INVESTIGATING GROUNDWATER AND LANDSLIDES RELATIONSHIP USING R: A STUDY ON LONG ISLAND'S NORTH SHORE

Badger, T.[1] , Parag, A.[1] , Pelletier, A.[1] , DeRocchis, S.[1] , Marsellos, A.E.[1], Tsakiri, K.G.[2]

[1]*Department of Geology, Environment and Sustainability, Hofstra University, Hempstead, NY 11549*
[2]*Dept. Information Systems, Analytics, and Supply Chain Management, Rider University, Lawrenceville, NJ 08648*

Abstract

The north shore, Long Island's coastline, has been experiencing a series of landslides and mudslides since 2010. Most landslides occur on the north shore of Long Island, an area with higher elevation. This research investigates the relationship between groundwater fluctuations and landslide occurrences. The methods employed in this research encompassed the construction of a digital elevation model of Long Island using GIS software (Global Mapper v.24.1) to delineate affected areas, plotting landslide occurrences reported by the media on a map of Long Island's north shore, and utilizing the USGS (United States Geological Survey) database of monitoring wells to analyze groundwater level for identifying areas of high- and low-groundwater fluctuations. Additionally, spectral analysis aimed to test the hypothesis that high-frequency groundwater level fluctuations might exacerbate underground erosion. At the same time, lower frequencies, such as those occurring annually, have a comparatively lesser impact on landslide formation.

Based on the results, fluctuations in groundwater level located along the outer shore of Long Island may trigger groundwater "vibrational" long-term movements causing accelerated erosion underground, leading to potential landslides. With the climate showing warmer temperature fluctuations, particularly in regions with higher latitudes, the risks of landslides grow more severe, notably due to increased underground water mobility during periods previously characterized by prolonged winter cold temperatures and water mobility pauses. Therefore, focusing on areas prone to landslides can prevent the loss of life, damage to roads and structures, and environmental decay.

Introduction

This study aims to provide crucial information about which areas of Long Island in New York are most prone to landslides to prevent future damage to roads and other structures. Due to climate change, there has been an increase in the severity and frequency of storms, which has led to an increase in groundwater. Since 1901, New York's annual precipitation has increased from 10% to 20%, and it is expected to keep increasing to 17% by the end of the century (New York

State Climate Impact Assessment 2024). One of the areas of Long Island most affected by these storms is the north shore. Long Island's north shore was predominantly formed from headland erosion, creating steep bluffs of sandy and glacial till. With an increase in groundwater, the sand and till loosens, increasing the risk of landslides or debris flows. As temperatures freeze, the groundwater becomes stuck in the bluffs and expands, resulting in cracks. These cracks separate the bluffs into large chunks of sediments, which slide down the face, resulting in damages to not only private property but also public beaches (Fallon 2018).

In 2014, a landslide occurred in Sea Cliff, NY, causing two retaining sea walls on private property to collapse. Since the property was on the verge of collapsing into Hempstead Harbor, it was left vacant by the homeowners. When a series of storms hit the town again in 2018, more of the property collapsed, exposing the foundation of the home (Seidman 2018). Landslides endanger the people living in these homes on the north shore but also put anyone walking along the beach at risk as the cliff keeps receding. Leading the north shore at an average rate of one to two feet a year. Bare or sparsely vegetated bluffs erode the fastest as wind and water can easily remove the unconsolidated material. To control further erosion, more vegetation has been planted because the roots can keep soil in place while taking in excess water in the bluffs (Fallon 2018).

Groundwater level fluctuations observed at the monitoring stations administered by the USGS exhibit various periodicities, ranging from high-frequency oscillations to longer-term cycles, such as annual cycles (Rienzo et al., 2019). The aim of this paper is to assess the data of North Shore groundwater wells being monitored by the United States Geological Survey (USGS) in order to determine the connection between groundwater fluctuations and landslides. The rapid fluctuation of groundwater can loosen the sediment on a slope allowing it to slide down and gather other sediment along the way. Since there has been limited research done on this topic previously, we have explored periodicities of the monitoring wells water level fluctuations. This research emphasizes the importance of more groundwater monitoring data as it can show which areas are most vulnerable in the future as precipitation increases. By having this information it can not only preserve infrastructure but also prevent further damage to the environment.

Methods

The areas in Long Island where landslides occur were collected by outlining the map of Long Island in the Google Earth program. Pinpoints of the landslide occurrence areas and site areas, near the occurrences, were also placed in Google Earth. Site areas used in this research were collected from the USGS National Water Information System. This data was then extracted into Global Mapper to create a path profile of the elevation of Long Island. The path profile proved that sites of landslide occurrences had higher elevations. Site areas of landslide occurrence as well as the outline of Long Island were extracted into Global Mapper and enhanced for better viewing. The groundwater data site locations were labeled on the map as well as the landslide occurrences.

Using the USGS National Water Information System, groundwater level data from eleven sites of landslide activity near the north shore of Long Island was analyzed. The measurements were taken in accordance with the National Geodetic Vertical Datum of 1929 (NGVD). This standard measures groundwater fluctuation from the elevation of a point above and depression below mean sea level (MSL). This data was then extrapolated using R language (RStudio), cleaned, and processed including any missing data in the original data found in the USGS National Water Information System.

