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ORIGINAL PAPER

A Study of the Impacts of Freeze–Thaw on Cliff Recession at the Calvert Cliffs in Calvert County, Maryland

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Abstract The Calvert Cliffs, which form much of the western coastline of the Chesapeake Bay in Calvert County, Maryland, are actively eroding and destabilizing, yielding critical situations for many homes in close proximity to the slope's crest. Past studies have identified that waves directly interacting with the slope toe control cliff recession; however, where waves do not regularly interact with the slope toe, freeze–thaw controls recession. This study investigated the validity of this second claim by analyzing the recession rate and freeze–thaw behavior of six study sites along the Calvert Cliffs that are not directly affected by waves. While waves do remove failed material from the toe in these regions, freeze–thaw is believed to be the dominant factor driving recession at these sites. Past recession rates were calculated using historical aerial photographs and were analyzed together with a number of other variables selected to represent the freeze–thaw behavior of the Calvert Cliffs. The investigation studied sixteen independent variables and found that over 65 % of recession at these study sites can be represented by freeze–thaw through the following variables: (1) slope aspect, (2) soil freeze–thaw susceptibility, (3) the number of freeze–thaw cycles, and (4) the weighted shear strength. Future mitigation techniques at these sites should focus on addressing these variables. Unmitigated, the Calvert Cliffs will continue to recede until a stable slope angle is reached and maintained.

Keywords Cliff recession · Freeze–thaw · Slope instability · Coastal slopes · Calvert Cliffs

1 Introduction

The Calvert Cliffs are a geologic feature occurring in Calvert County, Maryland. These coastal bluffs occur along the western coastline of the Chesapeake Bay in Calvert County. This coastline is 45 km long, and the Calvert Cliffs compose almost 30 km of the total coastline (Wilcock et al. 1993). The location of Calvert County in Maryland with respect to the Chesapeake Bay is shown in Fig. 1a.

The Calvert Cliffs are composed of steep Miocene age sediments, 11–35 m high (Wilcock et al. 1993). The stratigraphy of the Calvert Cliffs is complex, featuring the Calvert, Choptank, and St. Mary's formations as well as post-Miocene deposits; stratigraphic units consist primarily of poorly-consolidated

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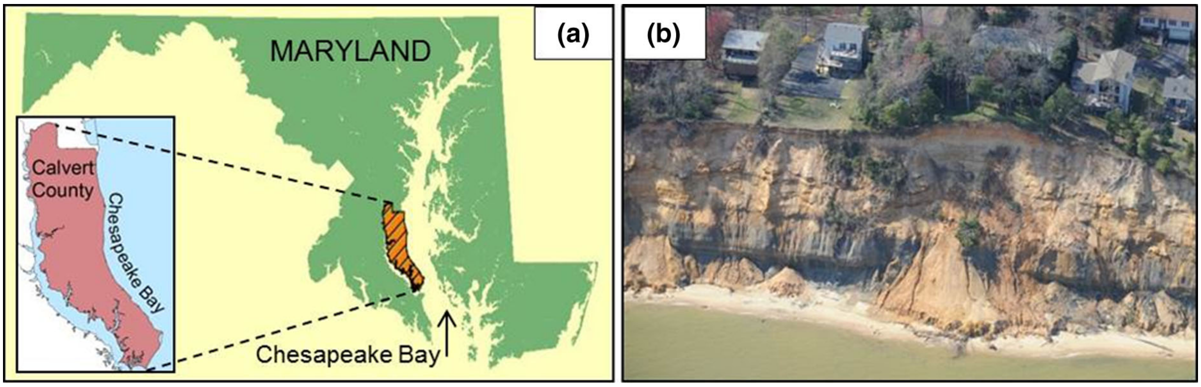

Fig. 1 **a** Map of Calvert County, MD, and **b** aerial photography showing study site (*data source* Calvert County Government 2012)

and interbedded sands, silts, and clays intermixed with shells and fossils (Ward and Andrews 2008). The cliffs are actively eroding, with recent recession rates published to be as high as 1.2 m/year (Miller 1995). The recession of the Calvert Cliffs significantly affects a number of homes located at the top of the slope throughout Calvert County, as shown in Fig. 1(b). As of 2010, there was one home that was overhanging the Calvert Cliffs. There were also nineteen homes that were within 1.5 m of the top of the slope, twenty homes within 3 m of the top of the slope, and forty-three homes within 6 m of the top of the slope (Calvert County et al. 2010).

There are multiple factors contributing to recession of the Calvert Cliffs. Previous studies (Miller 1995; Wilcock et al. 1998) identified that recession along the Calvert Cliffs has one of two primary driving mechanisms: (1) wave undercutting or (2) freeze–thaw induced soil strength reduction. These studies found that, where waves directly interact with the toe of the Calvert Cliffs, wave action controls recession; however, where waves do not regularly interact with the toe of the Calvert Cliffs, freeze–thaw events likely control recession. Both studies examined the relationship between cliff recession and the interaction between the waves and the cliffs to validate their claims. However, there was little explanation as to how or why it was established that freeze–thaw drives recession rate along the Calvert Cliffs where wave action did not.

The objective of this study is to determine if a meaningful relationship does exist between freeze–thaw and cliff recession rate in areas where waves do not directly interact with the base of the Calvert Cliffs. If such a relationship does exist, this work will identify the specific variables that control recession rate. These critical variables can be used to develop mitigation strategies to address the key factors in freeze–thaw controlled recession.

2 Study Area

The study area lies within a 30 km section of the Calvert Cliffs coastline, which includes 19 km of cliffs. In this study, six sites were selected for investigation, as identified in Fig. 2. From north to south, these sites are: SCN (Scientists' Cliffs North), SCS (Scientists' Cliffs South), CB (Calvert Beach), CCSP (Calvert Cliffs State Park), PC (Park Chesapeake), and CRE (Chesapeake Ranch Estates). These study sites were selected for a number of reasons. For each study site selected, historical data were available and/or the study site was accessible for observation from the beach. Accessibility from the beach enabled field visits, and availability of data enabled a reasonable analysis to be conducted. Additionally, past work (Miller 1995; Wilcock et al. 1998) indicated that the cliff recession at four of these sites (SCN, SCS, CCSP, and CRE) is driven by freeze–thaw action and is not regularly affected by waves. The other two sites were selected because, observationally, waves do not interact with the cliff toe during regular weather events (although waves do gradually remove failed material from the slope toe). At least four sub-sites were identified at each study site so that the variation of properties within each site could be explored. The latitude and longitude of each sub-site is given in Table 1.

2.1 Previous Studies on Instability and Recession of the Calvert Cliffs

There is significant variation in the hydrologic regime and strength of the soils along the length of the Calvert Cliffs (Miller 1995; Ward and Andrews 2008). In some locations, slopes can reach near-vertical as they erode and evolve—slope angles in this study were measured as steep as 88 degrees. However, field surveys by Clark et al. (2004) indicated that the slopes are stable at angles of 30°–35°, assuming that wave action is not affecting the toe of the slope. If the toe of the slopes along the Calvert Cliffs is protected, stable slope angles can be achieved in 30–40 years.

