Analysis of Hydrologic Factors at the Deer Run Heights landslide in Jeffersonville, VT

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Contents

1. Thesis

The silty-clay horizons at Deer Run Ridge are saturated and act as a potential slip plane. Precipitation similar to that of 1998 and 1999, will raise the water table, and trigger another landslide.

2. Abstract

Water, coupled with enumerable variations in environmental conditions, can lead to an increase in slope stability, or instability. Analyses of hydrologic factors and the underlying geology along the landslide at Deer Run Heights, with respect to the resisting forces, are critical in assessing the potential for a mass wasting event. *Onset* data loggers recording stream flow, rainfall, and water table height were used to correlate precipitation to groundwater flow. This analysis includes data from May 11, 2011 to April 19, 2012; data collected during Tropical Storm Irene and the spring flood are especially important as it is generally accepted that the rapid rise of rainfall-induced pore-water pressure is critical to the initiation of slope failures (Johnson and Sitar, 1990). These data have shown that there is a correlation between precipitation, stream flow, and groundwater flow in monitoring well 2. Precipitation events, especially those that are large, lead to an increased water table height in monitoring well 2. The presence of two dry wells—screened at depths above and below monitoring well 1 and 2—show that there is a perched water table atop very low permeable silty-clay horizons (silty-clay horizons determined by core samples). The perched water table is fed by the upper stream and infiltration from precipitation; water tends to persist in the slope for months. The accumulation, or loading, of water above the silty-clay horizons adds to the total mass above the slip surface, thus increasing driving forces and making a landslide more likely. Precipitation trends prior to the Jeffersonville Landslide in 1999 are very similar to those in 2011 and 2012; it is likely that groundwater flow for the two periods are also quite similar. Making connections between the amount and rate of rainfall in 2011-2012 and 1998-1999, to water table height in 2011 and 2012 may allow for water table height in 1999, just prior to the landslide, to be determined. Knowing where the water table was upon initiation of the landslide in 1999 will enable an early warning for landslides along Deer Run Ridge to be made in the future.

3. Introduction

A most challenging issue with landslides is to predict the time, location and intensity of slope failure in order to mitigate environmental and socioeconomic impacts (Schuster and Highland, 2001); in the United State alone, between 25 and 50 people are killed each year, and total annual cost of damages is about $3.5 billion (Keller, 2011) . A mass wasting event is likely to occur when driving forces overcome the resisting forces—friction, cohesion and strength—of slope materials. In more general terms, slope steepness and stability determine whether or not a slope will fail (Watkins and Hughes, 2012). Consideration of hydrologic factors assisting driving forces overcoming resisting forces of the slope material is critical in assessing the potential for another mass wasting event along the Deer Run Heights Ridge. For the majority of landslides, it is agreed upon that rainfall and earthquakes are the main triggers and that the former is far more frequent than the latter (Ren et al., 2011) (e.g., Schuster and Highland, 2001). Hydrologic factors (i.e., correlation of precipitation to groundwater flow) and their effects on the resisting forces, in regards to the Deer Run heights landslide, are focused upon in this paper. An introduction to landslides and the balance between driving forces and resisting forces is given first.

3.1 *Mass Wasting - Landslides*

A mass wasting event can be defined as the down slope movement of earth (Keller, 2011). A landslide is more specifically defined as "the movement of a mass of rock, debris, or earth down a slope" (Cruden, 1991). Various factors that can lead to the initiation of a landslide include, rainfall, snowmelt, changes in water level, stream erosion, changes in groundwater, earthquakes, volcanic activity, disturbance by human activities, or any combination of these factors (USGS, 2012). At the Deer Run Heights landslide, existing factors that may lead to the initiation of another landslide are rainfall, snowmelt, changes in water level, stream erosion, and changes in groundwater. Although the influence may be small, disturbance by human activities (e.g., nearby G.W. Tatro construction, VT RT 15 traffic, and upstream alterations to the Brewster River) may also contribute to slope failure.

3.1.1 *Driving Forces vs. Resisting Forces*

Before explaining how hydrologic factors are influencing the resisting forces at Deer Run Heights, it is important to first understand the relationship between driving forces and resisting forces. As long as the resisting forces are stronger than the driving forces, a slope is stable. Under the influence of gravity, driving forces promote the down slope movement of material. Driving forces include, slope angle, climate, type of slope material (including anything superimposed on the slope, such as vegetation, fill material, buildings, or cultural debris) and water (Keller, 2011). Driving forces increase as the slope of a hill or potential slip plane increase. Material on most slopes is moving down the slope continuously at rates that vary from an imperceptible creep of soil and rock to avalanches and landslides that move at high velocities (Keller, 2011). Resisting forces oppose the movement by driving forces.

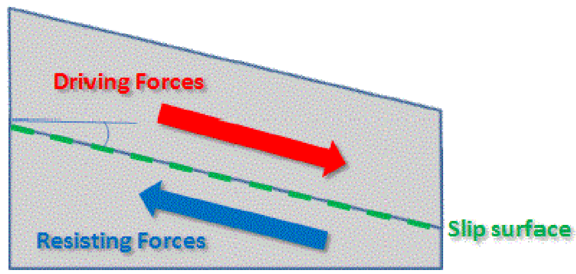

Figure 1. Driving forces vs. Resisting Forces

Resisting strength of slope materials describes the resistance to failure by sliding or flowing along surfaces of weakness in the slope material, or slip planes (Keller, 2011). The two other interrelated resisting forces are cohesion and internal friction. Cohesion is the ability of particles to attract and hold each other together, and internal friction is the friction between grains in a material (Watkins and Hughes, 2012). When a slope fails along a slip pane, it may be due to decreased friction caused by water that has accumulated along, say, an impermeable formation. Although vegetation can increase the probability of a landslide, it can also be an important factor in slope stability. Vegetation cushions the impact of rain on slopes, thereby impeding direct grain-by-grain erosion on the surface (Keller, 2011). Root systems also increase cohesion and strength of slope materials.

