape evolution. Superimposed on the disturbed site and soil is the response of vegetation. Landslides result in a variety of habitats that differ from the surrounding matrix and provide substrates for both primary and secondary succession. In some landslides, rafts of vegetation and even stands of trees may simply move (translate) from one location to another, but in general deep unweathered parent material or rock is exposed, turning back the ecological clock to primary succession. The landslide, then, is one of the disturbance agents that contributes to habitat diversity by changing site, soil, and vegetation patterns.

In forested landscapes there is a distinct vegetative difference between landslides and the surrounding forest. For example in the Chisca River area of northern BC, a rock avalanche spread over black spruce muskeg; willow and birch shrubs have replaced the original forest. The larger, low gradient earth flows tend to create very complex microtopographies, resulting in a wide range of moisture regimes. A corresponding spectrum of vegetation occupies the microhabitats in response to the variable site characteristics. Aquatic vegetation forms in ponds – often eventually passing on to peatland communities. Dry-site lichens may cover rubble and gravelly ridges in landslides. Such differences can persist for centuries, as on old landslides on the coast, where eventually coniferous forest takes over but remains different (species composition, productivity, soils) than the surrouding matrix forest.

Landslides of different age and type result in a mosaic of successional stages across landscapes. Globally landslide-ecological studies have been reported in Africa (Lundgren, 1978), in the Caribbean (Guariguata, 1990; Dalling, 1994; Walker et al., 1996; Myster et al., 1997; Myster and Walker, 1997), in Japan (Sakai and Oshawa, 1993; Yamamoto et al., 1995; Yajima et al., 1998; Nakamura et al., 2000), in New Zealand (Mark et al., 1964; Trustrum et al., 1984; Smale et al., 1997; Mark and Dickinson, 2001; Wells et al., 2001; Vittoz et al., 2001; Claessens, 2005), in the United States (Langenheim, 1956; Flaccus, 1958, 1959; Hull and Scott, 1982, Miles et al., 1984; Miles and Swanson, 1986; Shimokawa, 1984; Lewis, 1998; Butler, 2001; Francescato et al., 2001; Restrepo and Vitousek, 2001), with numerous publications on vegetation establishment on the landslides at Mount St. Helens (e.g., Dale and Adams, 2003), and in Canada (Lambert, 1972; Revel and Maze, 1972; Burn and Friele, 1989; Geertsema and Pojar, 2007).

In New Zealand, cohorts of trees result from earthquake induced landslides (Wells et al., 2001), generating habitat diversity across the landscape (Vittoz et al., 2001). Claessens found that kauri trees grew preferentially on recent landslide scars, and played an important role in stabilizing the landscape.

At Mount Tokachi in Japan, variable vegetation types covered a 1926 debris flow-generated landscape. Birch grew on sand at the outer margins of the debris flow deposits. Inward from the margins, on sandy-stony sediment, birch grew with a coniferous understory. The cobbly central areas of the debris flow were occupied by spruce (Yajima et al., 1998, Nakamura et al., 2000).

Lewis (1998) demonstrated that aspen stands occupied landslide deposits on the otherwise steppe-covered slopes of Kathul Mountain, Alaska. Mineral soil exposure and snow trapping on rough landslide deposits favoured the establishment of aspen. Aspen was unable to compete with steppe vegetation on the non-landslide terrain.

Lambert (1972) studied plant succession on tundra mudflows in the Canadian Northwest Territories. Two seres of plant succession occurred. Exposed silty soil was first colonized by a *Senecio* and cottongrasses, and later by grasses, horsetails, and the forb *Petasites*. Another community in the landslides included rafted islands of intact surface material and climax vegetation, including an assortment of lichens, mosses, grasses, sedges, forbs and shrubs. The mudflows then, set the successional clock back asynchronously to produce a mosaic of successional stages on the tundra.

Burn and Friele (1989) studied retrogressive thaw slumps in permafrost terrain near Mayo, Yukon. They distinguished seven vegetation units in the landslides, ranging from pioneer assemblages to 40-year old forest. Their work shows that episodic retrogression by thaw slumping produces a mosaic of vegetation communities.

