tion of wave surges that can overtop the dam, (2) increased sedimentation with resulting loss of storage, and (3) dam failure.

Flood surges can be generated either by the sudden detachment of large masses of earth into the reservoir, or by the formation and subsequent failure of a landslide dam across an upstream tributary stream channel. Waves formed by such failures can overtop the dam and cause serious downstream flooding without actually causing structural failure of the dam.

Landsliding into upstream areas or reservoirs can greatly increase the amount of sediment that is deposited in the reservoir, ultimately reducing storage capacity. This increases the likelihood that the dam will be overtopped during periods of excessive runoff, causing downstream flooding. Excessive sedimentation can also damage pumps and intake valves associated with water systems and hydroelectric plants.

Actual dam failure could be caused by landsliding at or near the abutments or in the embankments of earthen dams.

In 1983 a large mass of rock detached from Slide Mountain in Nevada. The mass slid into Upper Price Lake, an irrigation reservoir, displacing most of the water which overtopped and breached the dam, flowing into Lower Price Lake. This lake's dam was also breached. The water flowed into Ophir Creek where it collected large amounts of debris and became a debris flow. After traveling about four kilometers and dropping 600 meters in elevation, the debris flow emerged from the canyon onto the alluvial fan of Ophir Creek (total time—15 minutes). One person was killed, four injured, and numerous houses and vehicles were destroyed (Figure 17) (Watters, 1988).

Rapid changes in the water level of reservoirs can also trigger landslides. When the water level in the reservoir is lowered (rapid drawdown), the subsequent loss of support provided by the water and increased seepage pressure can initiate sliding (Figure 18). Alternatively, the increase in saturation caused by rising water can trigger landslides on slopes bordering the reservoir.

Eisbacher and Clague (1984) describe an excellent example of the potential impacts of landsliding on dam safety: the 1963 Vaiont dam disaster in Italy. The Vaiont Dam, a hydroelectric dam, was completed in 1960 to impound the Vaiont Torrent, a major tributary of the Piave River in the southern Alps of Italy. The dam is 261 m high and spans a steep narrow gorge. The southern wall of the valley behind the dam is a steep dip slope. Within two months after the reservoir was filled, a 0.7×10^6 m^3 mass of rock slumped away along the submerged toe of the southern embankment. Over time, deep-seated movement of the slope occurred in response to changing levels of the reservoir. As a result of these movements,

Figure 17. House destroyed by 1983 Slide Mountain, Nevada landslide (photograph by Robert J. Watters, University of Nevada, Reno).

Figure 18. Jackson Springs landslide on the Spokane arm of Franklin D. Roosevelt Lake, Washington, 1969. This landslide was triggered by extreme drawdown of the lake (photograph by the U.S. Bureau of Reclamation).

monitoring instruments were set up on the slope.In August and September of 1963, precipitation in the Piave Valley was three times higher than normal and infiltration of the precipitation into the slope probably contributed to its eventual failure. The day before the catastrophic slope failure creep rates of 40cm/day were registered.

On October 9–10, 1963, in the night, a large slab of the unstable slope failed and slipped into the reservoir. The volume of material was estimated to be 250 x 10^6 m^3 (a slab 250 m thick). A wall of water 250 m high surged up the opposite side of the valley, then turned and overtopped the dam. The concrete dam held, and the wall of water (30 x 10^6 m^3) dropped into the narrow gorge below, scouring loose debris as it went and destroying several communities below the dam. At least 1,900 people were killed.

The site of the dam has been left as it remained after the disaster, as a monument.

Landsliding and Flooding

Landsliding and flooding are closely allied because both are related to precipitation, runoff, and ground saturation. In addition, debris flows usually occur in small, steep stream channels and often are mistaken for floods. In fact, these events frequently occur simultaneously in the same area, and there is no distinct line differentiating the two phenomena.

Landslides and debris flows can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back-up (Figure 19). This causes backwater flooding and, if the dam breaks, subsequent downstream flooding. Also, soil and debris from landslides can "bulk" or add volume to otherwise normal stream flow or cause channel blockages and diversions creating flood conditions or localized erosion. Finally, large landslides can negate the protective functions of a dam by reducing reservoir capacity or creating surge waves that can overtop a