3.1.2 *Role of Water in Landslides*

Water plays an integral role in most landslides; excess water often helps cause landslides, while severe drought conditions may also lead to the development of landslide conditions (USGS, 2009). Varying degrees of saturation can either help support geologic materials, or cause instability. Consider sand castles, without water they will not stand well, too much water and they will not keep shape; a certain degree of saturation allows the sand to keep its shape.

Water is most beneficial when pore spaces between grains are partially filled with water (Watkins and Hughes, 2012). The water acts as a binder due to the molecular attraction between soil particles and water (Fetter, 2001).

During heavy rain events, saturation of slope soils may lead to shallow landslides (Keller, 2011). It is generally accepted that the rapid rise of rainfall-induced pore pressure is critical to the initiation of slope failures (Johnson and Sitar, 1990). Landslides also occur long after it has rained or snow has melted, and it has infiltrated into the slope (Keller, 2011). Saturation of slope materials also means that the weight of the water has added to the total mass subject to gravity, thus increasing driving forces (Watkins and Hughes, 2012). Elevated water content can increase chemical weathering of slope materials (Watkins and Hughes, 2012). Water can also cause landslides by contributing to spontaneous liquefaction of clay-rich sediments, also known as quick clay (Keller, 2011). As sliding begins, once solid material is turned into liquid mud (Leggett, 1973). So, if spontaneous liquefaction of clay-rich layers occurs, a small event can turn quite large. Water can also erode the toe, or base, of the slope, thereby removing material that is supporting the overlying material. According to Keller (2011), slides are often initiated by erosion of the toe of the slope.

3.2 *Deer Run Heights*

Heavy or prolonged rain events and spring snowmelt threaten the stability of slopes at the Deer Run Heights landslide in Jeffersonville, VT; water from these events infiltrates the ground and leads to increases in water table height. The water table marks the top of the zone of saturation, so as the water table rises sediments become more saturated. Saturation of sediments reduces the resisting forces of cohesion and friction, while increasing driving forces due to the increased mass, or loading, of the water. Also, when water permeates to the decollement zone, just above the clays, it acts as a lubricant. Precipitation is also associated with increased stream discharge; increased stream discharge in the Brewster River means that the toe of a slope along an outside bank may be eroded. Erosion of the toe of a slope is thereby removing the material—reducing resisting forces—that is holding up the slope. While excess groundwater alone does not typically lead to mass wasting events, the geology of Deer Run Heights, and the fact that it is adjacent to the Brewster River, makes the ridge highly susceptible to failure.

3.2.1 *Site Overview*

The Deer Run Heights Ridge is located in Jeffersonville, VT, just south of Vermont Route 15 along the eastern bank of the Brewster River (western margin of the Deer Run Heights ridge). To the east of the ridge is a small unnamed stream, hereafter referred to as the upper stream. In the immediate down slope vicinity west of the ridge, there are private and commercial businesses, as well as Cambridge Elementary School. Figure 1 shows the study area, along with the location of the various data loggers and instruments used to track water movement.

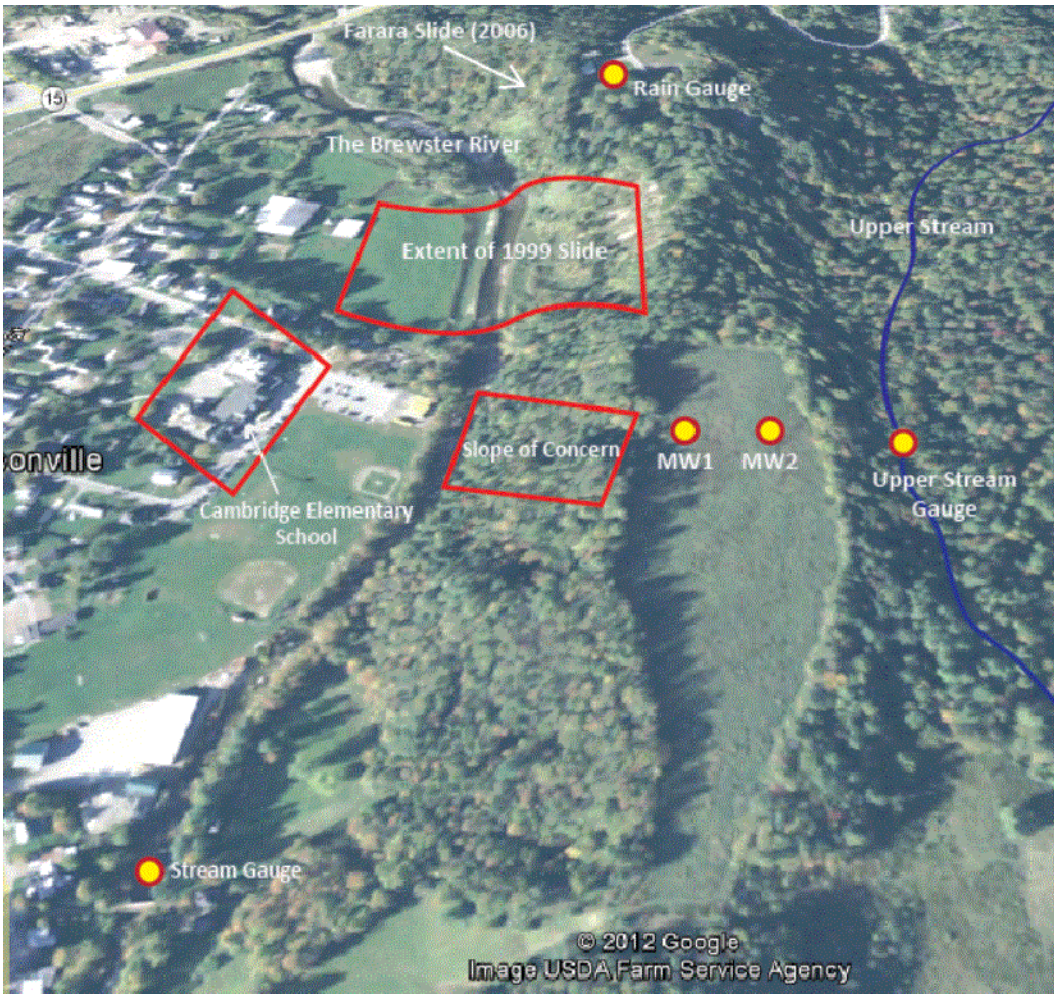

Figure 3. Study Area

3.2.2 *Significance of Analysis*

The purpose of my analysis of hydrologic factors at the Deer Run Heights landslide is to predict the onset of another landslide so that potential impacts may be mitigated. Since excess groundwater is often attributable to slope failures, monitoring and analyses of hydrologic conditions are essential in landslide predictions. Developing a prediction of when a landslide will occur will not only allow residents of the village, especially students and faculty of Cambridge Elementary, to evacuate, but town and state authorities will also be able to implement other preventative measures to avoid additional impacts, such as the damming of the Brewster River and subsequent flooding.