In BC, Smith et al. (1986) studied revegetation patterns on debris slides and flows on the Queen Charlotte Islands. They distinguished 8 vegetation groups on 49 landslides. The differences were primarily attributed to age and position on the landslide. The deciduous red alder dominated the stands for about 5 decades, but then began to decline under as Sitka spruce became dominant. Rock-dominated slopes typically were not colonized by red alder – there western hemlock and Sitka spruce occupied the landslides.

Large earth flows or slides with hummocky or ridged microtopography often form ponds. Sometimes the microtopography predisposes sites to colonization by beaver. Thus landslides can both create ponds and facilitate the construction of beaver ponds – and support associated flora and fauna. In turn, at the landscape scale, beaver increase habitat diversity (Wright et al., 2002).

The pioneer vegetation established on many landslides provides important browse for ungulates – particularly in terrain dominated by conifer forests with moss-dominated understories. The floristic explosion on a landslide deposit also support other deciduous-dependent fauna.

Cliff collapse and large rotational landslides often create cliffs, usually with associated rubble fields. Soil cliffs provide habitat for cavity nesters such as bank swallows and kingfishers, and the rubble is excellent escape terrain for small rodents and contains den sites for a variety of mammals. Rock cliffs also provide safe escape terrain for mountain goats and mountain sheep.

Landslides may impound streams and drown upstream forests (Fig. 31.11). This can leave a legacy of standing dead trees (snags) and coarse woody debris providing habitat for many species (Swanson and Franklin, 1992). Snags are particularly important for cavity-nesters, and may be used as perch trees by raptors.

Fig. 31.11 This landslide on Wrigley Creek, Northwest Territories, Canada has increased the diversity of this landscape. The landslide created a hummocky microtopography, exposed cliffs, formed a lake, and drowned a floodplain forest

31.4.4 *Influence of Landslides on Forest Productivity*

Soil-stripping by landslides generally reduces the productivity of forests (e.g. Smith et al., 1986). In some environments however, the most productive forests grow on disturbed terrain. There are several examples of this. In the rainforests of coastal British Columbia thick mosses blanket stable slopes. Trees on these slopes have much slower growth rates than trees colonizing landslides (Banner et al., 2005). The same is often true for muskeg terrain in the boreal forest. Thick saturated moss slows tree growth. Landslides remove the surface cover, mix organic matter with mineral soil, allow soils to be warmer, and offer a more hospitable environment for trees.

31.5 Invited Presentations

31.5.1 *The Spatial and Temporal Influence of Landslides on Stream Channels in Mountainous Terrain, British Columbia, Canada*

Dan Hogan (BC Forest Service, Canada)

Landslides are an important geomorphic agent in British Columbia's steep, forested, coastal terrain.

They are episodically occurring, natural disturbance events that produce large quantities of clastic sediment and large woody material (LWM) that is delivered to adjacent streams. Because landslides leave a distinct footprint on the landscape, their historic date of occurrence can be determined and their temporal and spatial impact on the stream environment can be documented. The direct link between landslide occurrence and the evolution of stream channel morphology is established and presented here. The influence of forestry activities on landslide activity is also considered in the context of impaired fish habitats.

Dendrochronological studies indicate that four large landslide episodes occurred in coastal BC over the last 200 years; the landslides that occurred in 1891, 1917, 1934 and 1964 had a combined total volume of materials accounting for 85% of the total for the entire 200 years of record. The sediment and LWM delivered to the stream tends to cluster and initiate the formation of in-stream log jams. The formation of these jam structures alters the transport of water, sediment and LWM along the channel which in-turn leads to distinct morphological changes. Log jams that are large relative to the stream and tightly packed are effective sediment transport inhibitors. Upstream of these structures the stream is transformed from the morphologically diverse and complex pre-disturbance channel state to a greatly simplified form with shallow, in-filled pools, extensive riffles, less stable bars and increased frequency, extent and duration of a dry channel bed. Downstream the bed is typically much coarser textured and bedrock exposures are prevalent. Spatially, the channel can be influenced for lengths equal to or greater than 100 channel widths. This channel state persists for approximately one decade after which the integrity of the log structure is gradually reduced and fluvial transport slowly returns to more normal fluvial processes. As the jam deteriorates, upstream local gradients are gradually increased as sediment is moved downstream beyond the structure where the gradients are subsequentially reduced. Pools are deepened, riffles are scoured and the bed becomes coarser upstream and bars are re-built downstream. Back-channels are developed as the streamflows adjust laterally to bypass the jam. This morphological reversal typically continues between the second and fifth decade post landslide input. After approximately 50 years the log jams are sufficiently deteriorated to no longer interrupt sediment transport. The channel returns to the pre-disturbance state; the complex and diverse condition typical of coastal streams is a result of the long-term channel adjustment to earlier landslide impacts.

