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Landslide Surveillance: New Tools for an Old Problem

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Landslides are one of the most widespread geological hazards on Earth, responsible for hundreds of deaths and billions of dollars in property damage per year. Landslides commonly occur with other natural disasters (e.g., earthquakes, floods) and leave the landscape prone to sedimentation, erosion, and further mass wasting.

Remote sensing, the Global Positioning System (GPS), and geographic information systems (GIS) are now mature technologies that can be used to monitor landslides and landslide-prone areas with greater accuracy than could be accomplished previously with field reconnaissance alone.

Recent studies that have used these tools, including high-resolution satellite imagery [e.g., *Haeberlin et al.*, 2004], light detection and ranging (lidar) [e.g., *McKean and Roering*, 2004; N. Glenn et al., Correlations between landslide morphology, motion, and topographic analysis using lidar, submitted to *Geomorphology*, 2004], synthetic aperture radar [e.g., *Colesanti et al.*, 2003], GIS [e.g., *Seker et al.*, 2004], and GPS [e.g., *Malet et al.*, 2002], have shown that they may revolutionize landslide monitoring, and provide an unprecedented opportunity for predictive modeling and risk analysis for these features.

This article describes a NASA-funded project to assess the value of high spatial resolution remote sensing, lidar, digital image processing techniques, GIS, and GPS for measuring the current and historical motion of an active landslide in Salmon Falls Creek Canyon, Idaho. The far-reaching goal of the project is to test these techniques, both individually and collectively, to better understand their efficacy for broad application in landslide studies and hazard mitigation.

This project demonstrates the ability to combine these different data types and analysis techniques in a complementary manner, by merging aerial photography with satellite imagery, remote sensing imagery with GPS data, and lidar digital elevation models (DEMs) with GIS techniques. This has allowed for more in-depth examination of landslide behavior than is possible using each data type and analysis technique individually.

The continued development of protocols for the use of these tools on active landslides and in landslide-prone areas should lead to improved mitigation and warning procedures and a substantial reduction in the risks of loss of life, property, and natural resources worldwide.

Salmon Falls Landslide

The Salmon Falls landslide, located about 10 km west of the town of Buhl in south central Idaho, is a canyon-rim slide descending from the east rim of Salmon Falls Creek Canyon. The canyon is typically V-shaped and about 100 m deep and 250–500 m wide over most of its length. However, the canyon widens dramatically to well over 1 km along a 4-km stretch of the Salmon Falls Creek known as "Sinking Canyon" (Figure 1).

The current landslide is at least the second significant episode of mass wasting activity in Sinking Canyon in the past century. In 1937, an

