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Characterizing Meteorological and Hydrologic Conditions Associated with Shallow Landslide Initiation in the Coastal Bluffs of the Atlantic Highlands, New Jersey

Ashland, F.X. fashland@usgs.gov
U.S. Geological Survey, Reston, VA 20192

Fiore, A.R., afiore@usgs.gov, Reilly, P.A., jankowsk@usgs.gov
U.S. Geological Survey, Lawrenceville, NJ 08648

ABSTRACT: Meteorological and hydrologic conditions associated with shallow landslide initiation in the coastal bluffs of the Atlantic Highlands, New Jersey remain undocumented despite a history of damaging slope movement extending back to at least 1903. This study applies an empirical approach to quantify the rainfall conditions leading to shallow landsliding based on analysis of overlapping historical precipitation data and records of landslide occurrence, and uses continuous monitoring to quantify antecedent soil moisture and hydrologic response to rainfall events at two failure-prone hillslopes. Analysis of historical rainfall data reveals that both extended duration and cumulative rainfall amounts are critical characteristics of many landslide-inducing storms, and is consistent with current monitoring results that show notable increases in shallow soil moisture and pore-water pressure in continuous rainfall periods. Monitoring results show that shallow groundwater levels and soil moisture increase from annual lows in late summer-early fall to annual highs in late winter-early spring, and historical data indicate that shallow landslides occur most commonly from tropical cyclones in late summer through fall and nor'easters in spring. Based on this seasonality, we derived two provisional rainfall thresholds using a limited dataset of documented landslides and rainfall conditions for each season and storm type. A lower threshold for landslide initiation in spring corresponds with high antecedent moisture conditions, and higher rainfall amounts are required to induce shallow landslides during the drier soil moisture conditions in late summer-early fall.

INTRODUCTION

The Atlantic Highlands area of Monmouth County (Fig. 1) has been identified as a distinct landslide-prone section of northern coastal New Jersey, and is characterized by relatively high relief, moderate to steep slopes, and the presence of non-indurated Upper Cretaceous to Tertiary sediments. Documented landslides consist of large, prehistoric to historical, deep-seated rotational landslides (slumps of Minard, 1974) and shallow landslides of various types (Rehm, 1977; Pallis, 2009). Slow damaging movement resulting from either global or partial reactivation, and local enlargement of deep-seated landslides in the early 1970s was described by

Minard (1974). Shallow landslides have been reported since 1903 (New York Times, 1903; Red Bank Register, 1903), but most of the documented shallow landslides have occurred since 1977 and subsequent to the completion of previous landslide research in the area (Minard, 1974; Rehm, 1977). Movement of both the large deep-seated and shallow landslides has resulted in extensive residential and municipal property damage and threatened human lives.

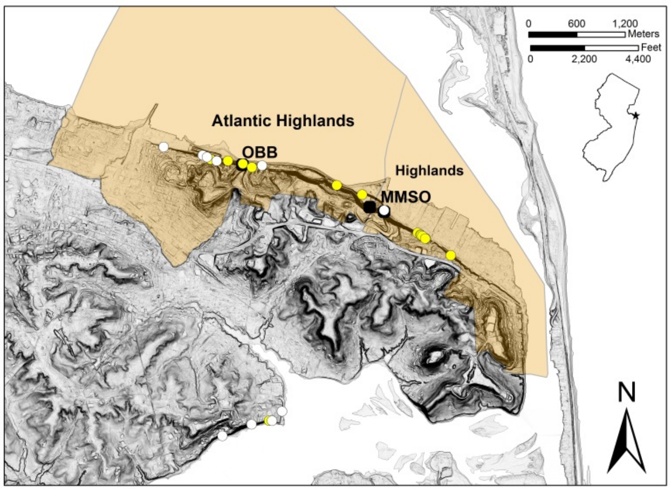


Figure 1. Location map of the Atlantic Highlands area, New Jersey. Historical shallow landslides in NJGWS database (yellow circles, Pallis, 2009), other historical shallow landslides (white circles, this study), and locations of Mount Mitchill Scenic Overlook (MMSO) and Ocean Boulevard Bridge (OBB) monitoring sites (black squares).

The susceptibility of slopes to rainfall-induced, shallow landsliding (Fig. 2) became increasingly evident when multiple landslides occurred as the result of successive nor'easters in March 2010 (Stanford, 2010) and again during Tropical Storm Irene in August 2011. Despite the apparent increasing frequency of shallow landslides since the mid-1970s and documented impacts, no basis for anticipating landslide movement exists. To assist the boroughs of Atlantic Highlands and Highlands in managing shallow landslide hazards, we began an investigation to identify specific criteria for forecasting the occurrence of shallow landslides in the area. Empirical rainfall thresholds and information on shallow soil moisture conditions have been used elsewhere in the U.S. for forecasting landslide occurrence and providing early warning of possible landslide hazards (Godt et al., 2006; Chleborad et al. 2008). This paper presents our preliminary rainfall thresholds for the area based on analysis of historical rainfall data and documented landslides, and our initial findings on hydrologic conditions in shallow soils from site-specific monitoring through late summer 2016.

A

B

Figure 2. Photographs of two recent shallow landslides (photos by Francis Ashland, USGS). A. April 2014 landslide in Atlantic Highlands. B. Upper right side of source area of May 2012 landslide in Atlantic Highlands and monitoring site OBB in figure 1.