The morphological changes that occur upstream and downstream of the jams impact a range of fish habitats. These include spawning beds, egg incubation environments and rearing habitats. Forestry activities can alter the type, size and frequency of landslide occurrence. Because the severity of these impacts vary over time, depending on landslide timing and resultant jam structure, it is important that the natural landslide activity patterns are not altered. It must be the focus of forest management practices to mitigate increased extent of landslides to avoid increased duration of the early phases of landslide impacts while not altering the long term patterns that lead to complex habitats.

31.5.2 Landslides, Natural Protected Areas, and the Long-Term Management of Mountainscapes: Emerging Challenges from the Study of the El Triunfo Biosphere Reserve, Chiapas, Mexico

Carla Restrepo, Juan Carlos Castro Hernandez, Saul Hernandez Bezares , Miriam Janette Gonzalez Garcia (University of Puerto Rico-Rio Piedras)

In 1998 and 2004 two tropical storms triggered hundreds to thousands of landslides in the Sierra Madre de Chiapas of southwestern Mexico. A region that was particularly affected by these storms and associated landslides was the El Triunfo Biosphere Reserve (ETBR), an area of ~120,000 hectares that was set aside eighteen years ago to protect the elevated diversity of organisms and ecosystems of the Sierra Madre de Chiapas while promoting its sustainable development. Extensive landsliding in the ETBR raises numerous questions about the large-scale dynamics and conservation of these and other mountain ecosystems worldwide. Here we combine the classification of SPOT images with spatial analyses to examine the role of land cover/land use and reserve zonation on the distribution and extent of landsliding. We discuss the implications of our work for the management of the ETBR, including the role of protected areas in the conservation of landsliding as a key process driving the large-scale dynamics of mountainscapes.

31.5.3 Geoecological Imprint of Slope Deformations on Habitats – The Case Studies from the Czech Part of the Western Carpathians (Czech Republic)

Jan Hradecký (Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava)

Slope deformations represent one of the dominant morphogenetic processes in the Czech part of the Western Carpathians. Landslides significantly participate in the modification of landscape evolution processes. Entirely new, and in many cases, unique habitats evolve on the base of the differentiation of originally direct undisturbed slopes caused by landsliding. The study area contains slope deformations of various types, size dimensions and time of origin. The study brings knowledge of four different groups of slope deformations; within the deformations it analyses and interprets various reflections of landsliding disturbance, namely in partial landscape components. The slope deformations have created locations of palaeoenvironmental record which represents a valuable source of information (chronological, palynological, etc.) in terms of understanding geoecological aspects of not only the location itself but also a wider surrounding area. Within Miaší Mt and Černá hora Mt slope deformations the study focuses on the imprint of landsliding in soil variability. Evolution of specific geotopes in the extension zone of the Čertův Mlýn Mt deep-seated slope deformation is accompanied by the creation of a trench that was subsequently infilled with organogenic sediments. The occurrence of peat-bog biotopes in the Czech part of the Western Carpathians is often confined to landslides as in the case of the peat-bog on the southern slopes of Groníček Mt. High dynamics of changes of geotope features correlates with the occurrence of flow-like landslides (case study of debris flows in Smrk Mt massif). Habitat formation in areas affected by the catastrophic process of rock avalanche (Ropice Mt) is then considered to be an extreme case.