According to Miller (1995), the slope failure mechanisms that act along the Calvert Cliffs all involve failure within the outer few meters of the cliff face. Spalling and shallow slides are the primary failure mechanisms that occur along the Calvert Cliffs. Deep seated slides do not commonly occur. These failure mechanisms can be triggered by internal instability or erosion forces overcoming the slope's resisting forces. Clark et al. (2004) noted that wave undercutting, freeze–thaw, and groundwater movement all contribute to cliff recession along the Calvert Cliffs. After rigorous studies at multiple locations of the wave activity along the Calvert Cliffs, Miller (1995) and Wilcock et al. (1998) broadly concluded that where waves interact with the toe of a slope (meaning that wave strength exceeds the soil shear strength), wave action controls recession rate. They also stated that, where waves did not interact with the toe of the slope, freeze–thaw controls recession rate. Wilcock et al. (1998) noted that both wave action and freeze–thaw can occur on the same slope, but that one process or the other is typically the dominant force driving recession. The dominant erosion force at a given slope depends on the stress magnitude of the waves, the frequency of wave interaction with the base of the slope, and the shear strength of the base of the slope (Miller 1995); the dominant force at a slope could conceivably vary with time, though this was not addressed by previous studies as no change in the dominant force driving recession at any slope was noted during the study periods. Both Miller (1995) and Wilcock et al. (1998) showed that recession rates for the slopes with recession driven by wave undercutting were higher than those for slopes with recession driven by freeze–thaw, but the recession rates for freeze–thaw controlled slopes were still measureable and significant. No study of the relationship between freeze–thaw and cliff recession for more than one or two locations along the Calvert Cliffs has been conducted. Schweitzer (1993) conducted a study in which erosion pins and catchment basins were installed and monitored for 1 year at two slopes in close proximity to each other (located at Calvert Cliffs State Park). This study concluded that freeze–thaw was important to the recession rate of the Calvert Cliffs, but did not quantify how freeze–thaw contributed to recession. Miller (1995) expanded this study by installing and monitoring erosion pins for 2 years in several locations (at Scientists' Cliffs and Calvert Cliffs State Park, identified in this study in Table 1 and Fig. 2). The freeze–thaw erosion measured using the erosion pins was found to contribute to a large percent of the recession rates. However, only a short time-period was analyzed and only the freeze–thaw at the base of the slopes was considered. After observing the erosion pins at one of these locations (Scientists' Cliffs) for over 10 years, Miller et al. (2006)

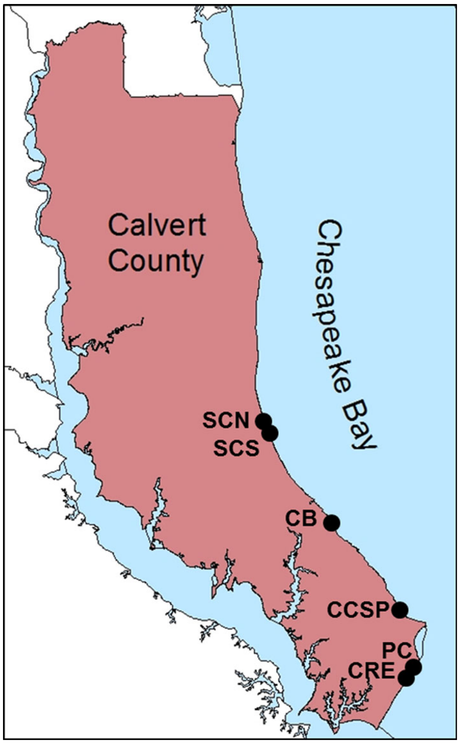

Fig. 2 Location of study sites within Calvert County (*map data source* Calvert County Government 2012)

Table 1 Geographic coordinates and calculated recession rates of study sub-sites

Study site		Sub-site	Latitude	Longitude	Recession rate (m/year) 2003–2006	Recession rate (m/year) 2006–2007	Recession rate (m/year) 2007–2011
Name	Symbol						
Scientists' Cliffs North	SCN	SCN1	38.5249N	76.5148W	0.00*	0.00*	0.18*
		SCN2	38.5242N	76.5146W	0.00*	0.00	0.07*
		SCN3	38.5224N	76.5138W	0.00	0.00*	0.00
		SCN4	38.5204N	76.5131W	0.00*	0.00*	0.00*
Scientists' Cliffs South	SCS	SCS5	38.5121N	76.5100W	0.22	0.26	0.17
		SCS6	38.5115N	76.5098W	0.58	0.57	1.37
		SCS7	38.5083N	76.5084W	0.12	0.00*	0.07
		SCS8	38.5050N	76.5068W	0.18	0.00*	0.41
		SCS9	38.5045N	76.5066W	0.13	0.71	0.56
Calvert Beach	CB	CB1	38.4760N	76.4873W	0.27	1.58	0.42
		CB2	38.4678N	76.4769W	0.00	0.00*	0.00
		CB3	38.4672N	76.4761W	0.00*	0.00*	0.70
		CB4	38.4670N	76.4758W	0.67	0.26	0.00*
Calvert Cliffs State Park	CCSP	CCSP1	38.4018N	76.4075W	0.27	0.52	0.55
		CCSP2	38.4010N	76.4074W	0.70	0.95	0.88
		CCSP3	38.4008N	76.4071W	0.56	0.50	0.66
		CCSP4	38.4004N	76.4070W	0.35	1.50	0.45
Park Chesapeake	PC	PC_G	38.3687N	76.3899W	0.00*	0.00*	0.21
		PC1	38.3682N	76.3899W	0.21	0.00*	1.02
		PC2	38.3671N	76.3899W	0.44	0.00*	0.23
		PC3	38.3667N	76.3899W	0.17	0.00*	0.19
		PC4	38.3663N	76.3901W	0.15	0.31	0.45
Chesapeake Ranch Estates	CRE	CRE1	38.3577N	76.3904W	0.37	0.76	1.56
		CRE2	38.3567N	76.3912W	1.17	0.92	0.25
		CRE3	38.3558N	76.3916W	0.28	0.27	1.44
		CRE4	38.3549N	76.3925W	0.55	0.65	0.36

* Calculated recession values (meters) lower than the image resolution were assumed to be 0

recommended that freeze–thaw drives cliff recession; however, only qualitative (rather than quantitative) evidence was presented to support these claims. It was also noted in their research that vegetated slopes were insulated in the winter, preventing cyclic freezing, and reducing recession rates compared to un-vegetated slopes.

3 Data Collection and Variable Definition

Cliff recession is a complex issue. The impact of freeze–thaw is not directly quantifiable, as it is a function of moisture conditions, grain size, relative density, soil thermal conductivity, and a number of other factors. Therefore, in this study the relationship between freeze–thaw and recession is indirectly investigated using a number of variables that are related to freeze–thaw and comparing the variables to recession rate.

Field work was conducted from June to August in 2012. The study sites were accessed from the beach below so that the entire face of the cliffs could be observed. Digital images were collected using a Kodak EasyShare ZD15 camera. Thermal IR images at all sites were also collected using a FLIR ThermaCAM SC640. Due to the instability of the cliffs, no invasive soil sampling or testing was performed on the cliffs. Rather, samples of failed material (where available) were collected from the base of the cliff for laboratory testing and classification. The impact of waves on each site was also noted to ensure that none of the sites had regular wave action, potentially contributing to cliff recession. While no wave action against the slope was noted during field exploration, storm events can bring storm surges; anecdotally, these infrequent storm surges can be in excess of 2 m. As mentioned previously, the impact of waves on cliff recession depends on the stress magnitude of the waves, the frequency of wave interaction with the base of the slope, and the shear strength of the base of the slope (Miller 1995), so the impacts of storm surges on cliff recession would have to be assessed on a case-by-case and site-by-site basis.

3.1 Cliff Instability and Recession

The stability of a slope is a measure of how much resistance it has against erosion, mass wasting, and other destabilizing forces. Soil's resistance to these forces, or shear strength, must be greater than the shear forces required to satisfy equilibrium with the destabilizing forces (Duncan and Wright 2005). This is simple enough in principle, but identifying and quantifying the destabilizing forces and determining the soil's shear strength are challenging.

