THE IMPORTANCE OF PROTECTED AREAS AS NATURAL LANDSLIDE LABORATORIES

JEROME V. DE GRAFF[1], GREG M. STOCK[2]

[1] Department of Earth & Environmental Sciences, California State University, USA
[2] National Park Service, Yosemite National Park, Resources Management and Science, USA

ABSTRACT

Geological hazards such as landslides pose potential threats to people and infrastructure, and, accordingly, are a high priority for scientific study. However, the very presence of that infrastructure in developed areas can potentially influence landslide behavior, complicating efforts to assess the natural triggering and displacement mechanics of landslide events. Protected areas – such as natural reserves, conservation areas, and national parks – are particularly valuable as laboratories for landslide studies because they typically exhibit only those natural factors important for understanding landslide behavior. In this paper we examine the importance of protected areas as natural landslide laboratories, consider the benefits of long-term landslide investigation, discuss how protected areas may be used to monitor different landslide types, and present some of the key investigational and operational characteristics of suitable natural landslide laboratories.

Keywords: landslides, natural laboratories, long-term investigation, protected areas

1. Introduction

Geoscientists conduct much of their research outside the controlled laboratory setting familiar to chemists and physicists. Observations and samples are often collected in physically challenging locations and hypotheses must be validated in settings with many unconstrained variables. Some geologic phenomena, landslides prominently among them, have the potential to be hazardous to people and the built environment upon which people depend. The scientific study of landslides is therefore the first of many important steps in ensuring public safety (De Graff 2012). In order to derive quantitative data on landslide triggering mechanisms and deformational mechanics, natural laboratories for landslide research are desirable.

Geoscientists investigating landslides and landslide processes often must determine how both natural and anthropogenic factors have influenced a particular landslide occurrence. Deconvolving these factors can be a difficult task in landscapes with considerable human development or other alterations (Griffiths 1999; Burns 2010). Anthropogenic activities in the past, as well as ones contemporaneous with a landslide occurrence, can cause, magnify, or mask the natural factors influencing a particular event. Distinguishing between natural and anthropogenic factors is critical for understanding what triggered a landslide and influenced its movement in order to successfully mitigate the hazard and risk posed by present and future landslides.

In this paper we discuss the importance of protected areas, such as natural reserves or conservation areas, which are for the most part undeveloped and, therefore free of direct anthropogenic influences, as laboratories for landslide research. We herein use the term "landslide" in a general sense to encompass movements of masses of rock, sediments, or soil under the influence of gravity (Clague 2013). Where a specific type of landslide is referred to, the terminology follows Varnes (1978) and Cruden and Varnes (1996). From our own monitoring experience and familiarity with other efforts in the United States, we suggest what investigational and operational characteristics may make a protected area especially suitable for the long-term study of landslide phenomena. Some landslide types appear to be more often used as natural laboratories based on our review of the literature. We discuss how protected or other undeveloped areas may be used to monitor the natural factors influencing rock fall which is one of the landslide types less frequently the subject of this type of monitoring effort.

1.1 Landslide Study in Developed Versus Protected Areas

The 1979 Abbotsford landslide in Dunedin, New Zealand illustrates the difficulty in ascribing the relative importance of natural and anthropogenic factors of a landslide occurring in a developed area (Hancox 2008). This large and catastrophic landslide was intensely studied and yielded several conclusions about the relative influence of site characteristics and triggering factors. First, increased pore water pressure caused by a rising ground water level was deemed to be a very significant factor (Hancox 2008). This rising of a water level was related to both infiltration of higher rainfall amounts during the preceding 10 years and to leakage from a water pipeline within the upper area of the landslide (Hancox 2008). Removal of natural vegetation due to development

http://dx.doi.org/10.14712/23361980.2015.95
De Graff, J. V. – Stock, G. M. (2015): The importance of protected areas as natural landslide laboratorie
AUC Geographica, 50, No. 2, pp. 165–172

activities was also considered a possible contributing anthropogenic factor causing changes to infiltration and the water level, but its significance could not be determined for lack of data (Hancox 2008). Second, landslide development was found to have been enhanced by the natural progressive downcutting of an adjacent creek (Hancox 2008). However, quarrying of a large volume of sand from the toe of the slope 10 years prior to the landslide event was also determined to be a significant slope-destabilizing factor (Hancox 2008). An unquantifiable, but deemed significant, factor influencing the landslide was urban development, which added weight to the slope, modified storm water infiltration, and allowed water from local waterline breaks to enter the slope (Hancox 2008). The uncertainty in fully distinguishing the extent to which the Abbotsford landslide was influenced by both natural and anthropogenic factors influenced the selection of suitable mitigation measures. This uncertainty also complicated identifying strategies for avoiding or mitigating future landslides in similar terrain in this part of New Zealand.