31.5.4 Mechanisms and Geoecological Consequences of Cryogenic Landslides in the Area of Marine Sedimentation – Russia

Marina Leibman (Earth Cryosphere Institute of Russian Academy of Sciences, Siberian Branch)

Maritime lowlands in the Arctic ocean margins are often composed of saline marine rocks, preserving their salinity due to perennially frozen state. Active surface processes such as landslides remove upper washed out soils, often of sandy-silty texture, to expose saline rather clayey deposits. Since the exposure, new geochemical properties and organic layer start to develop in a newly formed surface and active layer.

Depending on the triggers of a cryogenic landslide: thawing of the icy layer at the active layer base or melting of massive ground ice, different sliding mechanism may develop: either block movement of the sandy-silty rocks, or creep/flow of liquefied silty-clayey rocks. Observed is also cryogenic sliding of frozen blocks along the frozen shear surface due to gravimetric effect and wave action. Each mechanism causes different complex of consequences: geomorphologic, geochemical and geobotanical.

All types of cryogenic landslides are found on Yamal Peninsula, Russia. This region is known for widely distributed saline rocks of various sandy to clayey texture, massive ground ice rather close to the surface, complicated topography with the area of slopes exceeding that of flat surfaces, and thus vast area of slopes re-worked by landsliding. Yamal Peninsula is also studied in most detail due to natural gas production prospects. One more advantage of using this territory as a key for cryogenic landslide study is a remarkable landslide activation in

1989 and long term observations of shear surface recovery in terms of geochemistry and geobotany undertaken since then. Far less landslides appear after 1989, most of them are linked to re-exposed massive ground ice in 2005–2006 with unusually warm summers.

The main conclusions made through detailed study on the key site in Central Yamal are grouped into those concerning ionic composition of soils and ground water, succession of vegetation and related permafrost/active layer features, short-term and long-term evolution of landslide affected slopes, and impact of landsliding and its environmental consequences: biodiversity and reindeer pastures changes.

Geochemical processes on slopes exposed by landsliding cause a redistribution of ions within the active layer and upper permafrost. Due to suction, capillary processes, washing out by ground water, slopewash and other processes active layer loose salts which are in part accumulating beneath the permafrost table or on the ground surface from which they are washed away and reach the drainage network.

Bare surfaces are re-vegetating rather slowly with full recovery after decades, vegetative complexes differ from those removed, and only after several centuries shrub-moss cover possibly restore. Landslide affected slopes on Yamal underwent several cycles of landslide events after which they obtained a different from surrounding stable slopes appearance.

In terms of lithology active layer of landslide-affected slope is composed of clayey rather than sandy-silty deposits. In terms of geochemistry active layer soils and ground water contain much higher concentration of main ions, though reducing in time and acquiring a continental mode instead of marine one. In terms of geobotany, dwarf shrub moss-lichen tundra is replaced first by grass-lichen tundra and then by willow shrub grass-lichen tundra. Initial exposure of the surface and formation of a concave landform promoted snow accumulation, thermoerosion, water drainage and as a result, active layer deepening, then re-vegetation starts the inverse process.

Relief and environment changes due to landslides cause decrease of biodiversity but increase of biomass, especially in long-term effect, which improve the situation with reindeer pastures.

31.5.5 Details of the 2007 Landslide in the Valley of Geysers

V.A. Droznin, V.N. Dvigalo, E.I. Gordeev, Y.D. Muravyev (Institute of Volcanology and Seismology FEB RAS, Petropavlovsk-Kamchatsky, Russia)

The Kamchatka geysers are located in the 4 km long Canyon-shape valley of the Geysernaya River that drains the east border of the Uzon-Geysernaya volcano-tectonic depression. The spur (791 m height) collapse in the basin of the Vodopadny stream, the left feeder of the Geysernaya River resulted in the large 3 June, 2007 landslide. Its deposits blocked the Geysernaya River and resulted in formation of the dammed lake. The lake was flooded 4 days later and on the 7th of June the water started to overflow through the dam. After 4 h the river made a new bed in the dam and the water level lowered on 9 m and the maximum lake depth comprised 20 m (on echolocation date). Several large geysers were destroyed, several others occurred in the flood zone; small landslides went down the bluff shores of the lake, new short-life thermal springs were formed.