SETTING

Northeastern coastal New Jersey is underlain by flat-lying, non-indurated, Cretaceous and Tertiary sediments. The formations in the coastal bluffs in the Atlantic Highlands area range from the Cretaceous

Mount Laurel Formation near sea level to the Miocene Cohansey Sand capping local ridgetops (Minard, 1969). A distinct contact occurs between the red Shrewsbury member and the underlying black Sandy Hook member of the Red Bank Sand. The glauconitic lower part of the Sandy Hook member and the clayey glauconite sand in the underlying Navesink Formation form a local aquitard and saturated zones occur directly above it in the lower part of the Shrewsbury member of the Red Bank Sand. Minard (1969) reported many springs flowing from the base of the Red Bank Sand. Local cementation of the units results in ironstone that ranges in thickness from a few millimeters to several meters and that varies in lateral extent, but is generally discontinuous. In many locations on the bluff slopes, some combination of sandy slope colluvium, landslide deposits, and fill unconformably overlie the flat-lying sediments. The Atlantic Highlands area is noted for its local high relief, which exceeds 76 m. Coastal erosion has locally steepened bluffs to a state of marginal stability resulting in deep-seated landslides (Minard, 1974). The interval that includes the Cretaceous glauconitic Navesink Formation and the Red Bank Sand underlie many of the recent shallow landslide scars. Slickensided clay derived from the Navesink Formation and glauconitic part of the Sandy Hook member is found in close proximity to shallow landslides and within the limits of slumps mapped by Minard (1974). Numerous open cylindrical voids of various sizes ranging up to about a meter across are evidence of local soil piping in the saturated zones in the Shrewsbury member of the Red Bank Sand and overlying slope colluvium and related soils.

A variety of hillside modifications have been made to the bluffs primarily related to residential development from the late 1800s to present. These include slope crest fills in backyards and along roads, artificial terracing for building lots, slope retention systems, localized attempts at slope dewatering, redirected runoff, and the use of residential septic systems in Atlantic Highlands. Slope terracing was identified as being a causative factor to the shallow landslides that occurred during a major storm in October 1903 (Red Bank Register, 1903).

The source areas for shallow landslides include moderate to steep slopes associated with prehistoric to historical, deep-seated landslides and similar slopes that have been over-steepened due to coastal wave erosion, particularly during storms with significant storm surge. Shallow landslides are dominantly complex earth slides–earth flows or rapid debris (earth) flows that involve movement of sandy colluvium, pre-existing landslide deposits, fill (where present), and the uppermost underlying Cretaceous units. Recent landslide scars expose in-place Cretaceous formations from the Navesink Formation to the Shrewsbury member of the Red Bank Sand (Fig. 2B). Shallow landslide features include scarp-bounded swales that are the source areas of previous landsliding, pull-apart features, and toe bulges. Tilted trees exist throughout the bluffs, and forward tilted trees are ubiquitous near the base of the bluffs, particularly adjacent to historical landslides. Evidence for secondary landslide features, such as toe bulges, abutting documented landslides suggests that undetected slope failure may have preceded some reported landslide occurrences. The secondary landslide features and additional undocumented landslides revealed by our field investigations suggest the potential for landslide movement is more widespread than suggested by the spatial distribution and extent of the documented landslides alone.

The study area is within New Jersey’s coastal zone where heavy rainfall is most commonly associated with two types of storms—nor’easters and tropical cyclones. Nor’easters are storms associated with a cold low pressure system that are characterized by heavy rain or snow and gale-force winds and are most common in the region between September and April. The Atlantic hurricane season officially extends from June through November and is most intense during late August and September. Official National Oceanic Atmospheric Administration (NOAA) data from the nearby National Weather Service (NWS) New York City Central Park (NYCCP) rain gauge has a period of record that extends back to 1869. Between 1869 and 2010, annual precipitation at NYCCP averaged 1146 mm with the wettest months being August, July, March, and September in decreasing order. In the three recent decades beginning in 1981, average annual precipitation increased to 1268 mm with the four wettest months being July, April, August, and June.

METHODS

We obtained dates of occurrence and landslide timing information for 26 shallow landslides from a statewide landslide inventory database published by the New Jersey Geological and Water Survey

(NJGWS) (Pallis, 2009) and news media articles from storm-specific searches (this study). Precise timing data exist for only one of the documented landslides that occurred in Highlands on January 3, 1999 (Figdore, 1999; Stanford, 1999) that showed correspondence between landslide initiation and both peak rainfall intensity and a period of continuous rainfall. The date of occurrence is documented for 16 other landslides, which in total are associated with eight storms. Some uncertainty exists regarding the dates of the remaining seven landslides, but four of these are known to postdate two nor'easters in March 2010 (Stanford, 2010). Reconnaissance field observations contained in unpublished reports provided by the NJGWS (Stanford, 1999, 2007, and 2010) yielded valuable information on landslide types and mechanisms, and other factors contributing to slope failure for some of the documented landslides between 1999 and 2011.

We compiled and analyzed official hourly and daily rainfall data from the NWS NYCCP weather station, based on its long period of record and its current status as the primary regional weather station for the metropolitan area that includes the Atlantic Highlands area. The period of record for official daily and hourly data at NYCCP extends back to 1876 and 1948, respectively. Monthly NWS climate reports extending back to 1889 provide additional hourly precipitation data that overlaps with all the documented shallow landslides in the Atlantic Highlands area. The documented landslides are associated with 13 or 14 separate storms, and based on this we initially assessed how these storms ranked in total storm rainfall (TSR) compared to all the storms in the period of record at NYCCP. For documented landslides where the actual date of occurrence is uncertain, we analyzed rainfall data from the most probable storm(s) that likely preceded the event. For our analysis of storm characteristics, we defined a storm as being bound by a period of at least 6 hours in duration of no measurable rainfall. We compiled two metrics of duration (total storm duration [TSD] and continuous rainfall duration [CRD]) and storm rainfall (total storm rainfall [TSR] and total continuous rainfall [TCR]) from which mean rainfall intensity was derived. Based on our analysis of the seasonality of major storms and landslides, we separated our analysis to reflect a notable difference in mean TSR and TCR between spring and summer-fall storms, most commonly associated with nor'easters and tropical cyclones, respectively.