The biggest concern at Deer Run Heights is that if a landslide of similar magnitude as the 1999 slide occurs further south at the slope of concern, it could hit Cambridge Elementary School, as well as nearby residences and businesses (Norwich, 2010). In Figure 3, if the extent of the 1999 slide was placed at the location of the slope of concern, it would include a portion of the school and numerous surrounding structures. The run out length of the 1999 slide was approximately six times the drop height (Nichols, 2012). Nichols (2012) suggests that hazard zones should be delineated at least 7 times the potential drop zone.

One of the largest dangers of another landslide of similar magnitude as the 1999 landslide is the potential for the damming of the Brewster River. If enough material is deposited into the channel of the Brewster River, the river may be diverted and flood the village. Since the river is bound on one side by the Deer Run Heights ridge, its only path would be directly through Jeffersonville and eventually into the Lamoille River. If a landslide is to occur simultaneously with heavy rains, the flooding could wreak havoc on the village, especially since all village residents live on the alluvial fan created by the Brewster River (Bierman et al., 1999). Dammed water may also lead to the creation of a small lake in the village, though I feel the Lamoille River's close proximity would provide a way for excess water to leave the area. If water does become dammed, the rapid release of water (once debris in the channel is eroded) may lead to even more flooding downstream, and potentially damage VT Route 15.

Due to the 1999 landslide, a house had to be removed from atop the ridge after the slide undermined its foundation; luckily no one was home at the time. This very same thing may happen to the Farara residence if a larger landslide were to occur in the same area as the 2006 landslide. The owner of the house, Joe Farara, has noticed that before previous landslides, water was entering his basement. Since groundwater entering foundations is most often due to saturated conditions, and thus high pore pressures, it may be used as an indicator as to when a landslide may occur. Dr. Leslie Kanat of Johnson State College has placed a water monitoring device in the basement of the Farara residence; if the monitor alarms that water is entering the basement, the Farara's have been recommended to evacuate.

3.2.3 *Geology and Hydrology*

The Jeffersonville slides originated from a steep bank of unconsolidated glacial and immediately post-glacial sediments (Bierman et al., 1999). During the most recent glaciation—as the Laurentide Ice Sheet retreated northwest—a series of glacial lakes formed (Bierman et al., 1999). These lakes deposited layers of poorly sorted sediments, called glacio-lacustrine sediments. The glacio-lacustrine deposits are represented by layers of clays, silts and fine sands that alternate and become progressively coarser moving up the slope (Forsberg, 2007). The steep banks were created as the Brewster River carved its way through the glacial deposits (Bierman et al., 1999).

A geotechnical slope investigation performed by Norwich University determined that cohesion of sediments is minimal to a depth of about 63 feet (Norwich, 2010); this is the depth where the silty-clay horizons begin. Cohesion of the silty-clay horizons, and all underlying layers, is sufficient to create steeper banks and support large volumes of sediment. The fact that cohesion of the silty-clay horizons supports large volumes of sediment means that a large landslide is possible—poor cohesion of the overlying material means that upon failure, materials will be highly mobile. It is also important to consider the fact that the base of the Deer Run Heights ridge consists mainly of old, inactive landslides. Erosion of inactive landslide segments is even more likely to trigger another landslide than if the base of the slope had not yet experienced landslide events (Keller, 2011).

The contrast in permeability moving up the slope tends to allow water to percolate through the coarser sand and accumulate above the silty-clay horizons; this stratigraphic control of groundwater flow can act as a lubricant that decreases frictional resistance, while the additional weight of the water increases the driving forces of gravity (Kim, 2000). Saturation also increases pore pressure, which can push sediment grains apart, thereby reducing the strength of the material. Drainage of water infiltrated after precipitation events may also be retarded by silts and clays with low permeability, thus maintaining high pore pressures and decreasing resisting strength (Bierman et al., 1999).