In order to develop sufficient data to validate hypotheses and determine relationships between natural factors and landslide responses, study must take place over an extended period of time. It often requires carrying out what can be termed investigative monitoring (DeGraff 2011). Landslides in highly developed areas are problematic for use in long-term studies due to the more immediate need to mitigate the landslide's actual or threatened impact to surrounding residences, businesses, and infrastructure; the affected population is unlikely to support the idea of withholding mitigation actions during many years of investigative monitoring. Accordingly, landslides suitable for extended study of natural factors influencing landslide formation and movement are more likely to be found in natural environments. Some landslides suitable for extended study may be within the vicinity of homes, roads, pipelines, power lines and similar human infrastructure; landslides in the areas where these anthropogenic influences are minor could still serve as suitable sites for the study of natural factors. Some areas where the land use is restricted to low-impact activities such as hiking, biking, or grazing might also serve as protected areas for landslide study. However, landslides found in protected areas such as land managed by private or governmental entities to preserve natural landscapes, protect wildlife habitat or watersheds, or promote scientific investigation are the most desirable for long-term study. In such settings, landslides can serve as laboratories where the variables important to landslide triggering and development are limited to natural factors.

The explicit recognition of a landslide in an undeveloped area serving as a natural laboratory was made in a U.S. Geological Survey (USGS) publication describing multi-year research findings for the Slumgullion earth flow (Varnes and Savage 1996). The Slumgullion earth flow in southwestern Colorado (Figure 1A) is an outstanding example of a landslide in a protected area that provides significant insight into natural factors influencing landslide triggering and morphological development. While roads and some seasonal residences are located in the vicinity of the earth flow, their location does not affect the natural processes influencing on the earth flow. The earth flow and surrounding area are located on public land managed by the U.S. Bureau of Land Management (BLM) and the U.S. Forest Service (USFS). Consequently, the location has remained in natural conditions. Since 1996, continuing study of the Slumgullion earth flow by the USGS and other geologists have yielded valuable insights on such factors as its rate of movement, internal deformation, and the seismic signature generated by movement on the basal slip surface and side-boundary faults (Messerich and Coe 2003; Baum et al. 2003; Coe et al. 2003; Parise 2003; Parise et al. 2003; Coe et al. 2009; Schultz et al. 2009a; Gomberg et al. 2011; Walter et al. 2013).

1.2 Benefits of Long-term Landslide Investigation

Investigating the formation, kinematics, morphology, and response to triggering events of landslides in a natural setting has numerous benefits. Systematic landslide studies within a geographic region, of a particular landslide type, or of landslide triggering mechanisms offer valuable information for understanding the formative landslide processes, establishing hazard and risk relationships, and identifying important design constraints for mitigating measures (Keefer 1994; De Graff 1994; Wieczorek and Snyder 2009; Cannon et al. 2010). The depth of understanding produced by detailed long-term study of a particular landslide feature or landslide type can potentially reveal previously unrecognized aspects of these phenomena. The measurements carried out at the Slumgullion earth flow, which enabled researchers to detect atmospheric tides as a component of movement, is but one example (Schulz et al. 2009b).

Water is one of the most significant factors associated with initiation and movement of landslides. However, water content, saturation ratio and pore-water pressure at the time a landslide occurs, or the landslide responses to water infiltration from rainfall or snowmelt, are not easily determined after the landslide occurrence. Long-term investigations such as those at Minor Creek (northern California) and Johnson Creek (western Oregon) have yielded important insights into the influence of water on landslide movement (Iverson and Major 1987; Priest et al. 2008; 2011). At the complex landslide feature in Minor Creek, the motion of the landslide was found to be controlled by both the near-surface hydraulic gradient and pore-water pressure waves initiated by intermittent rainfall (Iverson and Major 1987). The translational landslide in local bedrock at Johnson Creek provided data demonstrating how movement was initiated and accelerated by rainfall-induced pore-pressure waves (Priest et al. 2008; 2011).

Another benefit from long-term detailed studies of landslides in undeveloped areas is providing data that are useful for modeling landside phenomena and validating new methods of numerical analyses (Iverson and Major 1987; Guzzetti et al. 2003; Gomberg et al. 2011; Brückl et al. 2013). The use of landslides as natural laboratories can also serve to test and refine study techniques and technology, which generally validates and improves their widespread application (Squarzoni et al. 2003; Coe et al. 2003; Casson et al. 2005; Jomard et al. 2010; Berger et al. 2010; Stock et al. 2012; Zimmer et al. 2012; Booth et al. 2013). Examples of recent techniques and technology include the application of SAR interferometry, the utility of high-resolution 3D imagery, and new designs for channel bed erosion sensors.

2. Characteristics of a suitable natural laboratory for landslides

A crucial suitability factor for a potential natural landslide laboratory is being able to protect that area from human activity that might alter natural factors affecting the landslide. Table 1 provides a sampling of landslides in undeveloped locations in North America and Europe currently or recently used as natural laboratories (Figure 1). The landslides listed in Table 1 are only representative of natural laboratories in undeveloped locations, rather than a comprehensive listing. All listed landslide study sites in the United States except for Minor Creek and Johnson Creek are on public land managed by governmental agencies such as the USFS, BLM, and National Park Service (NPS); these agencies have the authority and responsibility for controlling land use activities where the study areas are found. Minor Creek is on land owned and managed by a single timber company. At Johnson Creek, protection is achieved by an Oregon Department of Transportation right-of-way agreement.