We derived separate rainfall thresholds using an iterative process beginning with rainfall values of storms in each seasonal period and a "best fit" approach separating total rainfall amounts (TSR or TCR) or their equivalent mean intensities from storms classified as being either associated with landslides in the Atlantic Highlands area or elsewhere in the New York City-northern New Jersey area, and storms without documented landslides. Storm-specific news media accounts were scrutinized to establish the absence of landslides, including from the nearby newspapers in the county that extend back to 1878. The existing database of documented landslides in the area was too small to evaluate the thresholds, but data from our current monitoring may allow further refinement of the thresholds as necessary.

Monitoring of meteorological and hydrologic conditions began at two sites of historical landslide movement in the summer of 2015. In June 2015, we installed a rain gauge and an observation well along with several survey targets to monitor slope movement using a total station. Additional sensors to monitor soil moisture and continuously monitor landslide movement and a second observation well were installed in August 2015. We added a second rain gauge beneath the forest canopy, additional soil moisture sensors, and sensor to continuously monitor landslide movement by December 2015.

Our initial monitoring site is located on the moderate slope below Mount Mitchill Scenic Overlook (MMSO) county park that is inferred to be the main scarp of a deep-seated rotational landslide in 1782 (Minard, 1974). The slope is covered with a veneer of historical slope colluvium that varies in thickness, but that is likely thickest in the lower slope. The site is adjacent to scars that were noted by Minard (1974) that we infer to be shallow landslide source areas, and that are close to soil piping openings of various sizes. Our second monitoring site is located on private property directly downslope of the Ocean Boulevard bridge (OBB), where a May 2012 shallow landslide damaged a trail at the base of the slope. The upper part of the landslide is a scarp-bounded scar, which is the source area of the 2012 landslide and exposes the upper and lower contacts of the Sandy Hook member of the Red Bank Sand (Fig 2B). In the side wall of the scar, two distinct layers of sandy colluvium are exposed with a contact tilted north generally parallel to the local slope. Lateral scarps that flank the area suggest the 2012 failure occurred within the limits of a pre-existing, likely historical landslide from which the bridge likely derives its nickname the "landslide" bridge. Both sites are covered by hardwood forest, but a cleared and generally level area exists at the base of the slope at MMSO that was previously the site of a house.

At the MMSO site, rainfall is monitored at both the cleared area and beneath the forest canopy by two Texas Electronics TR-525USW rain gauges. The rain gauges have a resolution of 0.25 mm and an accuracy of 1 percent up to 50 mm/hr. Five Campbell Scientific CS655 sensors monitor volumetric water content (VWC) of the sandy colluvium at depths up to 50 cm in three locations on the slope and in different positions beneath the forest canopy. The CS655 probe is configured as a water content reflectometer and VWC is derived from the probe's sensitivity to dielectric permittivity (accuracy ~ ±3 percent). Sensor SM1 (depth 37cm) is located at the base of the slope at the edge of the clearing where the slope is covered by ground ivy and leaf litter. Sensors SM2 (depth 25cm) and SM3 (depth 50 cm) are located directly downslope of one of the largest deciduous trees on the slope. Sensors SM4 (depth 25 cm) and SM5 (depth 50 cm) are located in an area of shallow ironstone. The groundwater level (GWL) is monitored in the lower part of the bluff a short distance east of the clearing in a 1.9-m-deep observation well in which a 350 kPa Geokon 4500S vibrating-wire piezometer (VWP) is installed. A second VWP measures barometric pressure. Manual GWL measurements were taken during site visits to calibrate the groundwater depth derived from the piezometer's pressure reading. Periodic total station surveying of targets grouted into the slope colluvium was used to monitor shallow slope movement in the lower bluff.

At the OBB site, the shallow GWL in the colluvium is monitored directly east of the scar of the 2012 landslide in the upper part of the slope in a 3.8-m-deep steel observation well. A Measurement Specialties PT8101 cable extension transducer (CET) monitors movement of the soil block across the left-flank of the failure. The CET has an accuracy of 0.1 percent of its full stroke (152 cm) that may result in deviations up to 1.5 mm. In addition, the stainless steel cable that spans the flank of the landslide and is attached to the CET is subject to temperature-related changes in the length of up to 1.7 mm.