Coastal cliff instability leads to slope failure and consequently cliff recession, which over time can be measured as a recession rate because coastal cliff recession occurs cyclically. First, one or more destabilizing mechanism acts on the slope. When the slope is no longer able to resist the destabilizing mechanism(s), failure occurs and delivers slope material to the toe of the cliff. This material is removed by waves, exposing the slope toe once again, and the cycle repeats (Edil 2010; Hampton et al. 2004). As this cycle repeats, material is lost from the top and face of the coastal cliffs and transported to the toe. As waves remove the failed material, more material is lost from the cliff and the process continues. Measured horizontally, this episodic loss of soil averaged over a period of time, or cliff recession, is particularly critical to structures constructed in close proximity to the top of coastal cliffs, which often leads to a desire to monitor recession rates.

Cliff recession can be monitored using a variety of methods. Some of the most common ways include using ground based surveys, aerial photography, and LiDAR. All methods have strengths and weaknesses. For instance, historical aerial photographs are available from a number of sources for as far back as the 1920's, which allows for long-term analyses. Aerial photographs also provide good spatial coverage, especially when compared to field methods such as ground-based surveys. However, there are inaccuracies that get introduced into the analysis when aerial photographs are used, both from the internal workings of the camera system and also from the positions of the camera in relation to the terrain being photographed. If this uncertainty is not rectified, small errors in the camera are translated to large errors in the ground scale in the images. Additionally, some recession rate analyses choose to track the change in position of the top of the cliff, while others choose to use the toe of the cliff. In both instances, the feature of interest (top or toe of cliff) may be obscured from view due to vegetative cover at the top of the cliff or failed material gathered at the base of the cliff. Newer technologies like LiDAR are being used and developed to overcome some of these obstacles, but historic data are not often readily available and can be expensive to obtain (Hapke 2004).

As mentioned previously, there are a number of factors that affect the rate of coastal cliff recession. Besides the destabilizing factors acting upon the cliffs, recession rates are also a function of the shear strength of the cliff material and the internal stability of the slope. Soil shear strength is a function of the soil's cohesion and internal friction angle, as well as the magnitude of the (effective) normal stress acting on the soil; soil shear strength varies based on sediment composition and differs between and within each soil strata. Shear strength can be assessed by a number of laboratory and field tests to varying degrees of accuracy (Duncan and Wright 2005; Holtz et al. 2011). The internal stability of a slope depends on not only the shear strength of the soil(s) but also depends on the geometry of the slope and the presence (or absence) of groundwater. Slopes with greater heights and/or steeper slope angles will have more unstable conditions than slopes with lower heights and/or shallower slope angles (Edil and Vallejo 1980). Investigations on the height of coastal cliffs in general have found no direct relationship with their recession rates (Buckler and Winters 1983; Kamphuis 1987), but the slope angles of coastal bluffs at one site along the Calvert Cliffs has been found to have a relationship with recession rates (Schweitzer 1993). The location of groundwater within a slope, as well as groundwater flow (seepage) is also critical to the slope's stability. As the water level rises within a slope, the stability decreases (Edil and Vallejo 1980; Sterrett and Edil 1982). Seepage, or water flow through soil, becomes a problem for slopes when there are soil strata with varying hydraulic conductivities, forcing the water out of the face of the cliff. It has been observed that, as the height of a cliff increases, the impact of groundwater seepage on that slope's stability also increases (Buckler and Winters 1983).

For this study, high-resolution aerial images of the cliffs from 2003, 2006, 2007, and 2011 were used in the recession rate analysis. The 2003 and 2006 have 30.5 cm/pixel resolution, while the 2007 and 2011 images have 15.25 cm/pixel resolution. The dates the images were collected are: April 6–7, 2003; March 18, 2006; March 20, 2007; and March 25, 2011 (Calvert County Government 2012). These images were used to calculate the amount of recession, in meters, that occurred between the years at each sub-site. Because the images were all taken at the same time of year, after the freeze–thaw season was over, the slight variations from whole years in the dates of the images were neglected. The recession rate analysis was performed using ArcMap 10. For each sub-site, the distance from a permanent structure to the crest of the cliff was measured for each aerial image; the change in this distance between images was the recession for the time interval between the images. This process is demonstrated in Fig. 3. Line 1 (Fig. 3) is the measured distance from a permanent structure to the crest of the cliff; the change in this distance between images was considered to be the recession for the time interval between the images. The measured distance, line 1, was calibrated by measuring a permanent structure, line 2, and scaling the measured distances by it as explained in Zwissler (2013); the directly measured recession was scaled to account for the slight variation in image scale that resulted from slightly different flight paths while the images were being collected. If the calculated total recession for a particular sub-site and time interval was smaller than the image resolution, the recession rate was assumed to be zero; these values are marked with an asterisk in Table 1, which contains the calculated recession rates.

3.2 Freeze–Thaw Behavior and Susceptibility

Freeze–thaw occurs when soil loses enough heat for the pore water to freeze. This freezing occurs from the ground surface—so for the Calvert Cliffs, from the cliff face—to a depth which is controlled by the magnitude of soil heat loss; the soil heat loss depends on the thermal properties of the soil (Gatto 1995). Freezing of the pore water leads to expansion, as water expands about nine percent by volume when it is frozen to ice (American Concrete Pavement Institute 2008).

For soils to experience freeze–thaw, pore water must be present. Silts are the soils that are the most susceptible to freeze–thaw issues. Silts have high capillarity, which pulls water to the freezing front; silts also have sufficient hydraulic conductivity to allow water to flow during a freezing event. Fine sands and clays can also experience freeze–thaw, but usually to a lesser degree (Gatto 1995; Michalowski and Zhu 2006)). The freezing behavior of soil with varying particle-size distribution and mineralogy also varies. While different minerals tend to have different thermal conductivities, particle-size distribution is what tends to control soil freezing behavior. Technically, soil is considered to be "frozen" when it is below 0 °C (32° F), regardless of the phase condition of the water–solid (ice), liquid, or intermediate. At what point the "frozen" soil pore water becomes solid ice depends on the particle size distribution. The freezing of sands and silts is a function of the pore diameter—finer pore spaces have more capillarity, or surface tension of water present within the voids. However, the freezing of clays is more complex. Clay particles are colloidal with very large surface areas compared to the particle thickness, which means that the negatively charged particles have the potential for a large amount of adsorption, resulting in a thick diffused double layer. Adsorbed water cannot readily freeze; any water present outside of the diffused double layer, or "free water", is what would freeze. Additionally, because of the small size of clay particles (diameter of less than 2 μm), the voids are small enough that capillarity prevents the water from freezing at 0 °C (McRoberts 1978).