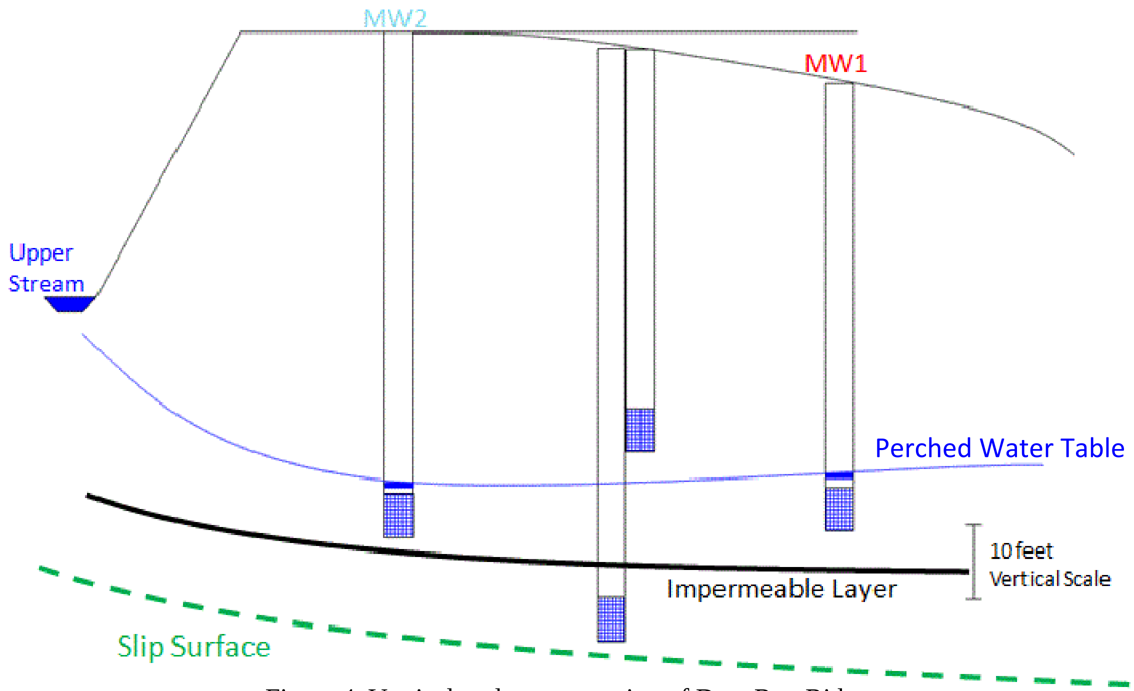

Figure 4. Vertical scale cross-section of Deer Run Ridge

Figure 4 is a vertical scale profile view of Deer Run Ridge showing a perched water table. The two wells in the middle are typically dry; MW1 and MW2 always have water in them. Since the wells in the middle—which are screened at depths above and below MW1 and MW2—are dry, but MW1 and MW2 hold water, there must be a perched water table present. The presence of a perched water table is directly related to the low permeability of the silt and clay layers, and results in the loading of water above these layers.


Figure 5. (Kanat, 2012)

Figure 5 shows a core sample taken at Deer Run Ridge. Notice the layers towards the bottom that show good cohesion; these layers consist of silts and clays that have a very low permeability, which means their ability to transmit fluid is poor. The low permeability of these layers leads to the accumulation of water above, and can be seen by the saturated sands; the saturated sands have poor cohesion and the water reduces frictional resistance. It is processes like these that retard the drainage of water, leading to loading that increases the mass above the slip surface (Figure 4), and may also lubricate the slip surface, thus increasing the driving forces. The slip surface is low in the slope, and is dominated by clays. Upon slope failure along this slip plane, the clays exhibit the strength—

cohesion and friction—of the sands seen in Figure 5. One can imagine that the accumulation of water, or loading, above a layer like that seen in Figure 5 would eventually trigger a landslide.

While monitoring of current hydrologic conditions helps to understand what is happening now, it is also important to consider the climate of an area when assessing a slopes potential for failure. The climate is important because it describes when, how much, and at what rate the rain comes; varying trends in precipitation produce different degrees of stress on slope materials. Climate also influences the amount and quality of vegetation that may acts as either a resisting, or driving force. It is noteworthy to mention that 1998 was the wettest on record in Burlington, Vermont (Bierman et al., 1999). If recent precipitation is well above average, and similar to that of 1998 and 1999, then hydrologic conditions at Deer Run Ridge are likely similar to those prior to the landslide in 1999. Large precipitation events are also important to consider, not only because it may lead to the rapid rise in rainfall-induced pore pressure, but because it is also associated with increased stream discharge that can erode the toe of the slope. The silty-clay horizons at Deer Run Ridge are saturated and act as a potential slip plane. Precipitation similar to that of 1998 and 1999, will raise the water table, and trigger another landslide. Remember that the water infiltrated from precipitation and water exfiltrated from the Upper Stream adds to the total mass, or loads, above the silty-clay horizons, as this is critical to the initiation of the next landslide.

3.2.4 *Landslide History*

Jeffersonville has long been plagued by landslides; slope failure at the site appears to be ongoing since 1911 (Becker et al., 2009). Historic photographs, mainly of remnant landslide scars, have enabled geologists to put together a chronology of landslide events along the Deer Run Heights ridge prior to their documentation. Several of these historic photographs show slide scars on the outside bend of the Brewster River, as well as fresh toe erosion, which suggests that erosion of the toe of the slope by the Brewster River is often attributable to slope failures. Actual documentation of landslide occurrences began in 1954, where landslides occurred on May 10 and 11. In these events, slide debris, including whole trees, was carried across the Brewster River (Becker et al., 2009). The 1954 landslide occurred in the same area—the Jeffersonville Clay Bank—as the more recent 1999 landslide (Becker et al., 2009).

The 1999 landslide, otherwise known as the Jeffersonville Landslide, occurred as three mass movements. The first two mass wasting events occurred on April 11 and 18 (largest release), carrying a volume of run out material of about 23,000 m^3 (Bierman et al., 1999). The last event occurred on July 4, 1999, carrying approximately 4,200 m^3 of run out material (Bierman et al., 1999). In all, the slides carried more than 27,000 m^3 of slope material into and across the Brewster River. Excess pore pressures (retained during mobilization) allowed the slide to cover such a large lateral extent (Bierman et al., 1999). Although the run-out distance—150 meters—placed residences in harm's way, it may have actually benefited the village overall. A lot of the debris translated away from its source (the slope), leaving mostly fine sand in the channel of the Brewster River (Bierman et al., 1999). The fine sand is easily erodible, and so the Brewster River was never dammed sufficiently for flooding to occur.

Several smaller slides occurred along the ridge in 2006 and 2008. The landslide in 2006—known as the Farara Landslide—occurred north of the 1999 slide; Figure 3 shows its location. The landslide in 2008 posed significant concern, since it occurred above Cambridge Elementary School (Becker et al., 2009). The 2008 event is characterized as renewed slumping in a gully-landslide complex on the slope above Cambridge Elementary School (Becker et al., 2009). Each subsequent landslide indicates that the Deer Run Heights ridge is still unstable, and needs continued monitoring.