The landslide occurred as the result of two collapses. First, the spur (791 m height) in the form of so-called equal-plane (“body” 1) collapsed and formed main landslide deposits down the valley. Than, the adjoining southwest spurs (“body” 2) went down to the free from the main spur area. Table 31.1 gives the results of photogrammetric processing of aerial photographs on 1993 August, 23 and 2007 June, 12 for the territory suffered by the landslide.

31.5.5.1 Precursors

Neither precursors nor triggers were recorded prior to the event because recently scientists have not carried out any special observations in the Valley. We can just mention that the reserve ranger

Table 31.1 Quantitative characteristics of the 2007 June, 3 landslide

#1 body volume	12238000 м^3
#2 body volume	4762000 м^3
Deposit volume	20752000 м^3
dike volume	4159000 м^3
underwater part of the dike	**759000 м^3
Total volume of mudflows	
Area of deposits	994096 м^2
Lake surface on 2007 July, 7	76100 м^2

Zlotnikov V.A. reported he smelled hydrogen sulfide a day prior to the event when he was going down the valley of Vodopadniy stream in the landslide zone.

The diagram of relative 3D tidal deformation shows the time of the landslide that occurred in intra-month maximum.

The 1st body plane of rapture goes through the fissure tracing the volcano-tectonic fault in submeridional direction. Aerial photos revealed this fault in 1973.

31.5.5.2 Thermal Anomalies

The collapse in zone of the spur breakoff (791 m height) was accompanied by a large steam plume. The flow contained portions of heat rocks, they kept teaming long after they had stopped moving. The heat rocks were penetrated in the zone of the landslide formation. Now this zone shows the formation of a new thermal anomaly. The thermal anomaly is projrcted on the clift plane of the #1 body.

The rock redeposition caused by the landslide generated heat sufficient for keeping high temperature (to 60°C) in Vodopadny stream as long as one month after the event. A half-year later the water temperature decreased to 7,8°C.

31.5.5.3 Some Peculiarities of the Landslide

The collapsed rocks that form the landslide body are represented chiefly by Pleistocene lake sediments and loosely cemented tuff. The flow may be classified as a large-block, though scientists have not measured the fractal size. The large blocks are several meters in lateral dimension. The recent flow obstructed the way due to the water-bearing filling material of the flow. The eyewitnesses reported the flow had passed about 2 km for 2–2.5 min. but such a data are questionable. The data probably concern just the visible upper part of the Vodopadny stream watershed that is no longer that 1 km.

In spite of the doublet character of the landslide the single collapse amphitheater was formed in the area of its origin. The body 2 formed more than 0.22 km^2 allochthon. At least in side and front parts, the landslide moved along the snow cover, involving snow into the flow. Natural obstructions significantly influenced the landslide dynamics and its deposits profile. Extrusive formation "Triumphalnye vorota" blocked the flow on the Geysernaya River and significantly increased the dam height. The Vodopadny stream surface water discharge was not yet finished. We are demonstrates possible to the summer 2008 lakes distribution area on the flow deposits. The total water volume may comprise 400,000 m^3, 250000 of them in the largest. So, here is possible the same scenario as during the dam of the dammed lake washing out.

Geysernaya River carried out fragmental material into Shumnaya River. This material deposited in the lake and increased the volume of alluvial deposits, manifested in the form of the mobile spit. On 12 July its volume comprised 5000 m^3, on 10 September 2007 comprised 8000 m^3. Most material was carried out during cyclones and in spring, during snow melting. The time of the lake filling up is 70–100 years.

31.5.5.4 Conclusions

The largest geological catastrophe of the year 2007 on the territory of Russia occurred in the Valley of Geysers on the 3rd of June on Kamchatka. The spur (791 m height) collapse in the basin of one of the Geysernaya feeders resulted in the 20 million m^{3}rocks slide, the mudflow into the Shumnaya River valley and the dam and the dammed lake in the lower part of the river formation. Several large geysers were destroyed or flooded. We observed the alteration of the surface thermal regime in the Geysernaya hydrothermal system, small landslides along the lake banks resulted in thermal zones and hot springs migration. The paper discusses some results on the catastrophe consequences: possible reasons, current processes during and after the landslide.