For those soils that experience freeze–thaw, the destabilizing effects develop during the freezing phase. When thawing occurs, larger voids are present in the soil matrix and the soil structure is disturbed due to the ice expansion during freezing. After thawing,

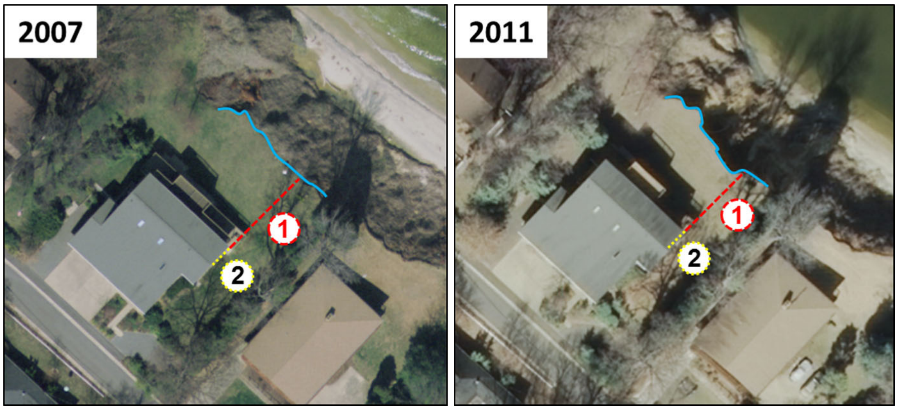

Fig. 3 Recession rate calculation demonstration (*image data source* Calvert County Government 2012)

there is also a higher moisture content present at the surface. These factors lead to a reduction in shear strength—there can be as much as a 50 % reduction in shear strength after a single freeze–thaw cycle (Gatto 1995).

3.2.1 *Temperature Profile and Frequency of Freeze–Thaw of Calvert Cliffs*

The thermal properties of soil and pore water affect the rate at which the temperature of the air interacts with the soil. The frequency and depth of the freezing pore water is what defines the freeze–thaw behavior of soil. Because the thermal properties of the layers of the Calvert Cliffs were not known, simplifying assumptions were made. A single "day of freezing" was defined as 1 day in which the average temperature remained below 0 °C. A single "freeze–thaw cycle" was defined as a single day in which the average temperature remained below 0 °C, or (when applicable) a group of days in which the maximum temperature remained consecutively below 0 °C. These two measures of freeze–thaw occurrence were chosen to assess if the amount of time the soil stays frozen (days of freezing) has more or less of an effect on recession rate than the number of times the soil freezes and thaws (freeze–thaw cycles). The typical method for accounting for the frequency and duration of freezing, called the freezing index (Joint Departments of the Army and Air Force 1987), was assesed but was not able to accurately represent freeze–thaw due to the lack of a well defined freezing period. For the Calvert Cliffs, counting the distinct freeze–thaw cycles and days of freezing is more useful.

Once these freeze–thaw metrics—days of freezing and freeze–thaw-cycles—were defined, the temperature profile of the cliffs was investigated. Temperature can vary greatly from one location to another, even over small distances and especially with elevation variations; being in close proximity to a body of water can also magnify these temperature variations. Because no temperature data were available for any of the study sites, regional temperature patterns were investigated by assessing spatial and temporal variations in temperature. Historical temperature data from 19 locations within 100 km of all study sites were obtained online from the National Climatic Data Center, or NCDC (NCDC/NOAA 2012). Ordinary kriging was performed using the statistical computing program R 2.15.0 (R Core Team 2012) to attempt to find a suitable model to represent the spatial trends in temperature. However, it was found that the spatial interpolation using kriging was no more accurate than using temperature data from an individual location. Because of this, temperature data (average, minimum, and maximum daily temperature) were used from the NCDC for Patuxent River Naval Air Station, the closest location with available data, which is located approximately 6.5 km southwest of CRE (southernmost site) and 26 km southeast from SCN (northernmost site). This temperature data were assumed to be representative of all study sites.

As discussed in Sect. 3.1, the amount of time between images was treated as whole years; the analysis was run from April 1 from the first year to March 31 of the last year in the time interval. These metrics—days of freezing and freeze thaw cycles—were then used to not only identify potential differences between the freeze–thaw instances in a given time interval, but to also determine if the number of instances of freezing and thawing or the amount of time the soil stays frozen in a given time interval was more influential in cliff recession.

3.2.2 Soil Layer Identification and Thickness Determination

In addition to the number of days of freezing and the number of freeze–thaw cycles, which were assumed to be uniform for the entire length of the Calvert Cliffs, the freeze–thaw susceptibility of the different stratigraphic units (henceforth called soil layers) composing the cliffs at the different study sites was also investigated. Before freeze–thaw susceptibility of the soil layers could be assessed, the layers present at each study sub-site were identified. Digital images taken at each sub-site were studied and compared to a subset of the previous studies conducted (Miller 1995; Shattuck 1904) to determine what each layer that was visually observed corresponded to in previous work. While not all of the sites selected for this work were studied previously, the cliffs are formed primarily of Miocene deposits dipping gently to the southeast (Kidwell 1997), which means that all layers appear in sequence and the stratigraphy at the previously unstudied sites can still be generally determined through interpolation.

Once the soil layers at each study site were identified, the thickness of each layer at each sub-site was measured using digital imagery. The actual height of the cliff at each sub-site was computed using topographic data in the form of 2 foot elevation contours from 2003; the contours have 16 cm/pixel resolution (Calvert County Government 2012). Using oblique aerial digital images from 2011(Calvert County Government 2012), which show the entire cliff height from a single reference point, the thickness of each layer and the total cliff height were measured using ArcMap 10. These thicknesses were then scaled by using the actual cliff height at each sub-site.

3.2.3 Moisture Conditions of Soil Layers

Moisture conditions of the soil layers were noted from historical data (Miller 1995), and were supplemented by analysis of digital and FLIR thermal IR images when historical data were not available. For study sites also investigated by Miller (1995), a geotechnical profile originating from soil boring information was available. This geotechnical profile noted soil moisture conditions. However, not all study sites were previously investigated. For the sites not previously investigated, if seepage out of the cliff face was noticeable, the soil was considered saturated. If no noticeable seepage was present, Miller's (1995) historical data for the soil strata at different study sites were verified with digital images and the FLIR thermal IR images. Moisture not detectable in digital images can be detected using the FLIR thermal IR images, which can be observed in Fig. 4. The image to the left is a digital image, and no noticeable moisture can be detected. The image to the right, a FLIR thermal IR image, shows a band of lower temperature with respect to the temperature of the surrounding soil, which is associated with moisture, near the top of the slope (Price 1980).

3.2.4 Freeze–Thaw Susceptibility of Soil Layers

After the layers present at each study site and sub-site were identified, their freeze–thaw susceptibility was analyzed. The soil samples collected during field work were tested in order to be classified using the Unified Soil Classification System (USCS). Testing of these samples included moisture content, specific gravity, grain size analysis, Atterberg limits, and USCS classification. These tests were performed, without deviation, according to the following standards:

- ASTM D422—63 (2007): Standard Test Method for Particle-Size Analysis of Soils
- ASTM D2216—10: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
- ASTM D2487—11: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
- ASTM D4318—10: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
- Micromeritics AccuPyc 1330 Helium Pycnometer User Manual (for specific gravity)

For the soil layers that were not represented by any of the soil samples analyzed in the laboratory, historical data were used from Miller (1995). While this data did not provide a USCS classification or enough data to obtain one, it did contain soil

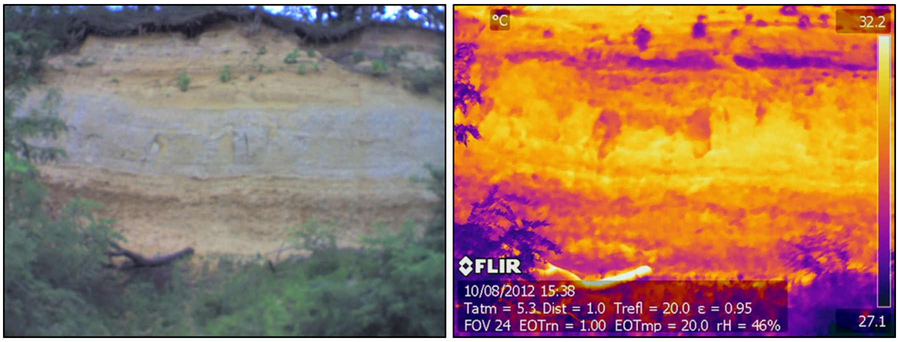

Fig. 4 Digital image and corresponding FLIR thermal IR image of a portion of a slope

descriptions and data on percent sand, silt, and clay.