Collaboration between governmental entities, universities, and research institutes provides the protection for the landslide study sites listed in Austria, France and Switzerland (Table 1). Illgraben, the Swiss study site (Figure 1B), illustrates how such collaborations can be carried out (B. McArdell, Swiss Federal Institute WSL, Written Comm., Oct. 2014). Most of the land outside the city limits of Susten, on the alluvial fan, is under the control of that municipality. Regulation guided by federally mandated, hazard-intensity maps provide protection of the channel where debris flows pass and are deposited. Most of the land within the Illgraben catchment is simply too hazardous for any activities other than seasonal grazing or use as a nature preserve. Consequently, researchers from entities like the Swiss Federal Institute for Forest, Snow, and Landscape Research are able to carry out long-term debris flow monitoring there (B. McArdell, Swiss Federal Institute WSL, Written Comm., Oct. 2014). Review of published findings and associated Internet sites suggests similar collaborations ensure the protection of the listed landslide study sites found in Austria and France (Table 1).

Tab. 1 Examples of landslide monitoring in protected areas within the United States and Europe.

Name	Landslide Type	Location	Main Study Period
Chalk Cliffs[1]	Debris flows	Rocky Mountains, CO, USA	2008–Ongoing
Cleveland Corral[1]	Earth flow	Sierra Nevada, CA, USA	1997–Ongoing
Doren[2]	Complex slide	Eastern Alps, Austria	2000–Ongoing
Ferguson[3]	Rock slide	Sierra Nevada, CA, USA	2006–2012
Gradenbach[4,5]	Deep-seated gravitational slope deformation	Eastern Alps, Austria	1999–Ongoing
Illgraben[6]	Debris flows	Valais Alps, Switzerland	2001–Ongoing
Johnson Creek[1]	Rock slide	SW coast OR, USA	2004–Ongoing
La Clapière[7]	Rock slide	Southern Alps, France	1987–Ongoing
La Valette[8]	Complex slide	Southern Alps, France	1988–Ongoing
Minor Creek[9]	Complex slide	Coast Range, CA, USA	1973–Ongoing
Slumgullion[10]	Earth flow	Rocky Mountains, CO, USA	1990–Ongoing
Yosemite[11]	Rock falls, rock slides	Sierra Nevada, CA, USA	1980–Ongoing

[1] http://landslides.usgs.gov/monitoring/, [2] Roncat et al. 2013, [3] Harp et al. 2008, [4] Brückl et al. 2013, [5] http://gbonline.tugraz.at/gb_welcome_en.php, [6] McArdell et al. 2003, [7] http://gravitaire.oca.eu/spip.php?rubrique15, [8] Squarzoni et al. 2003, [9] Iverson and Major 1987, [10] Varnes and Savage 1996, [11] Stock et al. 2013

In general, initial identification of landslides suitable for use as natural landslide laboratories result from studies initiated in response to some actual or threatened impact. A number of landslides listed in Table 1 came to the attention of researchers because of adverse effects to roads or the potential for altering river flow. For example, the Ferguson rock slide in central California (Figure 1C) completely blocked a major highway used to access a local community and Yosemite National Park, and threatened to dam a major river (Harp et al. 2008). Other landslides were identified due to the effects of much earlier movement. For example, movement of the Slumgullion earth flow nearly 700 years ago was responsible for forming Lake San Cristobal (Figure 1A; Varnes and Savage 1996), and the persistence of this natural dam stimulated interest in the earth flow that had created it.

There are both investigational and operational characteristics that make a landslide in an undeveloped area

Fig. 1 Examples of protected areas in North America and Europe used as natural landslide laboratories. (a) The Slumgullion earth flow in the Rocky Mountains of Colorado, USA, photograph courtesy of the U.S. Geological Survey; (b) The Illgraben debris flow study area in the Valais Alps, Switzerland, photograph by Franz Iseli; (c) The Ferguson Rock Slide in the Sierra Nevada mountains of California, USA.

suitable for use as a natural laboratory. Investigational characteristics include: 1) the availability of existing data such as maps of the local geology and landslide features, 2) identification of movement type and amount, and 3) the likelihood that additional movement will occur. Operational characteristics include: 1) being present within an undeveloped area, 2) a low likelihood of intentional or inadvertent human interference with study efforts, and 3) sufficient access for repetitive measurements and to install and maintain instrumentation.

2.1 Investigational Characteristics

Initial investigation of a landslide produces data on the triggering mechanism, mode of movement, and internal deformation. This data provides a starting point for further study. The initial understanding of the landslide serves as the basis for designing specific long-term monitoring to address particular study objectives. Whether this happens or not is largely dependent on the mission or research interest of organizations initially involved with the landslide, or the interests of individual researchers within reasonable geographic proximity of the landslide.

Landslide monitoring and investigation is a significant component of the geologic hazards mission of the USGS (see http://landslides.usgs.gov/monitoring/). Thus, it is not surprising that USGS geologists contributed to research for all the United States landslides noted in Table 1. As one example, the real-time monitoring of the Cleveland Corral landslide was undertaken by the USGS in cooperation with the USFS to provide timely emergency response for any significant movement, which would threaten U.S. Highway 50 (Reid and LaHusen 1998). Blockage of Highway 50 and temporary damming of the South Fork of the American River by the nearby Mill Creek landslide in 1997 had heightened concern about future movement by the Cleveland Corral landslide.