RESULTS

Seasonality of landslides and major storms

The seasonality of landslide occurrence in the Atlantic Highlands area can generally be divided into two periods (Fig. 3): (1) spring and (2) late summer-fall, which correspond to times when nor'easters and tropical cyclones affect the area with heavy rainfall, respectively. Of the 26 documented landslides in Atlantic Highlands area landslides, more than half occurred between August and October, coincident with the peak of the Atlantic hurricane season. Most of the remainder of the documented landslides occurred in March or April, and are associated with springtime nor'easters. Analysis of late summer-fall storm data showed a high proportion of major storms induced landslides in the study area when the total storm rainfall (TSR) was above 174 mm. Since 1876, six of the 11 late summer-fall major storms where TSR exceeded 174 mm storms have induced landslides in the Atlantic Highlands area. Most of these late summer-fall major storms were associated with tropical cyclones including historic storms such as the 1938 Great New England and 1944 Great Atlantic hurricanes, and most recently, Tropical Storm Irene in 2011, all of which occurred between August and November (Fig. 3). For the major storms where TSR exceeded 174 mm in less than 72 hours, the percentage that induced landslides in the Atlantic Highland area ranged from 70 to 75 percent. Two of the other late summer-fall major storms caused landslides elsewhere in Monmouth County, and another caused landslides in the New York City metropolitan area which includes northern New Jersey. One other major storm is the result of a springtime nor'easter. Most of the documented spring landslides are related to storms where TSR was above 102 mm. Two-day rainfall periods where total rainfall exceeds this value (Fig. 3) captures the springtime nor'easters that triggered landslides in the Atlantic Highlands area.

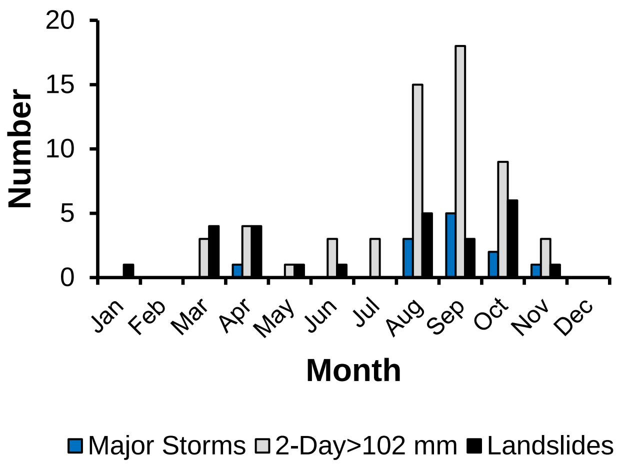


Figure 3. Seasonality of selected storms (1876-2016) and documented landslides (1903-2016). Major storms have total storm rainfall above 174 mm, and all but one occurred between August and November. Plot also shows seasonality of successive 2-day rainfall periods with total rainfall amounts exceeding 102 mm. This rainfall metric captures springtime nor'easters some of which have induced landslides.

Critical rainfall characteristics

Rainfall characteristics for storms associated with landslide movement vary seasonally in intensity and rainfall amount, but extended duration is characteristic of all storms that induced movement (Table 1). Mean peak rainfall intensity and rainfall amounts (TSR, TCR) of springtime storms are notably lower than for storms that occur later in the year during hurricane season. Both mean total storm and continuous (hourly) rainfall duration (TSD, CRD) are notably high for all storms that induce landslide movement.

Table 1. Comparison of critical rainfall characteristics for springtime and late summer-fall storms that induced landslides.

	I_P mm/hr	TSR mm	TCR mm	TSD hrs	CRD hrs
	Springtime storms (nor'easters)				
Mean	19	133	106	37	21
Range	10-30	104-214	51-141	18-52	9-36
	Late summer-fall storms (tropical cyclones)				
Mean	27	209	179	41	24
Range	20-40	142-295	75-295	30-79	13-33

Ip – peak rainfall intensity; TSR – total storm rainfall; TCR – total continuous rainfall; TSD – total storm duration; CRD – continuous rainfall duration.

Provisional rainfall thresholds

We subdivided the limited rainfall data based on the seasonality of landslide occurrence and preliminary data on seasonal variation in hydrologic conditions to derive two provisional rainfall thresholds for shallow landslide initiation. For late summer-fall storms between late July and November, the rainfall threshold was derived from data from six storms that induced landslides and 11 storms with no documented landslides that has the equation:

$$I = 88.79D^{-0.82} \tag{1}$$

where I is the rainfall intensity (mm/hr) and D is the duration of rainfall (h).

Figure 4A shows the summer-fall rainfall threshold plotted with actual data from storms with shallow landslides in the Atlantic Highlands area, elsewhere in the northern New Jersey-New York City area, and from storms with no documented landslides. Rainfall values fall below the threshold for only one summer-fall Atlantic Highlands-area storm associated with failure of a modified residential backyard slope. The threshold is most robust for storms where the rainfall duration exceeds 24 hours. For spring nor'easters, we developed a second provisional rainfall threshold (Fig. 4B) derived from data from five storms that triggered landslides and 10 spring storms with no documented landslides that has the equation:

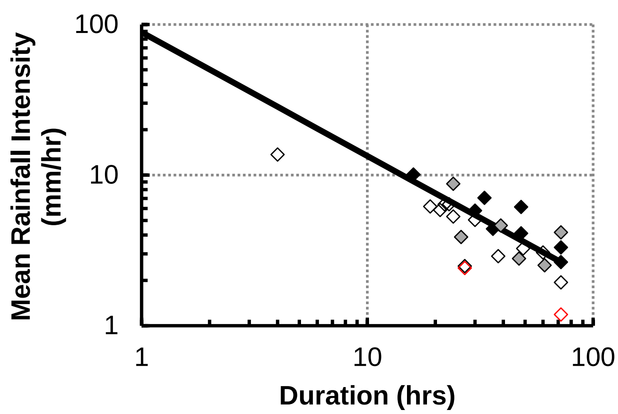
$$I = 68.63D^{-0.90} \tag{2}$$

with the variables as defined above.