Using the classification data for the soil layers, the freeze–thaw susceptibility of each layer could be assessed. This was analyzed using the frost susceptibility groups developed by the U.S. Army Corps of Engineers (Department of the Army Corps of Engineers Office of the Chief of Engineers 1984). This system identifies four freeze–thaw susceptibility categories, from F1 (least susceptible) to F4 (most susceptible). For the soil layers that had a USCS classification associated with them, the USCS and the percent of soil finer than 0.075 mm was used to determine the freeze–thaw susceptibility. For the soil layers lacking a USCS classification, the soil description and the percent silt/clay were used to determine the freeze–thaw susceptibility. Traditionally, the percent of soil that is finer than 0.02 mm is used in analyzing freeze–thaw susceptibility. However, because the percent of material that is finer than 0.02 mm was not available for any soil layer classified using the Miller (1995) data, it was adjusted so that all of the soil could be classified. The particle size of 0.075 mm was selected because this is the size that differentiates between coarse-grained materials (gravel and sand) and fine-grained materials (silt and clay) according to USCS, and thus data were available for all soil layers present at all study sites.

Once a freeze–thaw susceptibility of F1 to F4 was assigned to all soil layers, these classifications were adjusted to account for soil moisture conditions; if there is no moisture present, no freeze–thaw can occur regardless of particle size, so soil layers that had no moisture were given a freeze–thaw susceptibility of F1. After these adjustments were made, the total height of each freeze–thaw susceptibility class that is present at each sub-site was calculated. These heights were used to calculate the percent of the total cliff height composed of each freeze–thaw susceptibility class.

While these freeze–thaw metrics—days of freezing, number of freeze–thaw cycles, and freeze–thaw susceptibility—do not directly account for the depth of freezing, they can still be used to indirectly represent depth of freezing. Because no spatial variation with temperature is being represented in this analysis, all study sites are assumed to have the same number of days of freezing and freeze–thaw cycles per winter season. Therefore, those soil layers with high freeze–thaw susceptibility (F4 or F3) should have greater depths of freezing in a given winter season than those soil layers with low freeze–thaw susceptibility (F2 or F1) for the same winter season.

3.3 Other Potentially Significant Variables

While the recession rate and the freeze–thaw behavior of the cliffs were essential components of this analysis, there were a number of other variables that were also considered for their potential impacts on the recession rate of the Calvert Cliffs.

3.3.1 Cliff Height and Slope Angle

Cliff height and slope angle were both analyzed for each sub-site. These variables were considered because, as discussed in Sect. 3.1, increasing slope height and slope angle lead to an increase in the likelihood of slope failure. It makes sense, then, that an increased likelihood of slope failure might also lead to an increased recession rate. Both cliff height and slope angle were analyzed using ArcMap 10. Data containing contours derived from 2003 LiDAR data (Calvert County Government 2012) were used to calculate both the cliff height and the slope angle of the cliffs at each sub-site. While the slope angle changes every time there is a slope failure, a single slope angle was used for each sub-site due to the lack of data from all years of interest. Additionally, different sections of the cliff face at each sub-site often have different slopes (Miller 1995); however, the average slope over the entire height of the cliff was used and assumed to be representative of the slope.

3.3.2 *Weighted Shear Strength*

Shear strength was analyzed for the slope face at each sub-site. At the face of the cliff, there is little overburden stress acting. Using the Mohr–Coulomb failure criterion:

$$\tau = c + \sigma \tan(\varphi) \tag{1}$$

where τ = shear strength, c = cohesion, σ = normal stress, and φ = internal friction angle, it can be assumed that the soil shear strength at the face of the cliff can be modeled as being primarily cohesive (Holtz et al. 2011). Therefore, in this work, soil shear strength is assumed to be entirely composed of cohesive strength. Historical data from Miller (1995) were used to determine the shear strength of all but one soil layer. In this data set, cohesion (c) was determined using Torvane shear tests, Unconsolidated Undrained "Quick" triaxial tests, and Unconfined Compression triaxial tests. When a range of cohesive strengths was given, the average value was used. One soil layer (Zone 23, CRE Clay; more information can be found in Zwissler (2013)) did not have cohesive strength data available. For this layer, Standard Penetration Test (SPT) data were available (Miller 1995). This was used along with Table 7.5 from Budhu (2007) to approximate the soil's shear strength. In order to have a single value to represent the shear strength of each sub-site, weighted shear strength was calculated. The weighted shear strength of a sub-site was developed by weighting the shear strength of each layer present by the thickness of the layer.

3.3.3 *Vegetation*

The amount of vegetation was determined for each soil layer present in the slopes at each sub-site. Vegetation was investigated for two reasons: (1) the root system from vegetative cover on a slope often helps to stabilize it from shallow failure, and (2) vegetation can serve to insulate the slope from air temperature fluctuations, affecting the slope's freeze–thaw behavior. The vegetation was analyzed by looking at digital images of the slopes. The following qualitative rankings were given based on the vegetation present: a ranking of 1 meant no vegetation was present; a ranking of 2 meant that there was some vegetation, either sparsely covered or seasonally variable; a ranking of 3 meant full vegetation was present. Each soil layer present at each sub-site was given a qualitative ranking of 1–3. When the percent of the total cliff height composed of each freeze–thaw susceptibility class was determined, each freeze–thaw susceptibility class was also assigned a qualitative vegetation ranking of 1-3 based on the ranking of all layers contributing to that class.

3.3.4 *Slope Aspect*

The slope aspect, or the cardinal direction that the cliff faces, was analyzed for each study site. This variable was considered for two reasons. The first was to account for winter sun exposure. Due to the geographical location of the Calvert Cliffs, those cliffs facing the south generally receive more sun exposure during the winter than cliffs facing the north. Sun exposure indirectly affects the freeze–thaw behavior of the cliffs (Harlan and Nixon 1978); greater sun exposure leads to higher daily temperature variations and more freeze–thaw cycles, whereas less sun exposure leads to more uniform daily temperatures and less freeze–thaw cycles (Gatto 1995). The second reason to consider the slope aspect is to account for wind direction. Wind direction varies along the Calvert Cliffs due to their proximity to the Chesapeake Bay and because the cliffs face a variety of cardinal directions along the bay (Miller 1995). Storms that could affect cliff recession at locations not typically affected by waves (i.e. the study sites selected) may vary their effects depending on the direction the cliff is facing, as could potential wind erosion effects. The slope aspect at each study site was determined from a map. The slope aspect varied from NE to SE for the study sites. Values were assigned to each study site to represent the slope aspect: 1 was assigned to all sites facing NE; 2 was assigned to all sites facing NE to ENE; 3 was assigned to all sites

Table 2 Statistical information for all variables with continuous data

Variable	Mean	Median	Min.	Max.	Standard deviation
Cliff height (m)	20.82	22.71	6.71	31.09	6.97
Slope angle (degrees)	46.04	44.30	35.10	88.30	10.40
Weighted shear strength (kPa)	35.29	36.65	16.00	51.30	10.41
% Of total height of F-T susceptible layers—F4 (represented as a decimal)	0.19	0.08	0.00	0.70	0.24
% Of total height of F-T susceptible layers—F3 (represented as a decimal)	0.29	0.27	0.10	0.61	0.13
% Of total height of F-T susceptible layers—F2 (represented as a decimal)	0.42	0.40	0.02	0.87	0.24
% Of total height of F-T susceptible layers—F1 (represented as a decimal)	0.10	0.00	0.00	0.45	0.17
Number of days of freezing per year	24.25	25.75	21.00	26.00	2.32
Number of freeze–thaw cycles per year	21.50	22.00	18.00	24.50	2.69
Rainfall per year (mm)	1,180	1,147	1,122	1,272	66.04
Recession rate (m/year)	0.38	0.26	0.00	1.58	0.41

facing ENE; 4 was assigned to all sites facing ENE to E; and 5 was assigned to all sites facing SE.