Such landslides or even larger ones are typical for this region and explained by the caldera side, deeply opened by erosion. They are caused by: volcano-tectonic effects; lacustrine sediments thickness, depositing at an angle to the Geysernaya River valley, thermal waters circulation and so on. Today Geysernaya hydrothermal system is adapting to the altered hydrogeological conditions.

31.5.6 Landslide Adds to the Mystery and Natural Beauty of the Valley of Geysers

Yulia Kugaenko (Kamchatka Branch of Geophysical Survey of RAS)

Kamchatka is a huge natural museum of volcanology; its “exhibits” are active and extinct volcanoes as well as different associated formations: geysers, fumaroles, thermal springs etc. Dangerous slope processes (landfalls, landslides) are rather frequent phenomena for present-day hydrothermal fields of Kamchatka. Landfall and landslide forms of different scale and age were recognized here. Thus the big landslide on June 3, 2007 is not a unique phenomenon for the Valley of the Geysers. This natural catastrophe has strongly changed the Valley of the Geysers landscape: Geyizernaya River is dammed up by landslide deposits, as a result a new picturesque lake has been formed; a part of the geysers has been destroyed. Nevertheless the Valley of the Geysers still remains one of the main objects of ecologic tourism on Kamchatka. The photos taken in the Valley of the Geysers in different years before and after landside on June 3, 2007 are presented in this report. The characteristic of the Valley of the Geysers as an object of UNESCO World Natural Heritage is given. The main information on the landslide which occurred here on June 3, 2007 is briefly summarized.

The events in the Valley of the Geysers on June 3, 2007 should not be considered as ecological catastrophe. It is a natural process, an element of geological evolution of the territory. This process introduced certain additions to landscape originality of UNESCO World Natural Heritage Object “Volcanoes of Kamchatka”. The unique landscape complex of the Valley of the Geysers did not become less interesting for the visitors. A picturesque lake has appeared here, on the caldera slope now there are nearly vertical parts of dislocation plane (wall length – 800 m, wall height – about 150 m), one can see some other results of catastrophic landslide. New lakes are observed on the avalanche flow surface.

The reorganization of surface hydrothermal system regime proceeds at present time in the Valley of the Geysers; abrupt alterations of the dam lake level activated further development of landslide processes on the Valley slopes. The Valley of the Geysers became even more interesting from the scientific point of view. The nature gives investigators a unique possibility to observe and study a wide spectrum of present-day geological processes caused by natural disaster on the geyser field.

31.5.7 Contribution of Topographically Bases Landslide Hazard Modeling to the Analysis of the Spatial Distribution and Ecology of Kauri (Agathis Australis)

Lieven Claessens (International Potato Centre, Kenya)

In this paper the use of topographical attributes for the analysis of the spatial distribution and ecological cycle of kauri (Agathis australis), a canopy emergent conifer tree from northern New Zealand, is studied. Several primary and secondary topographical attributes are derived from a Digital Elevation Model (DEM) for a study area in the Waitakere Ranges. The contribution of these variables in explaining presence or absence of mature kauri is assessed with logistic regression and Receiver Operating Characteristic (ROC) plots. A topographically based landslide hazard index, calculated by combining a steady state hydrologic model with the infinite slope stability equation, appears to be very useful in explaining the occurrence and ecological dynamics of kauri. It is shown that the combination of topographical -, soil physical – and hydrological parameters in the calculation of this single landslide hazard index, performs better in explaining presence of mature kauri than using topographical attributes calculated from the DEM alone. Moreover, this study demonstrates the possibilities of using terrain attributes for representing geomorphological processes and disturbance mechanisms, often indispensable in explaining a species' ecological cycle. The results of this analysis support the 'temporal stand replacement model', involving disturbance as a dominant ecological process in forest regeneration, as an interpretation of the community dynamics of kauri. Furthermore a threshold maturity stage, in which trees become able to stabilize landslide prone sites and postpone a possible disturbance, together with great longevity are seen as major factors making kauri a 'landscape engineer'.