As with the summer-fall threshold, rainfall values from only one spring storm associated with landslide movement fall below the curve. The landslide that occurred during this May 2012 storm was the partial reactivation of a pre-existing landslide at our OBB research site, and was preceded by the heavy rainfall during two previous storms in 2007 and 2011. We speculate that movement of the landslide may have initiated during a previous storm based on a photograph of the site taken in 2007, but remained restricted to the upper slope until movement accelerated during the later May 2012 storm and damaged the trail at the base of the slope.

Continuous meteorological monitoring

Rainfall monitoring at MMSO occurred during a period of below normal rainfall in the region. The data collection period therefore lacked a threshold-exceeding storm, but included a major regional blizzard that resulted in heavy snowfall. Daily rainfall exceeded 25 mm only ten times between June 2015 and July 2016. During the monitoring period the highest daily rainfall was 61 mm associated with a five-day nor'easter-like storm from September 29 through October 3, 2015 for which the total rainfall amount was 94 mm. Successive daily rainfall amounts of two- and three- days duration exceeded 25 mm only 13 and 16 times, respectively. Our rain gauge installed beneath the canopy indicated that the canopy intercepted about 9 percent of the total rainfall for the entire overlapping monitoring period (December 2015-July 2016) (Table 2) and that the highest canopy interception (21%) occurred during meteorological spring (March-May) when deciduous trees and shrubs leaf out. In winter and spring, effective canopy interception decreased during storms where daily rainfall exceeded 13 mm. The snow water equivalent (SWE) of the snowpack resulting from a January 22-23, 2016 blizzard was not representatively recorded by either rain gauge. The NYCCP rain gauge reported a snow fall amount of 681 mm with a SWE of 59 mm. Based on blizzard conditions at the site, we speculate that most of the snow fall was not retained in the collectors. The small portion of snow that remained in the collectors likely melted during and in between rain-on-snow events in early February.



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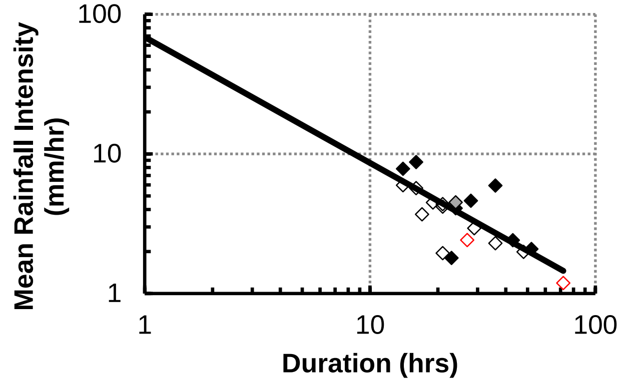


B

Figure 4. Rainfall thresholds for summer-fall storms (A) and spring nor'easters (B) in the Atlantic Highlands area. Actual rainfall amounts for major storms that caused landslides in the Atlantic Highlands area (black diamonds), elsewhere in nearby New Jersey and the New York City area (gray diamonds), and storms with no documented landslides (open diamonds). Red open diamonds from storm in current monitoring period. A storm may be represented by several data points representing mean intensities of different duration within the storm.

Table 2. Comparison of effective rainfall ratio beneath canopy for entire monitoring period (Dec 16, 2015 to July 31, 2016) and meteorological seasons for various daily rainfall ranges.

Daily Rainfall (mm)	Monitoring Period			
	Entire	Winter	Spring	Summer
	Ratio (%)			
0-38	91	91	79	104
>13	92	91	83	103
2.5-13	82	77	68	110

Continuous hydrologic monitoring

The results of soil moisture monitoring at MMSO (Figs. 5, 6A) indicated heterogeneous response to rainfall in shallow colluvium depending on location on the forested slope. The VWC of the well-drained sandy colluvium was relatively low throughout the monitoring period, remaining below 10 percent except for transient increases during moderate to heavy rainfall. A minimum TSR or daily rainfall value of about 10 mm was generally required to initiate a notable increase in soil moisture. The highest measured VWC reached slightly above 18 percent during a 2-day storm in mid-February. Soil moisture response corresponded to TSR or daily rainfall above the minimum value at two locations on the slope—at the base of the slope (SM1) in a location with little canopy cover and in the upper middle slope (SM4 and SM5) in an area with smaller deciduous trees and shallow ironstone. The transient soil moisture response to storm rainfall directly below a large deciduous tree (SM2 and SM3) was negligible throughout most of the period until late May 2016. The conditions contributing to the enhanced response that began in May 2016 are unclear, but may include an increase in the contribution of macropores associated with rotted roots or rodent holes to local infiltration or a local reduction in canopy interception. In general, the absolute and average magnitude of the soil moisture response was highest where and when the ground was least protected by the forested canopy. At SM1 where only ground vegetation (ivy) and leaf litter intercepts most rainfall, the magnitude of the storm-induced transient soil moisture rise (TSMR) ranged from 1 to 12 percent. On average, the TSMR at SM1 was nearly the same in the three of the four seasons (fall, winter, and summer) and only slightly lower in spring, possibly due to the absence of heavy rainfall during spring in 2016. In contrast, the TSMR was considerably lower at the other two locations on the slope below the canopy, and on average was generally less than half that at SM1 for all but the winter season when leaves are off the dormant trees. Soil moisture decreased rapidly from the peak transient level upon cessation of rainfall or a decrease in intensity. Excluding the storm-induced TSMR, soil moisture gradually rose from an annual low in late September to annual high levels in late winter and spring.