Another important investigational characteristic is the amount of movement occurring within a landslide being considered for long-term monitoring. All or a significant part of the landslide must be sufficiently active to further the research undertaken. This can be slow but measureable deformation such as that measured at the Slumgullion earth flow, or brief episodic events such as those occurring at Illgraben (Table 1). Given the expenditure of time and funds for investigative monitoring, landslide movement needs to occur at a frequency sufficient to warrant continued study. The Ferguson rock slide is no longer monitored partly because the movement nearly ceased thus reducing its hazard, and, in turn, its risk (Table 1). Significant reactivation of movement took place beginning in 2006 on this pre-existing rock slide (Harp et al. 2008). Real-time monitoring of the Ferguson rock slide during the next few years showed that movement consistently accelerated within days following major rainfall (De Graff et al. 2014). Subsequently, total cumulative movement decreased during several years of lower-than-normal total rainfall to the point that only detectable, small movement was recorded even during significant storm events.

2.2 Operational Characteristics

As noted previously, the availability of a landslide for long-term study is a characteristic more likely to be found for a landslide in a protected area or relatively undeveloped area rather than in a densely developed area. The generally lower likelihood that a landslide poses a risk to the smaller population of an undeveloped area in the landslide's vicinity reduces the need for immediate mitigation of further movement. Also, the land values in undeveloped areas do not typically support the cost-benefit ratio of many mitigation measures commonly applied to urban landslides. Before committing to using a particular landslide as a natural laboratory, it would be important to determine the current and planned land management of adjacent areas. Timber harvest, access road construction, or similar land uses could alter groundwater patterns influencing landslides. The Ferguson rock slide (Figure 1C) was wholly within a part of a national forest managed as a scenic river corridor and for wildlife habitat. This ensured that no land use activity occurred that might alter the natural processes involved with this landslide.

The smaller human population present in the vicinity of a landslide in an undeveloped area limits the likelihood of intentional or inadvertent interference with monuments and instruments installed as part of long-term studies. However, study design should consider how to limit the effect of such interference. Depending on the arrangements with the land owner or whoever has control over the likely access points to the landslide, there may be ways to further reduce vulnerability to human interference. A closure order to public entry was issued by the USFS for the Ferguson rock slide and surrounding national forest land. Later, fencing and traffic control associated with installation of a road detour further limited the ability of individuals to reach the landslide.

Accessibility is another operational characteristic important in selection of a landslide for long-term study. Seasonal changes may render access more difficult and, thereby, affect the timing of certain repetitive measurements or justify the costs for remote recording or transmitting capability. Some instrumentation may be unsuitable because it is too heavy, requires emplacement using equipment that cannot reach the landslide, or does not justify the expense of helicopter delivery. Access is also a consideration for operating instrumentation dependent on maintenance including scheduled battery replacement or seasonal effects on solar panels efficiency. At the Ferguson rock slide (Figure 1C), instrumentation capable of transmitting movement data in real-time via radio and dedicated phone line was installed (De Graff et al. 2014). The urgency of receiving this information during the impending rainy season justified using a helicopter for emplacing the instruments. This approach was facilitated by the availability of a USFS helicopter and a nearby heli-spot operated by Yosemite National Park. While the instrumentation could operate for a year on batteries, it required an annual trek by a crew to carrying replacements up a long, steep trail. A companion system monitoring the water level of the river upstream and downstream from the Ferguson rock slide reported through a battery-powered satellite transmission system (De Graff 2011). The battery was recharged by solar panels. Positioned in the bottom of a steep-sided canyon, the solar panels were incapable of fully charging the battery during the winter when the low sun angle placed the monitoring station in shadows for much of the day. Batteries recharged off-site needed to be brought to the site every ten days during the winter months to ensure data were reported via the satellite system.

Another operational characteristic that may be important is that some protected areas such as national parks or wilderness areas may have rules limiting the extent, duration, or visibility of scientific instrumentation on landslides. In these cases, the deployment of instrumentation may be of short duration, or may have to be concealed or camouflaged to reduce the visual impact to visitors. There may also be rules limiting the type of equipment that can be used for transporting or installing instruments. Such rules may constrain the instrumentation suitable for long-term study in these protected areas.

3. Investigating an individual landslide versus areas with multiple landslides

Table 1 is not a comprehensive list of landslides in protected areas presently or recently used as natural laboratories. However, it is representative of some well-known examples and illustrates the predominance of individual, large landslides being used for this purpose. This listing also demonstrates that all landslide types (Varnes 1978; Hungr et al. 2014) are not equally represented in these long-term study efforts. The potential for destructive effects is not limited to large, individual landslides similar to the ones noted in Table 1. Two landslide types, debris flows and rock falls, are also notable for their destructive capability because they move rapidly and can travel some distance from their initiation point.

Debris flows and rock falls range from small to large discrete events often affecting the same general area. It can be difficult to identify undeveloped areas where debris flows will occur frequently enough to permit the kind of studies comparable to those applied to large individual landslides. Illgraben (Figure 1B) and Chalk Cliffs are two exceptions where watersheds are subject to repeated debris flow occurrence on a time scale consistent with long-term study (Table 1). Both of these study areas utilize the tendency of debris flows to flow down existing channels. In contrast to debris flows, rock fall will often be concentrated along a linear area defined by escarpments composed of susceptible bedrock where long-term study can be carried out.