31.5.8 Environmental Effects of Possible Landslide Catastrophes in the Areas of Radioactive Waste Warehousing in Kyrgyzstan (Central Asia)

Isakbek Torgoev (Scientific Engineering Center GEOPRIBOR of the National Academy of Sciences of Kyrgyz Republic)

The vast majority of natural and/or man-made catastrophes on the territory of Kyrgyzstan are triggered by earthquakes and mass gravitational movements on mountain slopes in the form of avalanches, landslides and mudflows. This happens due to the fact that mountain areas of Tien-Shan are forming the territory of the country bounds. About 90% of the whole territory is at a height of more than 1000 m, and more than 50% of the territory is at more than 2500 m above sea level.

The specific character of mountain areas of Kyrgyzstan, particularly the following: hillside topography in combination with tectonic deformations and frequent earthquakes; presence of areas with weakly stable soils (loess) and areas with a lot of atmospheric precipitation; intensive development of erosion; high mountain vulnerability to man-made influence - all this contributes to active development of landslide processes.

Presently the number of landslide sources in the country is more than 5000, from which 1000 landslides directly or indirectly threaten settlements, economic objects and infrastructure. About 15 thousand km^2 (or 7.5% of the country) are under potential landslide influence. The most number of landslides is registered in a comfortable for life activity mid-mountain area over 800–2000 m altitude ranges. The volumes of rocks and soils moving in the time of landslides run up to many millions of cubic meters.

Every year landslides in Kyrgyzstan cause very substantial economic, environmental and social damage. Within the 1993–2008 period more than 300 events of very large-scale landslides ($V \geq 10^5$ m^3) were registered as a result of which 240 people have been killed. Only the direct economic loss from landslides is on average $2 million annually.

In compliance with statistical data in Kyrgyzstan up to 70% of present landslides are related to human activity in mountain areas. These include mining of mineral resources, building and maintenance of transport communications, hydraulic structures and associated infrastructure in mountain areas. The distinctive features of "man-made" landslides are the following: considerably larger scale than the natural ones have; concentration of man-made landslides on the small-scale mining territories; long-term and continuous nature of their development, as well as higher hazards and geoecological risk due to their vast gravitational energy and accompanying multi-hazards. The greatest geoecological risk these landslides of man-made genesis represent in the warehousing areas of radioactive and toxic waste of mineral resource industry.

Under the conditions of complex mountain topography and deficit of balanced and available areas, the radioactive waste storehouses (tailing dumps and waste piles) were placed along riverbeds, in floodplains and over-floodplain terraces of mountain rivers, at the foot of slopes and/or on the slopes themselves including weakly stable ancient slope-sites. Taking into account that such a situation is highly subjected to landslide processes and events, as well as their frequent recurrence, landslides represent a source of a considerable environmental risk for a population of Kyrgyzstan.

The most hazardous are landslides, which are formed on the rims of river valleys since their development and especially the final stage - movement is often of synergetic nature (domino-effects). The synergetic nature of landslide movements in basins of river valleys is that a landslide event in narrow river valley generates a series of other hazardous events by the following scenario: landslide → rock fall-slide blockage of river bed or river valley → inundation upstream of the landslide dam → dam break → flood or mudflow downstream. Quite often these hazardous events triggered by landslides even exceed the initiating landslide event by their destructive force and causing damage.

The special hazard of development of such synergetic scenarios is that in the areas of landslide mass transit, in inundated zones or in outburst flood zones both dwellings, radioactive waste and dump sites may be at risk. In case of possible failure of these storehouses the distribution sphere of radioactive materials stored in them may be enlarged greatly due to their propagation through drainage network. Therefore, local landslide risk may be transformed into regional and/or transregional risk of radioactive contamination of surface waters of the area. In the present report were discussed the environmental risks related to direct and/or indirect landslide influence upon tailings of radioactive waste generated from mining and processing of uranium ore in two landslide hazardous areas of Kyrgyzstan, such as Mailuu-Suu and Min-Kush.

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