3.3.5 *Rainfall Data*

Rainfall data were analyzed for the Calvert Cliffs as a whole. This variable was used, in addition to the slope aspect, to attempt to represent the effect that storms may have on recession rate. Rainfall data were obtained from the NCDC for Baltimore Washington International Airport, the closest location with available data, which is located approximately 73.5 km north–northwest of SCN (northernmost site) and 94 km north–northwest of CRE (southernmost site). The average yearly rainfall was calculated during each time intervals between the images used in the recession rate determination. Any missing data were assumed to be negligible. Just like for days of freezing and freeze–thaw cycles (described in Sect. 3.3), average yearly rainfall was calculated starting on April 1 of the first year and ending on March 31 of the last year of the time interval being studied.

3.4 Variable Statistics

After the data for the variables being considered to explain recession rate were compiled, the variable statistics were analyzed. Table 2 contains the statistical information for all variables composed of continuous data, while Table 3 contains the statistical information for all variables composed of categorical data. These two tables show all variables that were used to try to relate freeze–thaw and recession rate. The data used for all variables can be found in Zwissler (2013).

4 Regression Development to Define Recession Rate

After the spatial and temporal trends of recession rate were investigated, the relationship between recession

Table 3 Statistical information for all variables with categorical data

Variable	Frequency of Value				
	1	2	3	4	5
Vegetation for F-T susceptible layers—F4[a]	14	1	2	N/A	N/A
Vegetation for F-T susceptible layers—F3[a]	14	7	5	N/A	N/A
Vegetation for F-T susceptible layers—F2[a]	16	10	0	N/A	N/A
Vegetation for F-T susceptible layers—F1[a]	1	5	1	N/A	N/A
Slope aspect[b]	4	4	9	5	4

[a] For vegetation: 1 = no vegetation present; 2 = some vegetation, sparsely covered or seasonally variable; 3 = full vegetation present

[b] For slope aspect: 1 = NE; 2 = NE to ENE; 3 = ENE; 4 = ENE to E; 5 = SE

rate and all other variables was explored. The goal of this data exploration was to find a multivariate linear regression to represent the relationship between recession rate and the independent variables.

Different variables were systematically added to and removed from regressions to assess the contribution of the variables to explaining recession rate. Statistical tools were used to assess the validity of the regressions as well as to evaluate what the selection of certain variables and their significance in the regression means. The validity of the regressions was assessed using tools such as root mean squared error (RMSE), coefficient of determination (R^2), and model residuals. The significance of the contribution of the variables was assessed using tools such as adjusted R^2 and regression parameter hypothesis test (*t* test). A complete discussion of the variable selection and testing process can be found in Zwissler (2013).

Statistical tools, like Q–Q plots and histograms, also helped to identify variables that could benefit from transformation. The original variables, as well as multiple transformations (e.g., log- and square root-transformations) were tested using the same process to assess which transformation, if any, added the most value to the regression. Statistical evaluations, such as Cook's Distance and predicted versus observed plots, were also used to help to identify outliers in the data set. Outliers for slope angle were identified as data points with slope angles greater than 55 degrees. The three data points with slope angles higher than 55 degrees were removed due to the lack of data in this upper range of slope angles. Outliers for recession rate were identified as values above 0.8 m per year. The ten data points with observed recession rates above 0.8 m per year were omitted because no linear regression using the variables considered was able to predict recession rates above 0.8 m per year, meaning that it was outside of the predictive capability of the model; it is likely that other factors that were not considered were the cause for these high recession rates.

The search for a final multivariate linear regression led to two possible options: one containing the number of freeze–thaw cycles, and the other containing the number of days of freezing. A summary of both regressions is shown in Table 4. For the multivariate linear regression containing the number of freeze–thaw cycles, a summary of the variable-assessment statistics is shown in Table 5 and the observed versus predicted plot is shown in Fig. 5. For the multivariate linear regression containing the number of days of freezing, a summary of the variable-assessment statistics is shown in Table 6, and the observed versus predicted plot is shown in Fig. 6.

Table 4 Summary of model-assumption statistics for search for final multivariate linear regressions

Variables Included* (listed in order of decreasing significance)	Sample size	R^2	Adjusted R^2	RMSE	Notes
f, $-(j)^{1/2}$, h, e, $(c)^2$	66	0.68	0.66	0.19	Uses freeze–thaw cycles
f, $-(j)^{1/2}$, d, h, $(c)^2$	66	0.68	0.65	0.20	Uses days of freezing

* Variables: a = cliff height; b = slope angle; c = weighted shear strength; d = days of freezing; e = number of freeze–thaw cycles; f = slope aspect; g = rainfall; h = % height of F4 soil; i = % height of F3 soil; j = % height of F2 soil, k = %height of F1 soil; l = vegetation of F4 soil; m = vegetation of F3 soil; n = vegetation of F2 soil; o = vegetation of F1 soil

Table 5 Summary of variable-assessment statistics for multivariate linear regression—freeze–thaw cycles

Variable	Estimate	Std. Error	t value	Pr(>|t|)	Significance[a]
Height_L4	0.3088	0.1585	1.948	5.60 %	.
$(\text{Su})^2$	−5.100E-05	3.550E-05	−1.437	15.60 %	
$(\text{Height\_L2})^{1/2}$	−0.5331	0.1651	−3.229	0.20 %	**
Slope aspect	0.0959	0.0251	3.817	0.03 %	***
F-T Cycles	0.0139	0.0072	1.941	5.69 %	.

[a] Significance level codes: 0–0. 1 % : '***'; 0. 1–1 % : '**'; 1–5 % : '*'; 5–10 % : '.'; 10–100 % : ''

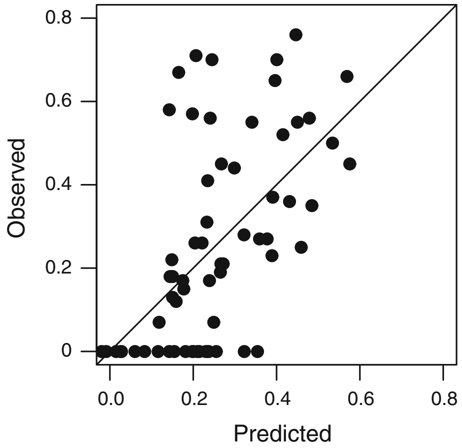

Fig. 5 Predicted versus observed plot for multivariate linear regression—freeze–thaw cycles

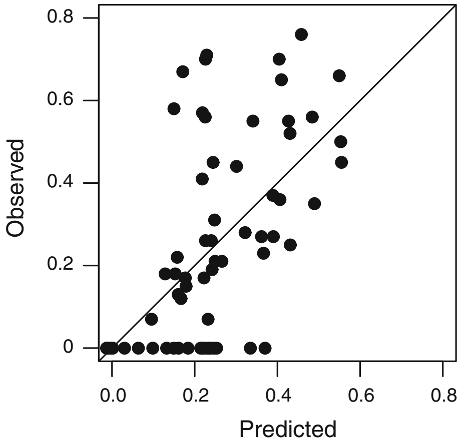

Fig. 6 Predicted versus observed plot for multivariate linear regression—days of freezing

These regressions are very similar, with very subtle differences. While some of the variables considered in each regression have very low significance, their presence leads to an increase in adjusted R^2 and a decrease in RMSE, indicating that the variables add value to the regression. Because these regressions are so similar, it is safe to state that there is not a significant difference between days of freezing and freeze–thaw cycles in this dataset. That is not to say that these metrics would not be more telling with other data, but no distinction can be made with this data.