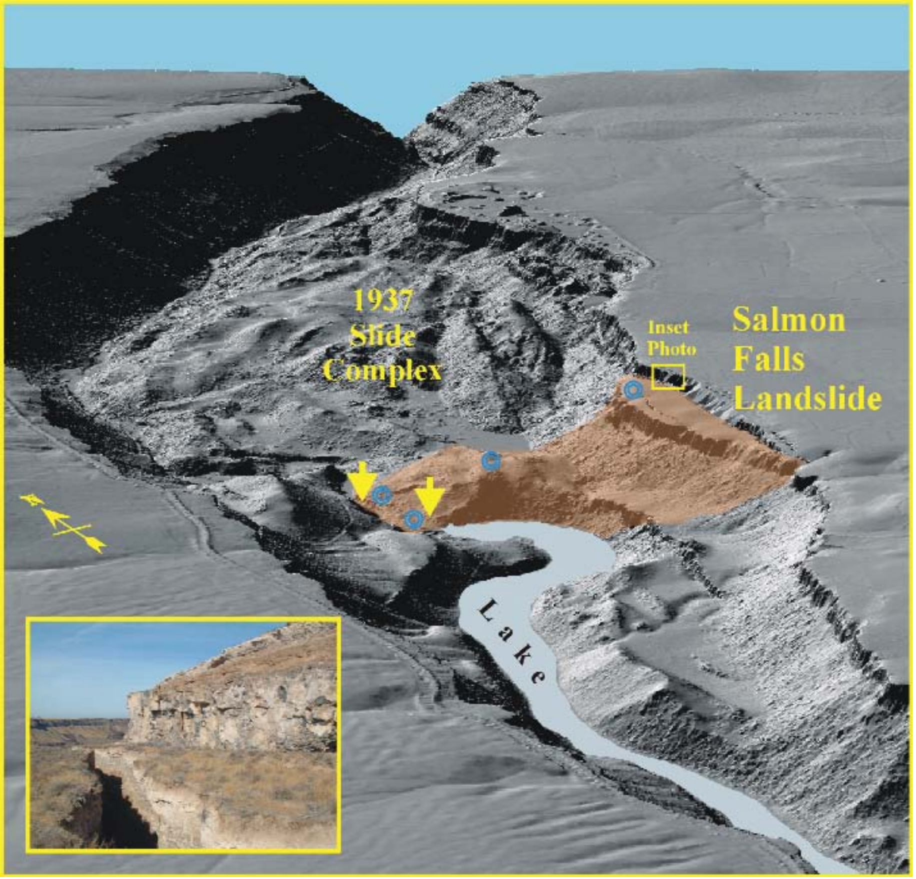

Fig. 1. Perspective view of lidar-derived digital elevation data of the "Sinking Canyon" area and Salmon Falls Creek landslide (highlighted). Movement of the slide has created two dams in the river (arrows) and a large lake behind them. The lidar data were useful for understanding the morphological elements of the canyon, as well as in modeling of flood scenarios that may result from breaching of the dams. The 1937 landslide complex is shown to the north of the current activity. The canyon is just over 1 km wide at its widest point. GPS stations are shown as blue circles. Inset: the headwall scarp of the landslide, showing approximately 15 m of offset from the canyon rim. Perspective DEM by J. Mundt.

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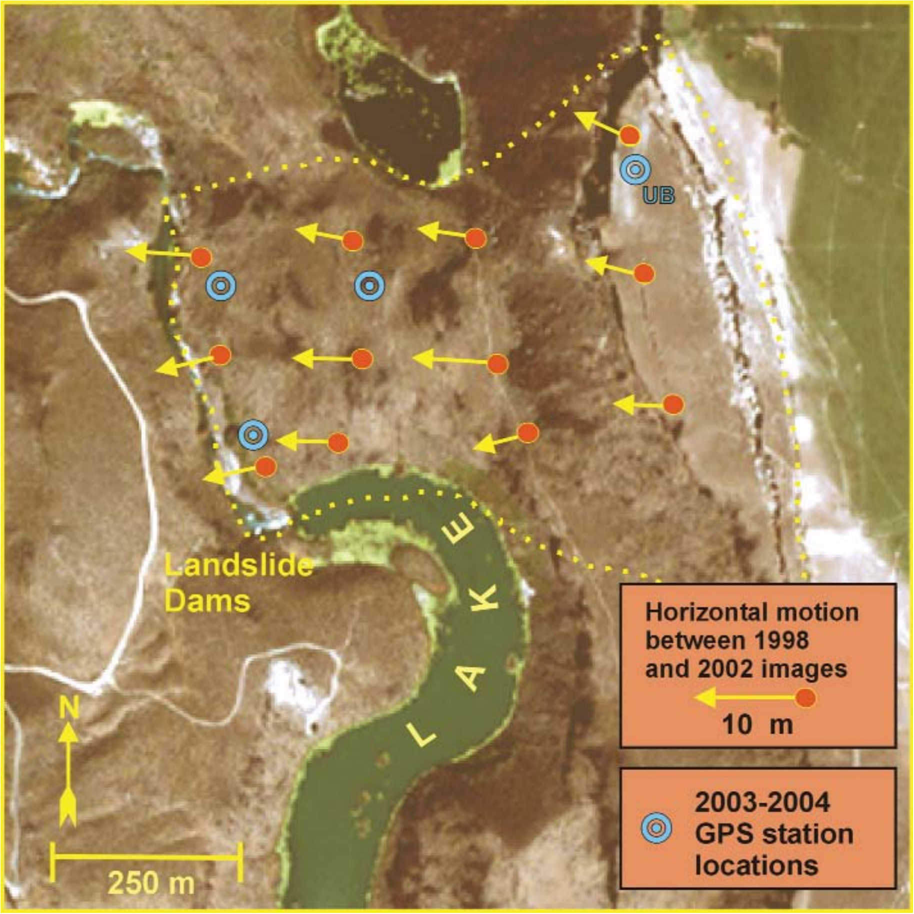

Fig. 2. Vectors showing the horizontal magnitude and direction of movement of image ground control points on the Salmon Falls Creek landslide between the July 1998 aerial photograph and the September 2002 QuickBird satellite image. GPS stations (blue) monitored the movement of the slide in three dimensions in 2003 and early 2004. The margin of the Salmon Falls landslide is outlined (dotted). Data shown in Figure 3 are for the "Upper Block" (UB) station.