Shallow GWLs fluctuated seasonally, diurnally, and responded to storm rainfall at both the MMSO and OBB sites. At MMSO, the average daily GWL fluctuated about 146 mm from an annual low level in early August 2015 to a peak in late February 2016 (Fig. 7). The peak GWL at MMSO followed the melting of the January 23, 2016 blizzard snowpack (for which the SWE likely exceeded 51 mm and two wet periods in early February, and also corresponded with the wettest day of the month. The GWL at MMSO was generally elevated from early October through early April when trees are dormant (leaf off conditions) and the slope shaded for most of the day due to its north aspect and seasonal low sun angle, and decreased hours of daylight. Subsequent to the peak annual level, the GWL at MMSO gradually decreased except for transient increases associated with storms or successive rainy days with moderate or heavy rainfall. At OBB, the annual low GWL in 2015 occurred in early September, slightly later than at MMSO. The average daily GWL rose 180 mm to a peak level at the end of February 2016, which was a few days later than at MMSO. The GWL at OBB was generally elevated from early November through the end of March and decreased rapidly from early May to August at nearly twice the rate as at MMSO.

Diurnal fluctuations in GWLs were also observed even during periods with no precipitation. In the hot summer portion of the growing season, the diurnal fluctuations had an inverse relationship with air temperature and were likely caused by variation in transpiration (Bond et al., 2002; Móricz, 2010). The relationship between air temperature and diurnal fluctuation in GWLs was not consistent throughout the year however.

Although a rainfall-induced transient rise in GWL occurred at both sites, at MMSO the response was similar to the response in shallow soil moisture (SM1) in both timing and duration (Fig. 6A). The peak transient GWL either corresponded with or occurred in close proximity with the peak rainfall intensity. As with the shallow soil moisture response, GWLs quickly decreased with cessation of rainfall or a decrease in intensity. A minimum rainfall amount of about 17 mm was required to generate a noticeable pore-water pressure response. At OBB, the magnitude of the transient rise was generally less than at MMSO and the time lag between peak rainfall intensity and the peak transient GWL was considerably higher (Fig. 6B). During summer storms where rainfall initiated overnight, the GWL response to rainfall was superimposed over the evening diurnal rise associated with decreased transpiration making it difficult to differentiate the relative contribution to the overall transient rise.

Periodic and continuous movement monitoring

Preliminary results of periodic and continuous movement monitoring indicate minor millimeter-scale movement at both the MMSO and OBB sites. Total station surveying results from June 2015 to August 2016 at the MMSO site indicate between 5 and 12 mm of horizontal displacement in the lower slope and yields a maximum average horizontal velocity of about 1 cm/yr. The highest average velocity was measured in the upslope target and both total displacement and average horizontal velocity decreased downslope. Total station surveying at the OBB site was adversely impacted by disturbance of the survey hub during maintenance activities along the trail. However, the results of surveying between

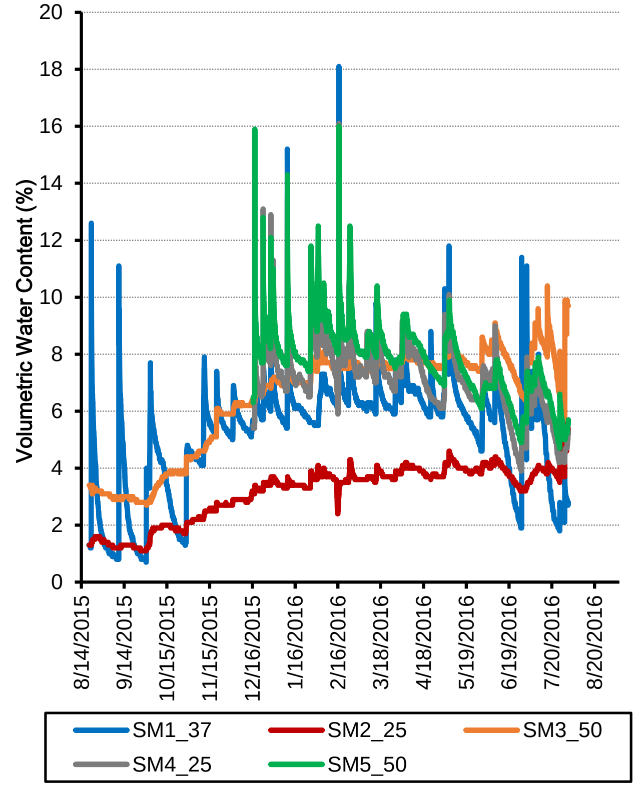
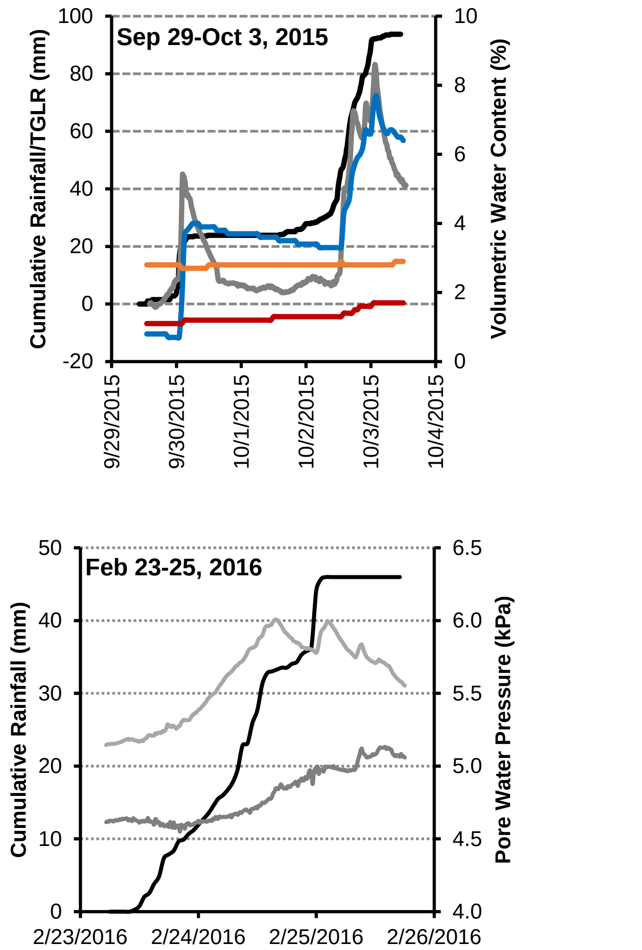