This means that the final regression used to describe the relationship between freeze–thaw and recession rate should use either the number of freeze–thaw cycles of the days of freezing. While either metric could be used for this dataset, because using freeze–thaw cycles yields a slightly higher adjusted R^2 value and a slightly lower RMSE, that is the final regression presented. Therefore, recession rate can be defined by the following equation:

$$\begin{aligned}&\text{Recession Rate} = 0.0940 * \text{Slope Aspect}\\ &\quad -0.5002 * (\%\ \text{Height F2})^{1/2}\\ &\quad +0.3081\ *\ \%\ \text{Height F4} + 0.0135 * \text{Freeze}\\ &\quad - \text{Thaw Cycles}\\ &\quad - 4.528\text{E} - 5 * (\text{Weighted Shear Strength})^2.\end{aligned}$$

5 Relationship between Freeze–Thaw and Recession Rate of the Calvert Cliffs

For the sites considered at the Calvert Cliffs, recession rate can be explained as a function of slope aspect, percent of total cliff height composed of freeze–thaw susceptibility classes F4 and F2, number of freeze–thaw cycles, and weighted shear strength. While there are specific coefficients associated with each of the variables, the variables themselves and the signs (positive or negative) associated with them are the most important factors. Statistically, these variables

Table 6 Summary of variable-assessment statistics for multivariate linear regression—days of freezing

Variable	Estimate	Std. Error	t value	Pr(>|t|)	Significance[a]
Height_L4	0.2859	0.1705	1.677	9.88 %	.
$(\text{Su})^2$	−5.485E-05	3.657E-05	−1.500	13.88 %	
$(\text{Height\_L2})^{1/2}$	−0.5574	0.1779	−3.133	0.27 %	**
Slope aspect	0.0927	0.0261	3.554	0.07 %	***
F-T days	0.0137	0.0073	1.887	6.40 %	.

[a] Significance level codes: 0–0. 1 % : '***'; 0. 1–1 % : '**'; 1–5 % : '*'; 5–10 % : '.'; 10–100 % : ''

were included in the final regression equation because they led to the highest R^2 and adjusted R^2 values while maintaining low Pr (>|t|) values. However, the selection of these variables and the omission of the other variables can also be assessed qualitatively.

It is first important to consider the variables included in the final regression equation. Based on the Pr (>|t|) values, the variables that have the highest significance to this final regression equation are slope aspect, followed by percent height of freeze–thaw susceptibility class F2, percent height of freeze–thaw susceptibility class F4, and number of freeze–thaw cycles. These variables are all directly related to freeze–thaw. The fact that they are considered significant variables in explaining recession rate indicates that freeze thaw is a dominant process in cliff recession. The least significant variable included in the final regression is shear strength. While including shear strength does improve both the R^2 and adjusted R^2 values for the regression, this variable has very low significance based on the Pr (>|t|) value. In typical slope stability problems, shear strength is a very important variable (as well as cliff height and slope angle, two variables not included in this regression). The fact that the variables directly related to freeze–thaw are more significant than shear strength also indicates that freeze–thaw processes may have more of an effect on cliff recession than typical slope stability processes. The signs associated with the variables also provide qualitative insight into the regression. Slope aspect is a categorical variable, so the sign associated is unimportant. Percent height of freeze–thaw susceptibility class F4 and number of freeze–thaw cycles are both shown to have a positive relationship with recession rate. In other words, as the percent height of F4 and the number of freeze–thaw cycles increases, so does the recession rate, which is logical. On the other hand, percent height of freeze–thaw susceptibility class F2 and weighted shear strength have a negative relationship with recession rate, indicating that a decrease in those values causes an increase in recession rate, which is also logical.

It is also important to consider the variables not included in the final regression equation. These variables were either not directly related to freeze–thaw or had significant uncertainty in the way that they were defined. The variables that were not included in the final regression equation are percent height of freeze–thaw susceptibility class F3 and F1, days of freezing, cliff height, slope angle, rainfall, and vegetation. It is not surprising that not all freeze–thaw susceptibility classes were included in the final regression, as they are related (as the percent height of one freeze–thaw susceptibility class goes up, the others go down). As discussed previously, there was little difference between the number of freeze–thaw cycles and the number of days of freezing, so including both variables would not add any value to the regression. Vegetation can be related to freeze–thaw processes, but the variable was not defined in this study in a way that added value to the regression; vegetation was quantified crudely by assessing a single set of digital images taken over one summer, which did not account for seasonal or temporal variability. The remaining variables—cliff height, slope angle, and rainfall—are not related to freeze–thaw, but were rather selected to represent other processes that could be contributing to recession rate. The fact that these variables were not included in the final regression provides further validation that the recession rate at the study sites considered along the Calvert Cliffs is dominated primarily by freeze–thaw processes.

This final multivariate linear regression utilizing slope aspect, percent height of freeze–thaw susceptibility classes F4 and F2, number of freeze–thaw cycles, and weighted shear strength has a coefficient of correlation (R) of 0.82 and is able to explain over 65 % of recession rate (based on an R^2 value of 0.68). Because of the variables used in this regression, it can be assumed that freeze–thaw is the dominant erosion mechanism where waves do not control recession along the Calvert Cliffs. There is certainly some scatter from the 1:1 line in Fig. 5. However, due to the complex nature of this problem, further study would be needed to try to reduce the uncertainty in the inputs and evaluate other critical variables. While fifteen variables were considered to explain recession rate, there are quite likely other factors that contribute to recession rate. The main goal of this research was to assess if freeze–thaw controls recession where waves do not interact with the cliff toe at the Calvert Cliffs. If the goal was to be able to explain 100 % of cliff recession, other factors such as seepage, wind erosion, soil desiccation, infrequent wave activity (like storm surge events), and even animal burrowing would need to be considered.

6 Conclusions

Freeze–thaw driven cliff recession is clearly a problem at the six study sites analyzed along the Calvert Cliffs where waves do not control recession. Based on the variables considered (specifically slope aspect, the percent of total cliff height composed of soil with freeze–thaw susceptibility F4 and F2, the number of freeze–thaw cycles, and the weighted shear strength), over 65 % of the cliff recession that occurred between 2003 and 2011 can be explained by freeze–thaw-related factors. This study was only aiming to assess the freeze–thaw behavior of the Calvert Cliffs and to determine if a meaningful relationship exists between freeze–thaw and recession rate at study sites not affected by waves. This was shown to be true. To account for more than 65 % of cliff recession, other potential recession-driving factors like seepage, wind erosion, soil desiccation, and infrequent wave activity (like storm surge events) would need to be considered.