Yosemite Valley in Yosemite National Park represents a somewhat unique case illustrating the importance of protected area status for long-term studies of rock falls. The ~1 km-tall, glacially steepened cliffs of Yosemite Valley experience many rock falls each year, ranging from small events on the order of 1 cubic meter in volume to larger events involving hundreds of cubic meters (Figure 2; Stock et al. 2013); the largest historical rock falls are hundreds of thousands of cubic meters in volume. The cliffs of Yosemite Valley are within a designated wilderness area within a national park, and are thus essentially free of anthropogenic influences. Conversely, the floor of Yosemite Valley, where rock fall talus is deposited, is relatively densely developed with campgrounds, cabins, restaurants, and other amenities serving approximately four million visitors a year. The combination of natural rock falls occurring in wilderness settings along with the substantial hazard and risk posed by these rock falls has led to detailed and long-term study and documentation of rock falls and rock-fall hazard in Yosemite Valley (e.g., Guzzetti et al. 2003; Stock et al. 2011, 2012, 2013; Wieczorek and Jäger 1996; Wieczorek and Snyder 1999; Wieczorek et al. 2000, 2008; Zimmer et al. 2012). Documentation of rock fall events, of which there are approximately 40–60 per year, extends back to 1857; the database of rock falls in Yosemite (Stock et al. 2013) now contains more than 1,000 events. This database can be used to identify the most active cliffs and lithologies for rock falls, the common environmental conditions that trigger rock falls, and the most frequent types of rock-fall impacts to human infrastructure.

The NPS, USGS, and academic researchers recently completed a comprehensive study of rock-fall hazard and risk in Yosemite Valley (Stock et al. 2014). This work focused on the evidence of past rock-fall activity in the form of boulders at and beyond the edge of the active talus slope. Yosemite's status as a protected area was vitally important in this regard, as these boulders were mapped with reasonable certainty that they had not be removed or relocated following their deposition. The undisturbed nature of rock fall deposits on the valley floor also allowed for accurate dating of their deposition (Stock and Uhrhammer 2010; Cordes et al. 2013; Stock et al. 2014). Based on this research, the NPS, which solely manages the park, was able to take aggressive steps to reduce risk by removing or relocating buildings and campsites from hazardous areas (Stock and Collins 2014).

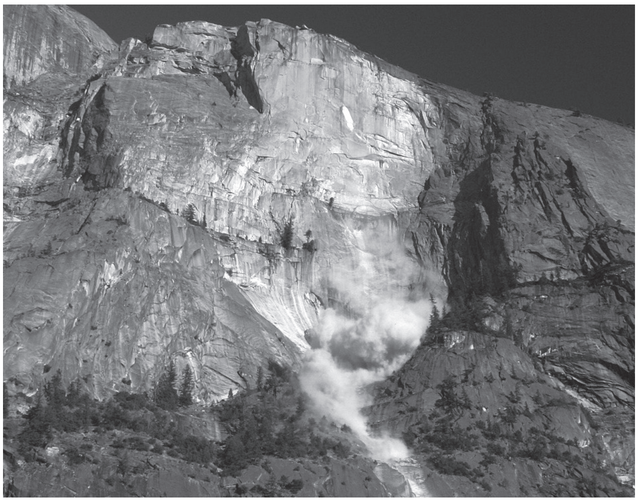

Fig. 2 A rock fall with a volume of approximately 150 cubic meters that fell on 24 July 2010 from a cliff west of Half Dome in Yosemite Valley, Yosemite National Park, California. The cliffs of Yosemite Valley are in a designated wilderness area within a national park, and thus represent an important natural laboratory for investigating rock falls and other landslide phenomena. Photograph courtesy of Ludovina Fernandez.

4. Conclusions

Landslides in protected or other undeveloped areas offer an opportunity to study in isolation the natural factors responsible for their formation, kinematics, morphology, and response to triggering events. The smaller human population, or even lack of population, in protected areas makes long-term study of landslides possible while limiting or avoiding introduction of anthropogenic factors. The suitability of protected areas to serve as natural landslide laboratories is facilitated by studying landslides that take advantage of both investigational characteristics, such as activity level, and operational characteristics, such as accessibility. Although a number of these natural laboratories exist, most study large individual landslides. There is a need for more natural laboratories devoted to the study of landslide types, such as debris flows and rock falls, involving multiple events rather than movements by the same landslide. The addition of any new landslides as natural laboratories will likely follow the pattern of existing ones; a significant landslide will take place in a suitable area resulting in an initial study. The initial study will stimulate an agency or research collaborative to seek funding for subjecting the landslides to long-term study. The investigational and operational characteristics previously described should be considered in determining whether a particular landslides is suitable for study in this manner.

Landslide study in protected areas can yield multiple benefits. These natural laboratories provide an ideal situation for testing instrumentation and investigative techniques that can then be applied to other landslide investigations with greater confidence in their validity and accuracy. Similarly, the long-term studies carried out in protected areas generate data that constrain models being developed to demonstrate landslide initiation, movement rates, kinematics, and provide reliable criteria for designing mitigation measures at locations with similar characteristics. In this regards, long-term study of landslides in protected areas is favorable for producing data useful for forensic investigations of landslides in developed areas to aid distinguishing the extent to which natural and anthropogenic factors are responsible for a particular landslide. This is especially important when considering the effect of water on triggering landslide movement, controlling the rate of movement, and its relationship to rainfall and snowmelt sources. The findings established in this manner could provide insight by defining how natural factors influence certain movement or deformation responses, identifying characteristic surface features and subsurface morphology, or determining stress-strain or pore-pressure constraints.