Figure 5. Soil moisture variation at the MMSO site. See text for explanation of sensor locations. Sensor label includes depth in centimeters (SM1_37).



A

B

Figure 6. Details of storm-induced transient soil moisture and groundwater level response. A. Response during September 29-October 3, 2015, storm event at MMSO. Transient rise in groundwater level at MMSO observation well (gray), and shallow soil moisture at two locations. SM1 (blue) is near base of slope. No response at location near large deciduous tree on slope (SM2; dark orange, SM3; orange). B. Groundwater (pore-water pressure) response during February 23-25, 2016, storm in two observations wells at MMSO (light gray) and OBB (dark gray). Peak response level at shallow MMSO observation well occurs during prolonged period of continuous rainfall. Peak response at deeper observation well at higher elevation on bluff at OBB follows cessation of rainfall by about 10 hours. Cumulative rainfall (black) shown on both plots.

May and August 2016 indicated up to 4 mm of movement, consistent with results from the CET for the same time interval (~3.5 mm of extension). Measured horizontal displacement of the lowermost three targets was no more than 2 mm and near the inferred resolution of the surveying method.

The CET data (Fig. 8) reveal episodic movement of the intact soil block of the 2012 landslide that corresponded with wet periods and some storms with moderate and heavy rainfall. Over a 305-day period from September 2015 to July 2016 the CET cable extended about 8 mm, which likely slightly underestimates the actual horizontal displacement, and yields an average horizontal velocity of about 1 cm/yr. The longest period of continuous movement lasted approximately 104 days between September 2015 and January 2016 during which the total movement was about 2.4 mm and the average horizontal velocity was 0.9 cm/yr. The highest average velocity occurred in the early part of this period and corresponded with the most significant storm of the entire monitoring period. Most of the subsequent movement episodes lasted no more than two weeks during which the average horizontal velocity was generally below 5 cm/yr.

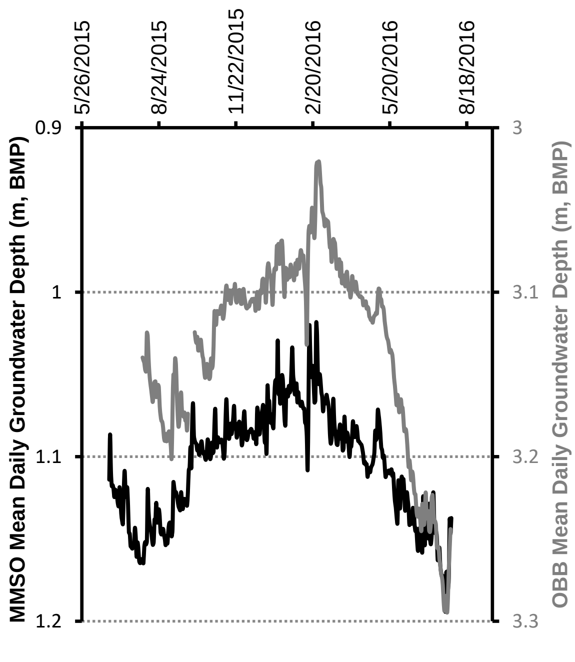


Figure 7. Average daily groundwater levels at MMSO (gray) and OBB (black) sites. Peak annual groundwater levels occurred in late February 2016 following the melting of the snowpack associated with a blizzard on January 23. Plot shows transient hydrologic response at both wells for daily or multiday rainfall amounts exceeding 17 mm.

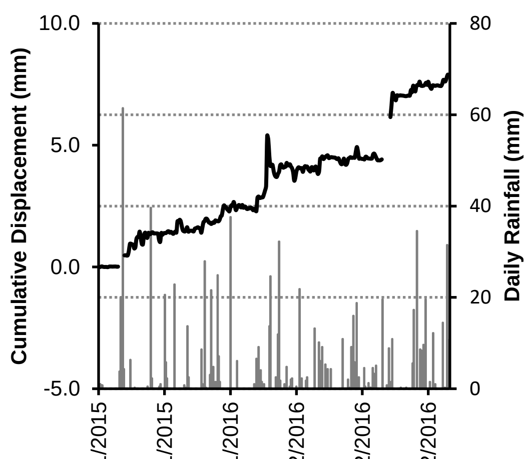


Figure 8. Approximate cumulative horizontal displacement of an intact soil block in the upper part of the 2012 landslide at the OBB site. Plot data is horizontal cable extension (black line) that has not been corrected and likely slightly underestimates actual horizontal displacement. Gaps are the result of temporary program shutdown and a tree fall on the cable, respectively. Small magnitude transient fluctuations are mostly due to temperature-related changes in cable length. Daily rainfall recorded at from MMSO rain gauge also shown.