In order to mitigate cliff recession at the six study sites considered along the Calvert Cliffs, freeze–thaw needs to be addressed, specifically the five variables identified in the final multivariate linear regression. Slope aspect and number of freeze–thaw cycles are two variables that cannot be addressed; slope aspect is a function of geomorphology, and the number of freeze–thaw cycles is a function of the weather, both of which cannot be directly controlled by humans. Mitigation approaches would need to address the remaining variables used to represent freeze–thaw processes. Unless the variables related to cliff recession affected by freeze–thaw are addressed and slope stability is achieved, cliff recession at these six study sites along the Calvert Cliffs will continue to occur until a stable slope angle is achieved and maintained.

7 Future Work

This work does establish a relationship between freeze–thaw and recession rate. However, more research is needed to more thoroughly delineate the effects of freeze–thaw on recession rate. Potential research could include the following activities:

- Thermal modeling: While freeze–thaw was quantified indirectly in a number of ways in this study (freeze–thaw susceptibility, number of freeze thaw cycles, etc.), the thermal properties of the materials composing the Calvert Cliffs were never studied or included in the work. Determining the thermal properties of the soil, like thermal conductivity, through in situ or laboratory testing would enable the determination of the depth of freeze–thaw penetration, which could then directly be related to recession rate. Having temperature measurements for each study site rather than assuming temperature is constant for the entire length of the Calvert Cliffs would also improve the thermal modeling of the cliffs.
- Soil sampling: Having samples of all soil layers present in the cliffs, specifically “non-disturbed” samples, could be beneficial. Laboratory testing on freezing behavior of the soils could be studied. Additionally, having a full grain size analysis run for all soil samples would enable the use of the original Army Corps freeze–thaw susceptibility rankings, rather than having to adjust grain size ranges to accommodate the historical data that were used.
- Recession rate determination: Recession rate data spanning more than eight winter seasons would provide a more comprehensive understanding of the recession rate trends present at the Calvert Cliffs. The aerial photographs used in this analysis had high resolution, but in some instances the measured recession rate was lower than the image resolution, so those small recession rates were assumed to be zero. Methods with higher resolution would enable the incorporation of these smaller recession rates into future models. LiDAR, which enables features like vegetation and loose soil to be trimmed from the dataset to reveal the ground surface, could also be used to more precisely monitor cliff recession at both the top of the cliff and the toe of the cliff.

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References

American Concrete Pavement Institute (ACPA) (2008) Frost-suscpetible soils. Concrete pavement technology series. ACPA, Skokie, Illinois

Buckler WR, Winters HA (1983) Lake Michigan bluff recession. Ann Assoc Am Geogr 73(1):89–110

Budhu M (2007) Soil mechanics and foundations, 2nd edn. Wiley, Hoboken

Calvert County Government (2012) Aerial imagery and ArcGIS shapefile data. Prince Frederick, MD

Calvert County, Maryland, Department of Natural Resources, Maryland Department of the Environment, United States Army Corps of Engineers, United States Fish and Wildlife Service, and Maryland Emergency Management Agency (2010) Chesapeake bay cliff erosion in Calvert County: draft steering committee report

Clark I, Larsen CE, Herzog M (2004) Evolution of equilibrium slopes at Calvert Cliffs, Maryland: a method of estimating the timescale of slope stabilization. Shore Beach 72(4):17–23

Department of the Army Corps of Engineers Office of the Chief of Engineers (1984) Pavement criteria for seasonal frost conditions: mobilization construction. USA

Duncan JM, Wright SG (2005) Soil strength and slope stability. Wiley, Hoboken

Edil TB (2010) Erosion, slope stability, prediction of future recession in actively eroding slopes. Geotech Eng J SEAGS AGSSEA 41(4):185-192

Edil TB, Vallejo LE (1980) Mechanics of coastal landslides and the influence of slope parameters. Eng Geol 16:83–96

Force JDotAaA (1987) Arctic and subarctic construction: general provisions. Vol 1. USA

Gatto LW (1995) Soil freeze–thaw effects on bank erodibility and stability. US Army Corps of Engineers Cold Regions Research & Engineering Laboratory, Hanover, NH

Hampton MA, Griggs GB, Edil TB, Guy DE, Kelley JT, Komar PD, Mickelson DM, Shipman HM (2004) Processes that govern the formation and evolution of Coastal Cliffs. Formation, evolution, and stability of coastal cliffs—status and trends. U.S. Department of the Interior, U.S.A.

Hapke CJ (2004) The Measurement and Interpretation of coastal cliff and bluff retreat. Formation, evolution, and stability of coastal cliffs—status and trends. U.S. Department of the Interior, U.S.A.

Harlan RL, Nixon JF (1978) Ground thermal regime. In: Andersland OB, Anderson DM (eds) Geotechnical engineering for cold regions. Mc-Graw Hill Book Co., New York, pp 103–163

Holtz RD, Kovacs WD, Sheahan TC (2011) An introduction to geotechnical engineering, 2nd edn. Pearson Education Inc, Upper Saddle River

Kamphuis JW (1987) Recession rate of glacial till bluffs. J Waterway Port Coast Ocean Eng 113(1):60–73

Kidwell SM (1997) Anatomy of extremely thin marine sequences landward of a passive-margin hinge zone: neogene Calvert Cliffs succession, Maryland, U.S.A. J Sediment Res 67(2):322–340

McRoberts EC (1978) Slope stability in cold regions. In: Andersland OB, Anderson DM (eds) Geotechnical engineering for cold regions. Mc-Graw Hill Book Co., New York, pp 363–404

Michalowski RL, Zhu M (2006) Frost heave modelling using porosity rate function. Int J Numer Anal Method Geomech 30:703–722

Miller DS (1995) A Field Investigation of the controls of the dominant erosion processes on the actively undercut, non-lithified coastal slopes of Calvert County, Maryland. Dissertation. Johns Hopkins University, Baltimore, MD

Miller DS, Prince N, Miller BJ (2006) A best management plan for the shoreline and slopes along the scientists' Cliffs shoreline of the chesapeake bay, Maryland. Scientists' Cliffs Association, Port Republic, MD

NCDC/NOAA (2012) Integrated surface hourly climate data. Asheville, NC

Price JC (1980) The potential of remotely sensed thermal infrared data to infer surface soil moisture and evaporation. Water Resour Res 16(4):787–795

Schweitzer JP (1993) Observations of soil wash on steep, unvegetated slopes: Calvert County, Maryland. Thesis. Johns Hopkins University, Baltimore, MD

Shattuck GB (1904) Geological and Paleontological Relations, with a Review of Earlier Investigations. In: Clark WB, Shattuck GB, Dall WH (ed) The miocene deposits of Maryland. Maryland Geological Survey, pp 33–94

Sterrett RJ, Edil TB (1982) Ground-water flow systems and stability of a slope. Ground Water 20(1):5–11

Team RC (2012) R: a language and environment for statistical computing. R Foundation for Statistical Computing. http://www.R-project.org/

Ward LW, Andrews GW (2008) Stratigraphy of the Calvert, Choptank, and St. Marys formations (miocene) in the Chesapeake Bay area, Maryland and Virginia. Virginia Museum of Natural History, Martinsville, VA

Wilcock PR, Miller DS, Kerhin RT (1993) Calvert Cliffs slope erosion project phase II final report—processes and controls of coastal slope erosion. Charleston, SC

Wilcock PR, Miller DS, Shea RH, Kerhin RT (1998) Frequency of effective wave activity and the recession of coastal bulffs: Calvert Cliffs, Maryland. J Coast Res 14(1):256–268

Zwissler B (2013) A study of the impacts of freeze–thaw on cliff recession at the Calvert Cliffs in Calvert County, Maryland. Thesis. Michigan Technological University, Houghton, MI