850,000-m^2 landslide slid several tens of meters into the canyon (Figure 1). The anomalous width and hummocky morphology of the floor of Sinking Canyon suggest the area underwent extensive mass wasting prior to the two historical events. The cause of this anomalous activity confined to this relatively small area is not known, but may be related to a locally greater thickness of the Glenns Ferry Formation, a weak sedimentary unit that underlies an upper layer of Snake River Plain basalt flows.

The current slide is about 500,000 m^2 in area. It developed on pre-existing canyon rim fractures, and has displaced about 20,000 m^2 of farmland on the canyon rim. The canyon rim has subsided up to 15 m into the canyon as a coherent block (Figure 1 inset). The slide's slow movement (cm/yr to m/yr) has encroached on Salmon Falls Creek, shifting the creek's course to the west and pushing the creek's original, now abandoned bed upward by over 2 m.

The motion of the slide has also created two natural dams caused by uplift of the terminus and by rockfalls into the watercourse. Behind these dams, lakes have formed (Figure 1), the largest of which is estimated to contain up to 150,000 m^3 (over 40 million gallons) of water. This presents a potential flooding hazard to properties downstream should the dams breach catastrophically.

The Past: Measuring Historical Landslide Movement

Movement on the relatively remote Salmon Falls landslide was first reported by rock climbers in the fall of 1999, but anecdotal reports suggest the landslide activity may have begun as early as 1995. When the U.S. Bureau of Land Management (BLM) began monitoring the landslide in 1999, field studies indicated that the slide had already undergone a period of rapid motion and had slid several meters into the canyon. In order to better constrain the date and amount of early activity, archival aerial photographs from June 1990 and July 1998 were digitized, and the landslide's historical positions were compared with its more recent location in a September 2002 QuickBird satellite image. Quickbird imagery has aerial photograph-like spatial resolution (2.4 m in four multispectral bands, and 60 cm in a fifth panchromatic band).

The digitized aerial photos and satellite image were co-registered, and common points were then selected on the landslide in each image. These common points exhibited spatial offsets representing the amount of horizontal movement over the 1990–2002 and 1998–2002 time periods (Figure 2). The results show that these points moved laterally up to 16.4 m (± 2.8 m) between 1990 and 2002, and that the same points moved up to 9.3 m (± 2.7 m) in the 1998–2002 comparison. This result indicates that while most of the landslide activity occurred after the 1998 aerial photo was acquired (which includes the period of formal BLM monitoring), significant motion occurred prior to 1998 [*Chadwick et al.*, 2005], as previously inferred by the BLM [*Ellis et al.*, 2004].

The use of both aerial and satellite images provided an opportunity to compare the utility of the two data formats for use in this type of analysis, and to evaluate the ease of data fusion. Aerial photographs, with their stereo viewing capability and high spatial resolution [e.g., *Casson et al.*, 2003], have been used extensively to characterize landslides and to produce landslide inventory maps.

The comparable spatial resolution of images from high-resolution satellite systems (such as QuickBird, IKONOS, and OrbView-3) and conventional aerial photos, and the availability of aerial photos well before the availability of commercial high-resolution satellite imagery have led to an inevitable and valuable pairing of aerial photos and satellite images for landslide change detection analyses.

The Present: Daily GPS Measurements

GPS has proven to be an effective tool for monitoring landslide movement with high precision [e.g., *Malet et al.*, 2002]. High spatial and temporal resolution positions on the landslide were collected using GPS in order to improve our ability to interpret the horizontal velocities for the Salmon Falls landslide derived from the image change detection results, accurately assess the ongoing hazard potential of the landslide in near real-time, and evaluate mechanisms of motion and response to changing precipitation conditions.

From February 2003 to April 2004, a network of autonomous GPS stations was installed at widely spaced locations on the landslide. The GPS receivers collected data for 4 hours each day, which permitted monitoring the day-to-day velocity and direction of movement of the slide. These data were downloaded in the field every 1–3 weeks. The technology exists that would allow the data to be automatically telemetered immediately after acquisition, allowing for a slide's movement and hazard potential to be evaluated in near real-time.

The use of a nearby, dedicated GPS base station and differential correction techniques greatly improved the accuracy of the raw data, and horizontal and vertical errors were about 2 mm and 1 cm, respectively. The time series nature of the data allows for least squares (best-fit line) corrections to be applied, which also reduces the effects of error.