4. Materials and Methods

Refer to Figure 3 in the Site Overview section for the location of the various tools and loggers used (denoted by yellow markers). A rain gauge was set up north of the 1999 slide, on top of Deer Run Heights Ridge. The rain gauge is a tipping bucket model, and each tip accounts for 0.01 inches of rain (each tip counts as an "event"). During the launch of the rain gauge, appropriate conversions were not set, and so each tip of 0.01 inches of rain reads as one event. In the results section, the rain axis is in hundredths of inches; to obtain correct rainfall amounts, simply multiply the value by 0.01. There are two stream gauges, one in the Brewster River and one in the upper stream. As the rain gauge records rainfall, the stream gauges should respond soon after with increased height and discharge. Two monitoring wells (MW1 and MW2) were placed on top of the ridge, directly behind the slope of concern. These monitoring wells provided water table heights, a significant factor in slope stability. Water table heights in the monitoring wells allow for correlations between precipitation and groundwater flow. Core samples were also taken during drilling, which enabled slope stratigraphy to be determined.

*Note: Water table height in MW1 seems higher, but due to a decrease in elevation between MW2 and MW1, they are screened at approximately the same depth.

5. Results

Figure 6 displays the hydrologic data collected at Deer Run Heights for the period of May 11, 2011 to April 19, 2012. The solid red line represents water table height in MW1; water table height values are negative, as they are a measure of the depth to the water from the well head. Water table height in MW1, which is closer to the slope face (Figure 6b), does not vary all too much in connection with the upper stream and rainfall. Although fluctuations can be seen, MW1 has an average water table height of -52.338 feet and a standard deviation of just 0.109 feet; this means that throughout the year, 68 percent of the recorded water table heights were within 0.109 feet of the average.

The lighter blue line represents water table height in MW2, which is closer to the upper stream (Figure 6b). The darker blue line represents stream height in the Upper Stream. Focus on the period of Tropical Storm Irene, which passed through Jeffersonville, VT on August 26, 2011. Tropical Storm Irene dropped approximately three inches of rain in one day, and the Upper Stream shows an almost immediate response in increased stream height. Notice that water table height in MW2 rose quite quickly after the rainfall from Tropical Storm Irene and associated increased stream height in the Upper Stream. Also take note that water table height in MW2 tends to persist for months after large rain events. MW2 had an average water table height of -61.366 and a standard deviation of 0.331; this is significant when compared to MW1.

Figure 7 shows Burlington's monthly precipitation totals in 2005 and 2006, compared to the 30 year average. Observe precipitation in 2005; about six months had above average precipitation. Moving into 2006, January saw almost double the average precipitation. May and June of 2006 also had well above average precipitation, and were followed by the Farara Slide (Figure 3) in late June or early July—the exact time of slope failure is unknown. Keep in mind that the water persists within the slope for months, as can be seen by the slow decline in water table height in MW2 in Figure 6.

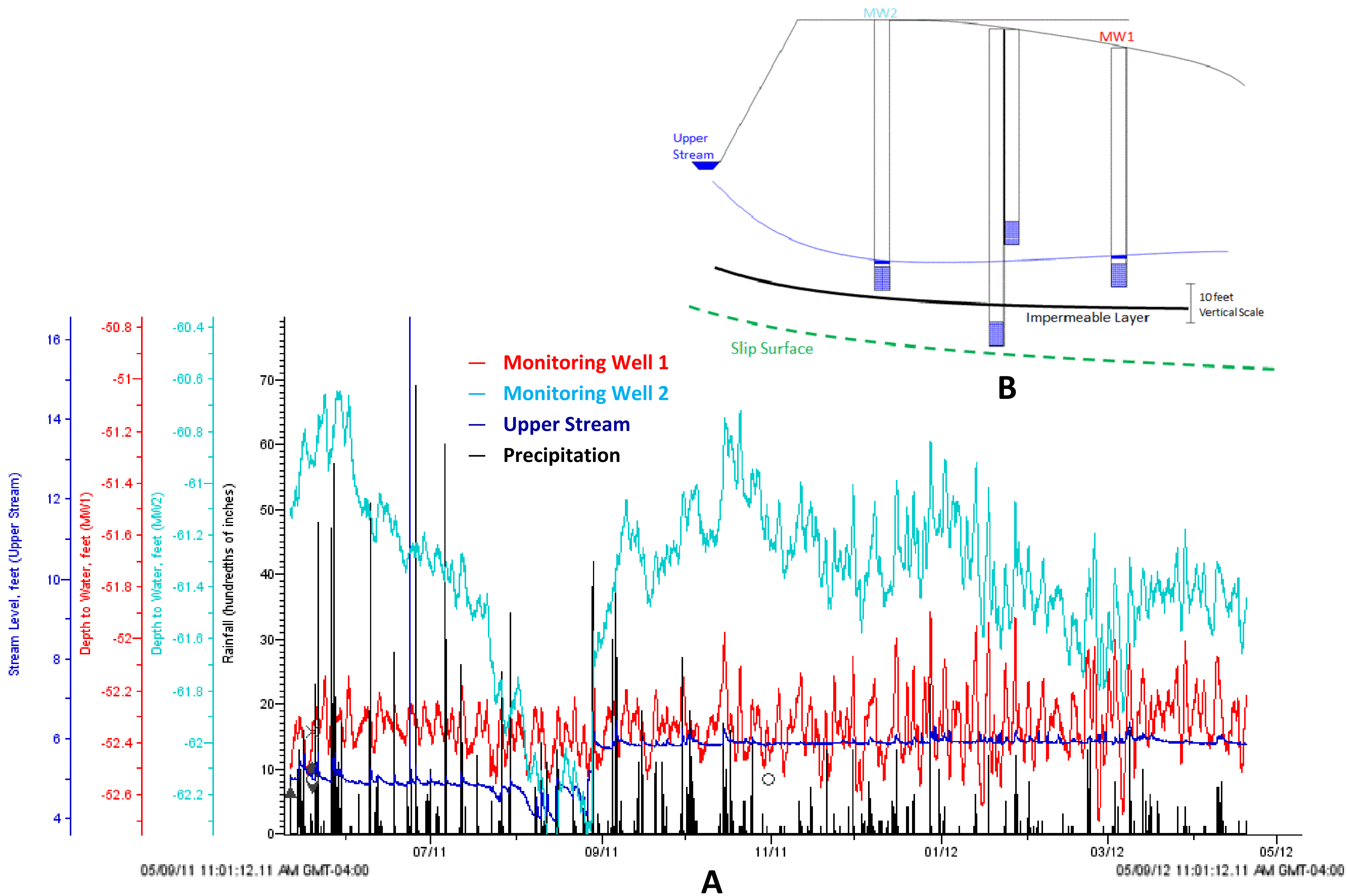

Figure 6a. Hydrologic data for Deer Run Heights for the period of May 11, 2011 to April 19, 2012.
Figure 6b. Vertical scale cross-section of Deer Run Ridge.