DISCUSSION

Analysis of historical data for the Atlantic Highlands area revealed that more than half the documented landslides were caused by major storms associated with tropical cyclones that occurred between August and October. Results from the initial year of monitoring however, showed that shallow soil moisture and GWLs in the slope colluvium approached annual low levels during this period. Thus, major storms capable of inducing landslide movement occur during a seasonal high in slope stability associated with dry antecedent soil moisture. During this period, a combination of sustained continuous rainfall and high mean rainfall intensity appears to be required to sufficiently wet soils and generate elevated pore-water pressures to initiate failure. Historically, peak rainfall intensities during storms related to late summer-fall tropical cyclones have also been generally higher than during spring nor’easters.

In contrast, late fall through spring storms occur during wetter antecedent soil moisture and elevated GWL conditions, as revealed by our preliminary monitoring data. Thus, storms that occur in late winter and spring coincide with a seasonal low in slope stability. The lower rainfall threshold (Fig. 4B) for springtime nor’easters reflects the elevated (near annual high) shallow soil moisture and GWLs, particularly as in 2016, when recharge to the local slopes includes snowmelt of winter snowpack. In 2016, storms that closely followed the snowmelt resulted in the highest measured soil moisture and GWLs. The maximum transient peak soil moisture levels were measured during storms that occurred between December and February. These levels surpassed summer and fall transient peaks including those during the wettest storm of the monitoring period that occurred between September 29 and October 3, 2015, but remained below threshold levels. The period of the highest measured soil moisture levels may have extended through the end of spring if March and April in 2016 had not been exceptionally dry.

Monitoring of rainfall and soil moisture beneath the forest canopy indicates heterogeneous wetting and soil moisture response. For a three season period (winter through summer, 2015-16), our rainfall gauge indicated seasonal variation in canopy interception of rainfall that was also dependent on total rainfall. In winter and spring, interception was consistently reduced for daily rainfall values above

13 mm. Our soil moisture monitoring data at MMSO showed variable response to storm rainfall depending on location, but soil moisture gradually changed seasonally at all three locations on the slope. The higher response at SM1 which is at the edge of the forested slope, suggests that clear areas on the bluff may be more favorable for landslide initiation. Three landslides in Highlands that occurred during Tropical Storm Irene in 2011 were located in gaps in the forested slopes. Several of the documented landslides are also bounded upslope by relatively flat, landscaped backyards that have few trees and are dominantly lawn—sites of likely enhanced infiltration of rainfall.

Differences in the timing and magnitude of the GWL response at the two observation wells may be due to several factors including depth-related travel time of infiltrating rainfall, enhancement of infiltration by macropore features (soil pipes), and differences in recharge area extent in the upper and lower bluffs. At MMSO, shallow GWLs response was similar to shallow soil moisture response in both timing and duration indicating rapid infiltration through the uppermost shallow colluvium to the shallow groundwater table. The proximity of soil pipe features to the well may facilitate both rapid infiltration and subsequent dewatering of the lower slope. In the deeper OBB observation well in the upper bluff, the time to reach the transient peak GWL was, on average, considerably longer, which may be due to the increased depth of the groundwater table. Another factor may include a greater recharge area contributing to the response of the OBB well, which includes the flat areas upslope of the bridge. If exfiltration to the base of the colluvium from perched water in the underlying Sandy Hook member contributes to the observed response at OBB, then groundwater travel times within the unit may, in part, explain the longer response time. Recharge areas for the Sandy Hook member are presumably a considerable distance upslope of the well or require movement of water through increasingly thicker section of the overlying Shrewsbury member of the Red Bank Sand in relation to upslope distance from the well.

The very slow downslope movement of slope colluvium at MMSO and the episodic movement of the upper part of the 2012 landslide at OBB revealed by total station surveying and continuous monitoring, respectively, suggest local marginal stability on bluff slopes, particularly in areas of historical landsliding. The magnitude of the measured movement (mm-scale) suggests that imperceptible slope movement may exist in other areas throughout the bluff. Such sites may also be susceptible to future damaging movement during rainstorms, possibly even when TSR falls below threshold levels.

CONCLUSIONS

We have defined provisional, seasonally variable rainfall thresholds for the Atlantic Highlands area based on our analysis of historical rainfall data from the NYCCP weather station and a limited dataset of documented shallow landslides that extends back to 1903. During the dry late summer and fall months, most of the historical major storms with rainfall amounts exceeding 174 mm have induced landslides. The percentage of these major storms that resulted in landslides is above 70 percent for storms where the critical rainfall amount occurred in 72 hours or less. During the spring when elevated soil moisture is near annual high levels, nor'easters with rainfall amounts exceeding 102 mm have set off landslides. Documented summer and fall storms for which the rainfall amounts exceed only the spring threshold have not triggered landslides.

An objective of our continued monitoring is to capture the hydrologic response and movement data during major storms and changes in antecedent soil moisture over various durations. Our initial results reveal seasonal changes in soil moisture and seasonally variable storm response. Our monitoring results also indicate heterogeneous soil moisture response beneath the forested slopes, and suggest that increased soil moisture and pore-water pressure is more likely in open areas or areas with decreased forest density, which may favor such sites for future slope failure. Movement monitoring suggests locally marginal stability in areas of historical landsliding and renewed movement may occur where historical landslides are present on the bluff at rainfall amounts below the threshold levels. The best documented case history of a slope failure (Stanford, 1999) also indicates that site-specific conditions may contribute to shallow landslides even when TSR falls below threshold levels.

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