Scientific knowledge is advanced by these studies when new principles and understandings are determined from these long-term data. Whether stated explicitly, as in the case of Johnson Creek landslide in the United States, or implied for long-term study at other landslides, such as LaClapière in France, research results are expected to be applicable to other landslides similar to the one under long-term study. The degree to which such findings are truly widely applicable is enhanced by achieving similar results at more than one long-term landslide study site, or by undertaking focused studies at a number of similar landslides to specifically test a finding. Ultimately, detailed studies of landslides in natural settings provide context for understanding landslides occurring in developed areas and may clarify the nature of human influence on landslide occurrence in urban settings.

Acknowledgements

The authors wish to thank their colleagues involved with long-term landslide monitoring in undeveloped areas for their time and insights when discussing aspects of their projects. The two anonymous reviewers provided suggestions giving us the opportunity to materially improve the clarity and readability of the final manuscript.

REFERENCES

BAUM, R. L., SAVAGE, W., WASOWSKI, J. (2003): Mechanics of earth flows. In Proceedings of the International Conference FLOWS, Sorrento, Italy.

BERGER, C., MCARDELL, B. W., FRITSCHI, B., SCHLUNEGGER, F. (2010): A novel method for measuring the timing of bed erosion during debris flows and floods. Water Resources Research, 46(2), W02502. http://dx.doi.org/10.1029/2009WR007993

BOOTH, A. M., LAMB, M. P., AVOUAC, J. P., DELACOURT, C. (2013): Landslide velocity, thickness, and rheology from remote sensing: La Clapière landslide, France. Geophysical Research Letters, 40(16), 4299–4304. http://dx.doi.org/10.1002/grl.50828

BRÜCKL, E., BRUNNER, F. K., LANG, E., MERTL, S., MÜLLER, M., STARY, U. (2013): The Gradenbach Observatory – monitoring deep-seated gravitational slope deformation by geodetic, hydrological, and seismological methods. Landslides, 10(6), 815–829. http://dx.doi.org/10.1007/s10346-013-0417-1

BURNS, S. F. (2015): Urban Landslides: Challenges for Forensic Engineering Geologists and Engineers. In Engineering Geology for Society and Territory-Volume 5. Springer International Publishing, 3–9. http://dx.doi.org/10.1007/978-3-319-09048-1_1

CANNON, S. H., GARTNER, J. E., RUPERT, M. G., MICHAEL, J. A., REA, A. H., PARRETT, C. (2010): Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. Geological Society of America Bulletin, 122(1–2), 127–144. http://dx.doi.org/10.1130/B26459.1

CASSON, B., DELACOURT, CH., ALLEMAND, P. (2005). Contribution of multi-temporal remote sensing images to characterize landslide slip surface? Application to the La Clapière landslide (France). Natural Hazards and Earth System Science 5(3), 425–437. http://dx.doi.org/10.5194/nhess-5-425-2005

CLAGUE, J. J. (2013): Landslides, In BOBROWSKY, P. T., ed., Encyclopedia of Natural Hazards: Springer, Heidleberg, 594–602. http://dx.doi.org/10.1007/978-1-4020-4399-4_212

COE, J. A., ELLIS, W. L., GODT, J. W., SAVAGE, W. Z., SAVAGE, J. E., MICHAEL, J. A., KIBLER, J. D., POWERS, P. S., LIDKE, D. J., DEBRAY, S. (2003): Seasonal movement of the Slumgullion landslide determined from Global Positioning System surveys and field instrumentation, July 1998 – March 2002. Engineering Geology, 68(1), 67–101. http://dx.doi.org/10.1016/S0013-7952(02)00199-0

COE, J. A., MCKENNA, J. P., GODT, J. W., BAUM, R. L. (2009): Basal-topographic control of stationary ponds on a continuously moving landslide. Earth Surface Processes and Landforms, 34(2), 264–279. http://dx.doi.org/10.1002/esp.1721

CORDES, S. E., STOCK, G. M., SCHWAB, B. E., GLAZNER, A. F. (2013): Supporting evidence for a 9.6 ± 1 ka rock fall originating from Glacier Point in Yosemite Valley, California. Environmental and Engineering Geoscience XIX, 345–361. http://dx.doi.org/10.2113/gseegeosci.19.4.345

CRUDEN, D. M., VARNES, D. J. (1996): Landslide Types and Processes, in TURNER, A. K., AND SCHUSTER, R. L., eds., Landslides: Investigations and Mitigation: Transportation Research Board, Special Report 247, Chapter 3, 36–75.

DE GRAFF, J. V. (1994): The geomorphology of some debris flows in the southern Sierra Nevada, California. Geomorphology, 10(1), 231-252. http://dx.doi.org/10.1016/0169-555X(94)90019-1

DE GRAFF, J. V. (2011): Perspectives for Systematic Landslide Monitoring. Environmental & Engineering Geoscience, 17(1), 67–76. http://dx.doi.org/10.2113/gseegeosci.17.1.67

DE GRAFF, J. V. (2012): Solving the dilemma of transforming landslide hazard maps into effective policy and regulations. Natural Hazards and Earth System Science, 12(1), 53–60. http://dx.doi.org/10.5194/nhess-12-53-2012

DE GRAFF, J. V., GALLEGOS, A. J., REID, M. E., LAHUSEN, R. G., DENLINGER, R. P. (2014): Using monitoring and simulation to define the hazard posed by the reactivated Ferguson Rockslide, Merced Canyon, California. Natural Hazards, 76(2), 769–789. http://dx.doi.org/10.1007/s11069-014-1518-4