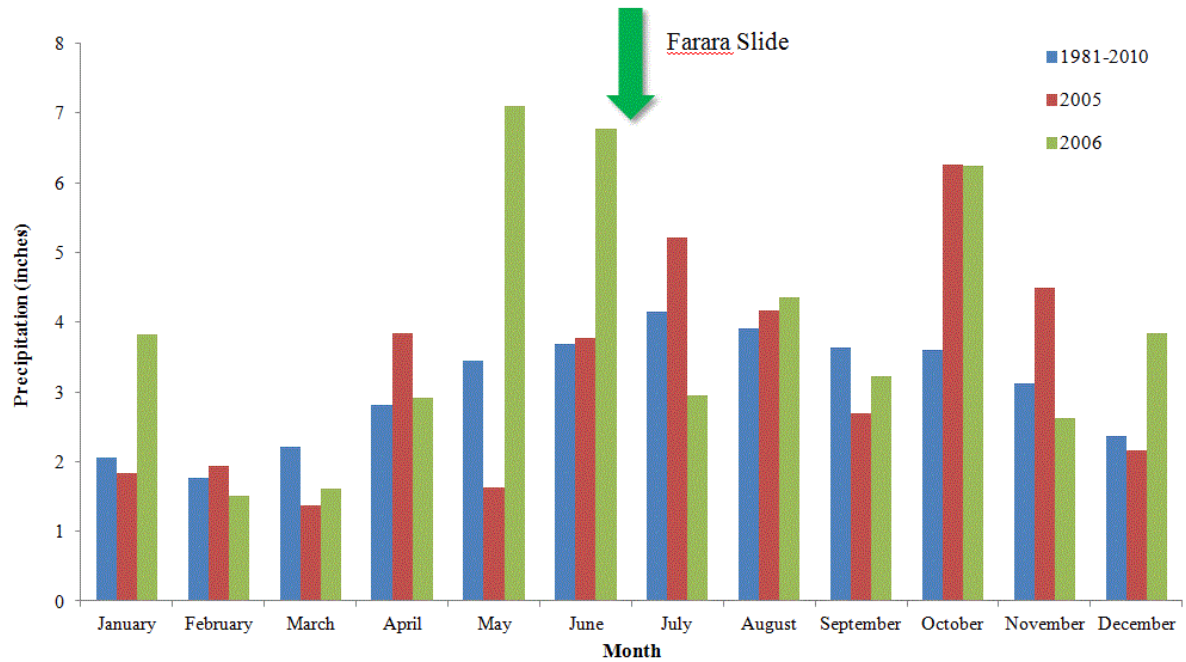

Figure 7. Burlington, VT Precipitation - Monthly Totals for 2005 and 2006 compared to the 30 year average (NWS, 2012a). Farara Slide occurred in late June-early July of 2006.

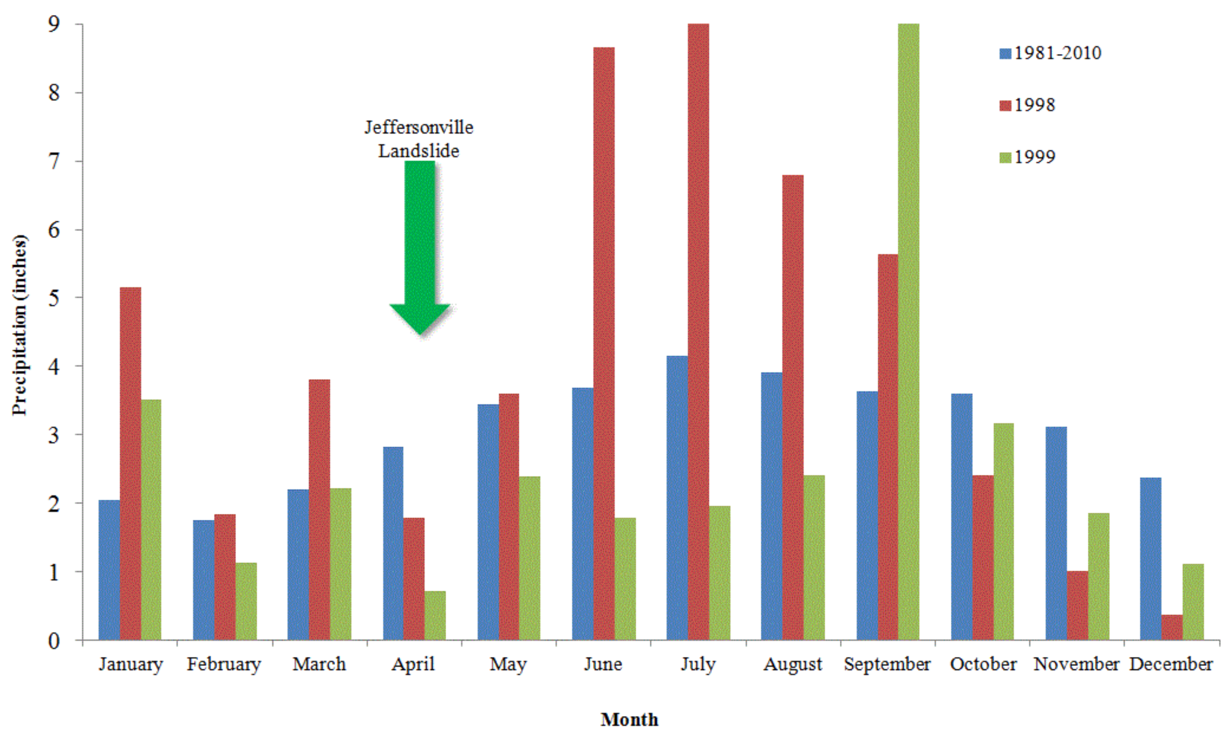

Figure 8. Burlington, VT Precipitation - Monthly Totals for 1998 and 1999 compared to the 30 year average (NWS, 2012a). Jeffersonville Landslide occurred in April 1999.