The results show that the slide's total (three-dimensional) velocity was about 7–8 cm/yr in early 2003, with slightly higher velocities recorded at the station on the subsiding canyon rim (see Figure 3). These velocities were considerably lower than the up to 200 cm/yr velocities recorded by the BLM in the two previous years using laser theodolite surveys. The GPS data confirmed field reports

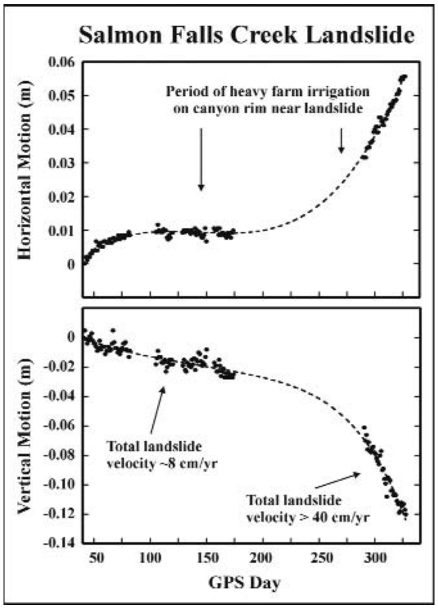

Fig. 3. Time series of positions for the autonomous GPS station on the upper headwall block (UB station) of the landslide (the portion of the canyon rim that is descending at the top of the slide; see Figure 2). The first day of the study (GPS day 47) was 16 February 2003. A clear increase in velocity is observed at all stations in late summer 2003, which occurred during a long period with little rainfall. Data were not acquired at this station between days 170 and 280 because a single receiver was rotated among all of the GPS stations during that period.

that the landslide's motion had slowed significantly. In September 2003, the velocity again increased to over 40 cm/yr, coinciding unexpectedly with the end of a significant dry period, a condition that is not considered conducive to landslide activity. This velocity increase may reflect shallow groundwater recharge due to extensive flood irrigation on nearby canyon-rim farms during the dry summer months.

The GPS data were also combined with the results of the image change detection study described above. Image change detection measures only two-dimensional (lateral) movement, but the GPS study measured total (three-dimensional) velocities for the landslide [*Chadwick et al.*, 2005].

With the assumption that the geometry of the detachment surface of the landslide and the ratios of horizontal to vertical movement have remained the same over time for a given part of the slide, a vertical component of the velocity was calculated and combined with the two-dimensional velocities measured in the image study, and total, three-dimensional velocities between 1990 and 2002 were calculated.

The results reveal that the landslide moved a total of about 12 m into Salmon Falls Creek Canyon since its activity began, which is consistent with field observations of the offset between the canyon rim and the headwall block.

Predicting the Future: Lidar Data and Flood Modeling

In the fall of 2002, airborne lidar data were acquired over an approximately 17-km^2 area on the landslide and in surrounding areas of Sinking Canyon. The data set was acquired with an Optech ALTM 2025 at 25 kHz (25,000 laser pulses per second) with an approximate horizontal posting of 1 m.

Post-acquisition processing has shown absolute vertical accuracies to be approximately 16 cm, while relative accuracies are approximately 5 cm. With more than 475,000 data points in the bald-earth data set alone (in which features such as trees and buildings have been removed via image processing, leaving only the bare ground surface), the canyon topography was modeled at intervals of 1 m. The DEM-derived image shown in Figure 1 was made from these data.

The lidar data were used for predictive flood hazard modeling, flood and landslide visualization, and surface roughness mapping. The DEM data were provided to the Idaho BLM for input into the U.S. Army Corps of Engineers' HEC-RAS (Hydrologic Engineering Centers River Analysis System) water surface profile model, and the National Weather Service's FLDWAV generalized flood routing program.

The lidar-derived DEM was also used for visualization of a "flooded" canyon by projecting different water surfaces at 1-m elevation intervals starting at 987 m (current creek level) to 1000 m throughout the canyon, simulating water levels that would result from breaching of the dams. Upstream flooding scenarios were also modeled by projecting lake levels that would result from increased dam-building. In addition, the bald-earth lidar data were used for surface roughness mapping and quantitative analyses of landslide morphological components in the Salmon Falls slide and in comparing the Salmon Falls landslide with the neighboring larger 1937 slide in Sinking Canyon (N. Glenn et al., submitted manuscript, 2004).

The High-Tech Future of Landslide Studies

This and related studies demonstrate the rich potential of using new technologies for landslide studies. Clearly, the advances of the past two decades in remote sensing, digital image processing, GPS, and GIS are revolutionizing the study of landslides and improving the ability of scientific and government agencies to monitor and manage landslide-prone areas. In particular, GPS can play an important role in monitoring landslide-prone areas for signs of current movement, and provide near real-time warnings of motion on slides that can endanger life and property. High-resolution imagery and topographic mapping can lead to improved understanding of landslide mechanics and hazard prediction. Continued research into methods of data collection, processing, and synthesis is needed to realize the full promise of these technologies for worldwide use in the coming decades.

Acknowledgments

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