GOMBERG, J., SCHULZ, W., BODIN, P., KEAN, J. (2011): Seismic and geodetic signatures of fault slip at the Slumgullion Landslide Natural Laboratory, Journal of Geophysical Research, 116, B09404. http://dx.doi.org/10.1029/2011JB008304

GRIFFITHS, J. S. (1999): Proving the occurrence and cause of a landslide in a legal context. Bulletin of Engineering Geology and the Environment, 58(1), 75–85. http://dx.doi.org/10.1007/s100640050070

GUZZETTI, F., REICHENBACH, P., WIECZOREK, G. F. (2003): Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. Natural Hazards and Earth System Sciences, 3, 491–503. http://dx.doi.org/10.5194/nhess-3-491-2003

HANCOX, G. T. (2008), The 1979 Abbotsford Landslide, Dunedin, New Zealand: a retrospective look at its nature and causes. Landslides, 5(2), 177–188. http://dx.doi.org/10.1007/s10346-007-0097-9

HARP, E. L., REID, M. E., GODT, J. W., DEGRAFF, J. V., GALLEGOS, A. J. (2008). Ferguson rock slide buries California State Highway near Yosemite National Park. Landslides, 5(3), 331–337. http://dx.doi.org/10.1007/s10346-008-0120-9

HUNGR, O., LEROUEIL, S., PICARELLI, L. (2014): The Varnes classification of landslide types, an update. Landslides, 11(2), 167–194. http://dx.doi.org/10.1007/s10346-013-0436-y

IVERSON, R. M., MAJOR, J. J. (1987): Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: Physical interpretation of empirical relations. Geological Society of America Bulletin, 99(4), 579–594. http://dx.doi.org/10.1130/0016-7606(1987)99<579:RGFASM>2.0.CO;2

JOMARD, H., LEBOURG, T., GUGLIELMI, Y., TRIC, E. (2010): Electrical imaging of sliding geometry and fluids associated with a deep seated landslide (La Clapière, France). Earth Surface Processes and Landforms, 35(5), 588–599. http://dx.doi.org/10.1002/esp.1941

KEEFER, D. K. (1994): The importance of earthquake-induced landslides to long-term slope erosion and slope-failure hazards in seismically active regions. Geomorphology, 10(1), 265–284. http://dx.doi.org/10.1016/0169-555X(94)90021-3

MCARDELL, B. W., ZANUTTIGH, B., LAMBERTI, A., RICKENMANN, D. (2003): Systematic comparison of debris flow laws at the Illgraben torrent, Switzerland. In Debris flow Mechanics and Mitigation Conference, Mills Press, Davos, 647–657.

MESSERICH, J. A., COE, J. A. (2003): Topographic map of the active part of the Slumgullion landslide on July 31, 2000, Hinsdale County, Colorado. US Geological Survey.

PARISE, M. (2003): Observation of surface features on an active landslide, and implications for understanding its history of movement. Natural Hazards and Earth System Science, 3(6), 569–580. http://dx.doi.org/10.5194/nhess-3-569-2003

PARISE, M., COE, J. A., SAVAGE, W. Z., VARNES, D. J. (2003): The Slumgullion landslide (southwestern Colorado, USA): investigation and monitoring. In Proceedings of the International Conference FLOWS, Sorrento, Italy.

PRIEST, G. R., ALLAN, J. C., NIEM, A. R., NIEM, W. A., DICKENSON, S. E. (2008): Johnson Creek Landslide Research Project, Lincoln County, Oregon: Final Report to the Oregon Department of Transportation. Oregon Department of Geology and Mineral Industries Special Paper 40, 227 pp.

PRIEST, G. R., SCHULZ, W. H., ELLIS, W. L., ALLAN, J. A., NIEM, A. R., NIEM, W. A. (2011): Landslide stability: role of rainfall-induced, laterally propagating, pore-pressure waves. Environmental & Engineering Geoscience, 17(4), 315–335. http://dx.doi.org/10.2113/gseegeosci.17.4.315

REID, M. E., LAHUSEN, R. G. (1998): Real-time Monitoring of Active Landslides Along Highway 50, El Dorado County. California Geology, 51(3), 17–20.

RONCAT, A., GHUFFAR, S., SZÉKELY, B., DORNINGER, P., RASZTOVITS, S., MITTELBERGER, M., KOMA, Z., KWARCZYK, D., PFEIFER, N. (2013): A natural laboratory – Terrestrial laser scanning and auxiliary measurements for studying an active landslide: 2nd Joint International Symposium on Deformation Monitoring.