Figure 8 shows Burlington's monthly precipitation totals in 1998 and 1999, compared to the 30 year average. Seven months in 1998 show above average precipitation; take note of the well above average precipitation in June through September. Late fall and early winter of 1998 experienced below average precipitation, but notice that January 1999 had above average precipitation. From the end of January until the landslide, rainfall was average to below average; this is significant in that the water persist within the slope for months and that landslides may occur during or after periods of below average rainfall

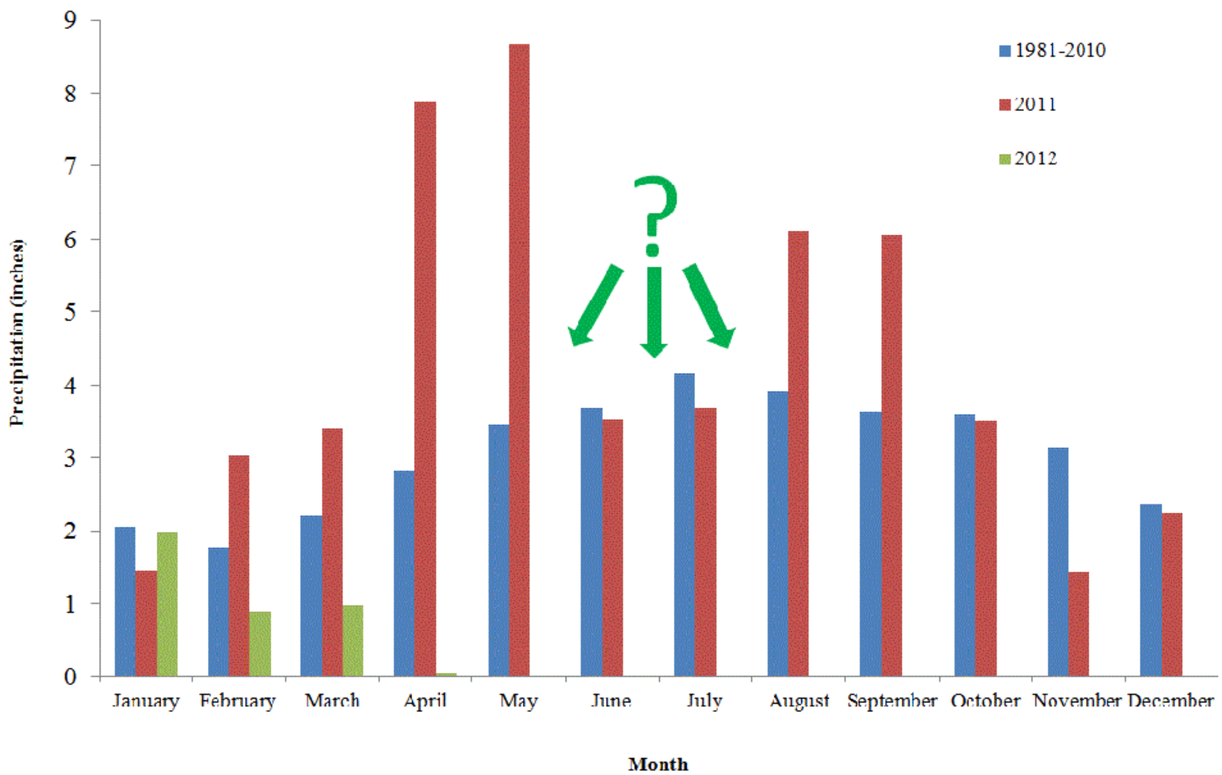

Figure 9. Burlington, VT Precipitation - Monthly Totals for 2011 and 2012, compared to the 30 year average (NWS, 2012a). The Jeffersonville Landslide occurred in April 1999.

Figure 9 shows Burlington's monthly precipitation totals for 2011 and 2012, compared to the 30 year average. Above average precipitation was experienced six months in 2011; notice that there was also a period of dryness in winter 2011-2012. Again, remembering that water persists within the slope for months, much of the water infiltrated during 2011 is still in the slope. Annual precipitation totals for 1998 and 2011 were within an inch of each other (approximately 50 inches), and so is significant in consideration of the current hydrologic conditions at Deer Run Ridge and those preceding the 1999 landslide.

6. Discussion

6.1 *Correlation of Precipitation, Stream Flow, and Water Table Height*

According to the standard deviation of water table heights for MW1, most of the records are within 0.109 feet of the average; this is less than a 2 inch variation over a majority of the period of observation. Since MW1 varies so little, and tends to return to a consistent static water level, it is statistically considered to be unaffected by variations in precipitation and the upper stream. This is likely due to water infiltrating more closely to MW2 (closer to the Upper Stream), and as the water is dispersed through the slope, its affect on water table height in MW1 (closer to the slope face) is minimal and not easily interpreted from Figure 6.

The standard deviation of MW2's water table height is higher than MW1's, and shows that MW2 varies more, and therefore must have a stronger connection to precipitation and/or the Upper Stream (as it should since MW2 is closer to the Upper Stream). The rapid rise in water table height in MW2 after the large rainfall of Tropical Storm Irene and its associated increased stream height in the Upper Stream also suggest a connection between precipitation, stream flow and groundwater flow in MW2.

6.2 *Precipitation*

The fact that annual precipitation totals for 1998 and 2011 are within an inch of each other suggests that current hydrologic conditions at Deer Run Ridge are similar to those prior to the initiation of the Jeffersonville Landslide. There seems to be a pattern of above average precipitation, followed by a landslide; it is important to realize that landslides didn't necessarily occur immediately after large rainfall events. Two critical factors to consider are the slow decline in water table height in MW2 after Tropical Storm Irene (Figure 6), and the fact that the Jeffersonville Landslide occurred even after a period of below average rainfall.

The slow decline in water table height means that the water persists within the slope for months, which allows water to accumulate within the slope (especially during times of heavy rainfall). The above average precipitation experienced in 1998 and in January of 1999 accumulated, or loaded, above the low permeable silty-clay horizons. The accumulation, or loading, above the silty-clay horizons increased the total mass above the slip surface, thus increasing the driving forces, and making a landslide more likely. The loading above the silty-clay horizons, which increased the mass above the slip surface, is the mechanism by which the large landslide experienced in 1999 initiated.

Since the initiation of the landslide occurred in April, after a few months of average to below average rainfall, this suggests that the above average precipitation experienced in 1998 and January 1999 was nearly sufficient for slope failure to occur. Since the water persists within the slope for months, the above average precipitation remained in the slope until the subsequent average to below average rainfall introduced just enough more water, or mass, above the slip surface for driving forces to overcome resisting forces, resulting in slope failure.

6.3 *Predicting the Next Landslide*

Since precipitation preceding the Jeffersonville Landslide in 1999 is statistically very similar to that of 2011 into 2012, it is likely that groundwater flow is also similar for the two time periods. Another large precipitation event, or even prolonged moderate rainfall, may load the slope to the point of failure. At the start of this analysis, the National Weather Service's original three month precipitation outlook for the northeast predicted average to below average rainfall (NWS, 2012b); if they were wrong, and we got a lot of rain, I suspected that a landslide would be likely in May or June of 2012, especially if the rain is coupled with high winds. Now, the three month outlook is predicting an equal chance of below, normal, or above average precipitation (NWS, 2012b). So, if the Jeffersonville area receives abundant precipitation in the near future, residents should be warned of the potential for slope failure.

6.4 *Further Work*

Since groundwater flow (water table height) is known for the 2011-2012 period, and precipitation is similar for the two periods, groundwater flow prior to the 1999 landslide can be determined using the proper mathematical techniques. Plotting water table height as a function of precipitation did not yield an understanding as to how much rain results in certain water table height increases. The unanswered question is at what height, which is proportional to the mass of the water above the slip surface, does the water table have to rise in order to trigger another landslide? Using precipitation and water table height data from 2011-2012, and making a connection to the trend in precipitation in 1998-1999, water table height in 1999, just prior to the Jeffersonville Landslide may be determined.

7. References

Becker, Laurence, George Springston and Leslie Kanat, 2009. *Progress Report for Geotechnical Study of the Jeffersonville Landslide, Northwestern Vermont, 2009.* Retrieved on 20 March 2012, from http://www.anr.state.vt.us/dec/geo/pdfdocs/ProgressJeff.pdf.

Bierman, P., Wright, S., and Nichols, K., 1999. Slope Stability and late Pleistocene/Holocene history, Northwestern Vermont; in Wright, S.F. ed., New England Intercollegiate Geologic Conference Guidebook Number 91, p. 17-50.

Cruden, D.M., 1991, A Simple Definition of a Landslide. Bulletin of the International Association of Engineering Geology, No. 43, pp. 27-29.

Fetter, C.W., 2001. *Applied Hydrogeology,* 4th Edition. Prentice Hall, New Jersey, 598 pages.

Gendron, Christopher, Stephen Kent, Christopher Rivet, 2010. *Norwich University Jeffersonville Geotechnical Slope Analysis.* Norwich University David Crawford School of Engineering: Department of Civil Engineering.

Johnson, K. A., and Sitar, N. _1990_. Hydrologic conditions leading to debris flow initiation. *Can. Geotech. J.*, 27_6_, 789–801.

Kanat, Les, 2012. *Deer Run Heights Landslide.* Retrieved on 13 January 2012, from http://kanat.jsc.vsc.edu/drh/default.htm.

Keller, Edward A., 2011. *Environmental Geology,* Ninth Edition. Prentice Hall, New Jersey, 562 pages.

Kim, J., 2000. *April 1999 Landslide at Deer Run Height, Jeffersonville, VT.* Retrieved on 12 March 2012, from http://www.anr.state.vt.us/dec/geo/jeffland.htm.

Leggett, R.F., 1973. *Cities and Geology*. New York: Mcgraw-Hill.

National Weather Service (NWS), 2012a. *Burlington, VT – Monthly Precipitation Totals.* Retrieved on 2 April 2012, from http://www.erh.noaa.gov/btv/climo/BTV/monthly_totals/precip.shtml.

National Weather Service (NWS), 2012b. *Three Months Outlooks.* Retrieved on 4 May 2012, from http://www.cpc.ncep.noaa.gov/products/predictions/long_range/seasonal.php?lead=1.

Nichols, Kyle K., 2012. *Jeffersonville Landslide*. Retrieved on 10 April 2012, from http://www.skidmore.edu/~knichols/Jeffersonville.htm.

Schuster, Robert L., and Lynn M. Highland, 2004. *Socioeconomic and Environmental impacts of Landslides in the Western Hemisphere.* Retrieved on 2 February 2012, from *http://pubs.usgs.gov/of/2001/ofr-01-0276/.*

Ren, D., Fu, R., Leslie, L. M., & Dickinson, R. E. (2011). Predicting Storm-triggered Landslides. *Bulletin Of The American Meteorological Society, 92*(2), 129-139. doi:10.1175/2010BAMS3017.1

United States Geological Survey (USGS), 2009. *Landslides Types and Processes.* Retrieved on 3 May 2012, from http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html.

United State Geological Survey (USGS), 2012. *What is a landslide and what causes one?* Retrieved on 6 February 2012, from http://www.usgs.gov/faq/index.php?sid=54684&lang=en&action=artikel&cat=17&id=304&artlang=en.

Watkins, Anni, and Scott Hughes, 2012. *Landslides, Slope Failure, and Other Mass Wasting Processes.* Retrieved on 3 March 2012, from http://wapi.isu.edu/envgeo/EG4_mass_wasting/EG_module_4.htm.