SCHULZ, W. H., MCKENNA, J. P., KIBLER, J. D., BIAVATI, G. (2009a): Relations between hydrology and velocity of a continuously moving landslide – evidence of pore-pressure feedback regulating landslide motion? Landslides, 6(3), 181–190. http://dx.doi.org/10.1007/s10346-009-0157-4

SCHULZ, W. H., KEAN, J. W., WANG, G. (2009b): Landslide movement in southwest Colorado triggered by atmospheric tides. Nature Geoscience, 2(12), 863–866. http://dx.doi.org/10.1038/ngeo659

STOCK, G. M., AND UHRHAMMER, R. A. (2010): Catastrophic rock avalanche 3600 years BP from El Capitan, Yosemite Valley, California. Earth Surface Processes and Landforms, 35, 941–951. http://dx.doi.org/10.1002/esp.1982

STOCK, G. M., COLLINS, B. D. (2014): Reducing rockfall risk in Yosemite National Park. Eos, 95(29), 261–263. http://dx.doi.org/10.1002/2014EO290002

STOCK, G. M., BAWDEN, G. W., GREEN, J. K., HANSON, E., DOWNING, G., COLLINS, B. D., BOND, S., LESLAR, M. (2011): High-resolution three-dimensional imaging and analysis of rock falls in Yosemite Valley, California. Geosphere, 7(2), 573–581. http://dx.doi.org/10.1130/GES00617.1

STOCK, G. M., MARTEL, S. J., COLLINS, B. D., HARP, E. L. (2012): Progressive failure of sheeted rock slopes: the 2009–2012 Rhombus Wall rock falls in Yosemite Valley, California, USA. Earth Surface Processes and Landforms, 37, 546–561. http://dx.doi.org/10.1002/esp.3192

STOCK, G. M., COLLINS, B. D., SANTANIELLO, D. J., ZIMMER, V. L., WIECZOREK, G. F., SNYDER, J. B. (2013): Historical rock falls in Yosemite National Park, California (1857–2011). U.S. Geological Survey Data Series 746. www.pubs.usgs.gov/ds/746/

STOCK, G. M., LUCO, N., COLLINS, B. D., HARP, E. L., REICHENBACH, P., FRANKEL, K. L. (2014): Quantitative rock-fall hazard and risk assessment for Yosemite Valley, Yosemite National Park, California. U.S. Geological Survey Scientific Investigations Report 2014-5129. www.pubs.usgs.gov/sir/2014/5129/

SQUARZONI, C., DELACOURT, C., ALLEMAND, P. (2003): Nine years of spatial and temporal evolution of the La Valette landslide observed by SAR interferometry. Engineering Geology, 68(1), 53–66. http://dx.doi.org/10.1016/S0013-7952(02)00198-9

VARNES, D. J. (1978): Landslide types and processes, In SCHUSTER, R. L., KIRZEK, R. J. (Eds.), Landslide Analysis and Control: Washington, D. C., National Academy Press, Transportation Research Board, National Academy of Sciences, Special Report 176, 12–33.

VARNES, D. J., SAVAGE, W. Z. (Eds.). (1996): The Slumgullion earth flow: a large-scale natural laboratory. U.S. Geological Survey Bulletin 2130, 1–4.

WALTER, M., GOMBERG, J., SCHULZ, W., BODIN, P., JOSWIG, M. (2013): Slidequake generation versus viscous creep at softrock-landslides: synopsis of three different scenarios at Slumgullion landslide, Heumoes slope, and Super-Sauze mudslide. Journal of Environmental and Engineering Geophysics, 18(4), 269–280. http://dx.doi.org/10.2113/JEEG18.4.269

WIECZOREK, G. F., JÄGER, S. (1996): Triggering mechanisms and depositional rates of postglacial slope-movement processes in the Yosemite Valley, California. Geomorphology, 15, 17–31. http://dx.doi.org/10.1016/0169-555X(95)00112-I

WIECZOREK, G. F., SNYDER, J. B. (1999): Rock falls from Glacier Point above Camp Curry, Yosemite National Park, California. U.S. Geological Survey Open-File Report 99-385.

WIECZOREK, G. F., SNYDER, J. B. (2009): Monitoring slope movements, in Young, R., and Norby, L, Geological Monitoring: Boulder, Colorado, Geological Society of America, 245–271.

WIECZOREK, G. F., SNYDER, J. B., WAITT, R. B., MORRISSEY, M. M., UHRHAMMER, R. A., HARP, E. L., NORRIS, R. D., BURSIK, M. I., FINEWOOD, L. G. (2000): Unusual July 10, 1996, rock fall at Happy Isles, Yosemite National Park, California. Geological Society of America Bulletin, 112 (1), 75–85. http://dx.doi.org/10.1130/0016-7606(2000)112<75:UJRFAH>2.0.CO;2

WIECZOREK, G. F., STOCK, G. M., REICHENBACH, P., SNYDER, J. B., BORCHERS, J. W., GODT, J. W. (2008): Investigation and hazard assessment of the 2003 and 2007 Staircase Falls rock falls, Yosemite National Park, California, USA. Natural Hazards and Earth System Sciences, 8, 421–432. http://dx.doi.org/10.5194/nhess-8-421-2008

ZIMMER, V. L., COLLINS, B. D., STOCK, G. M., SITAR, N. (2012): Rock fall dynamics and deposition: an integrated analysis of the 2009 Ahwiyah Point rock fall, Yosemite National Park, USA. Earth Surface Processes and Landforms, 37, 680–691. http://dx.doi.org/10.1002/esp.3206

Jerome V. De Graff
Department of Earth & Environmental Sciences
California State University, 2576 East San Ramon Ave.
M/S ST24, Fresno, CA 93740 USA
E-mail: jdegraff@csufresno.edu

Greg M. Stock
National Park Service, Yosemite National Park
Resources Management and Science
PO Box 700, El Portal, California 95318 USA
E-mail: greg_stock@nps.gov