Underground water level data were obtained from 11 USGS monitoring stations located in the adjacent region affected by landslides, accessed through the USGS National Water Information System (NWIS) (https://waterdata.usgs.gov/nwis/). Utilizing the "data.table" (Barrett et al., 2024) package in R, the time series of groundwater, along with corresponding dates for each station, were extracted and organized. Subsequently, the groundwater level data underwent cleaning and processing procedures. Missing data or gaps within the time series were interpolated using the "imputeTS" package (Moritz et al., 2017), employing the function na_interpolation(). Date manipulations were performed using the "lubridate" package. Moving averages were applied to utilize the Kolmogorov-Zurbenko filter to smooth the data and reduce noise, which was implemented through the "kza" package (Close et al., 2020). Periodograms were constructed to analyze the frequency components of the groundwater fluctuations using the "TSA" package (Chan et al., 2022), with the function periodogram(). To facilitate comparison across different sites, all periodograms were normalized using the "BBmisc" package (Bischl et al., 2022) and the function normalize().

Furthermore, to enhance the visibility of short-term fluctuations and highlight higher frequencies present in the groundwater data, a trend was subtracted from the raw data. This trend was derived from a moving average computed using the Kolmogorov-Zurbenko filter with a window size of 29 days, applied three times consecutively (kz(29,3)). By subtracting this trend from the groundwater levels, the resultant data set more effectively captured short-term variations and revealed the presence of higher frequencies where they existed. Additionally, to mitigate spectral leakage in the periodogram analysis, the zero tapering method was employed. Furthermore, the dataset was replicated ten times to enhance spectral detection in the low periodicities, following a method described in previous literature (Tsakiri & Marsellos, 2024). This preprocessing step aimed to provide greater insights into the dynamics of groundwater fluctuations and their potential relationship with landslide occurrences.

From the graphs created in RStudio, (Figure 3), the moving average was applied to subtract the low frequencies to study the presence of any hidden higher frequencies. The occurrence of these higher frequencies of water was detected using the periodogram method, where station 9 displayed a very high period (low frequency of mostly annual periodicity), and station 11 displayed a very low period (high frequency of mostly monthly or weekly periodicity). Stations 9 and 11 were selected to show the contrast between high- and low-frequency water level fluctuation. Those stations are depicted on the map (Figure 1) to determine the relationship between landslide occurrences and frequencies.

Results

The study uncovered a partial correlation between the frequency of groundwater oscillations at certain monitoring wells and the proximity of landslide events. Sites with elevated groundwater frequency fluctuations coincided with areas of frequent landslide activity, underscoring the impact of groundwater dynamics on slope stability and landslide susceptibility. With the exception of missing data from some of the studied sites, most landslide occurrence points displayed a roughly annual fluctuation in groundwater level (spike occurring roughly every 365 days). The sites that experienced the most fluctuations throughout the year are at the greatest risk for landslide occurrences. The periodograms show the frequency of the groundwater fluctuations (Figure 5). As rainfall in New York significantly increases on an annual basis there are rapid movements in groundwater going from above sea level to below sea level.

Based on the result, the lower frequencies occur at station 9 which is located in the inland area of Long Island and the higher frequencies occur at station 11 which is located on the outer shoreline of Long Island. Stations 3, 10, and 11 have more frequent changes. Along the coastline, groundwater has more frequent fluctuations and doesn't follow the annual recharge cycle. Station 7 and others like it are exceptions to this.

Figure 1: Map of Long Island's recorded landslide occurrences (red dots) and groundwater monitoring stations by USGS (blue dots). Blue dots represent the stations used to gather groundwater data. Stations 6 and 7 are located at the same point. These sites are located in areas of higher elevation.

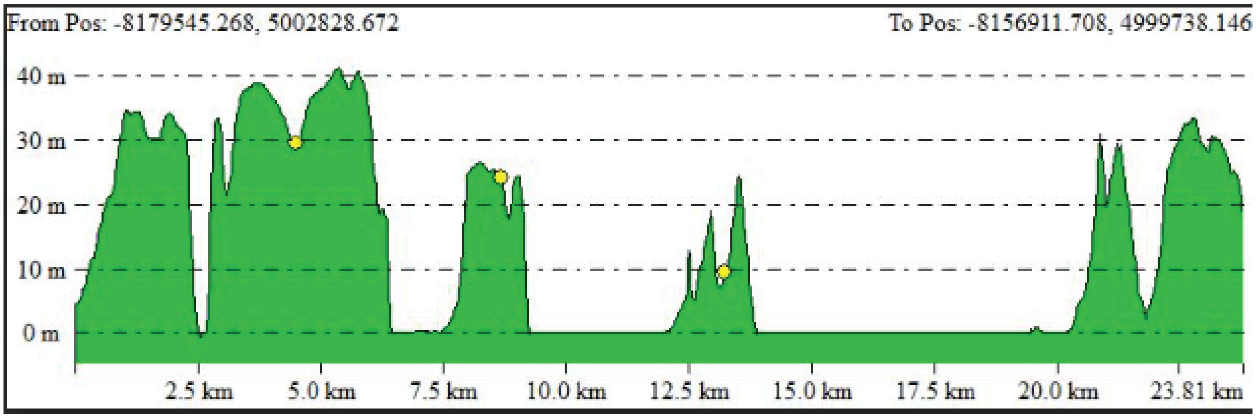

Figure 2: Path profile of Long Island's north shore created in Global Mapper.

```
filtered ground water = groundwater - moving_average(groundwater, window(27),iterations(3))
```

Figure 3: The groundwater equation is used to process raw groundwater data with a 27-day moving average filter with an iteration of three times. This period corresponds to the lunar cycle, highlighting its potential impact on groundwater levels.

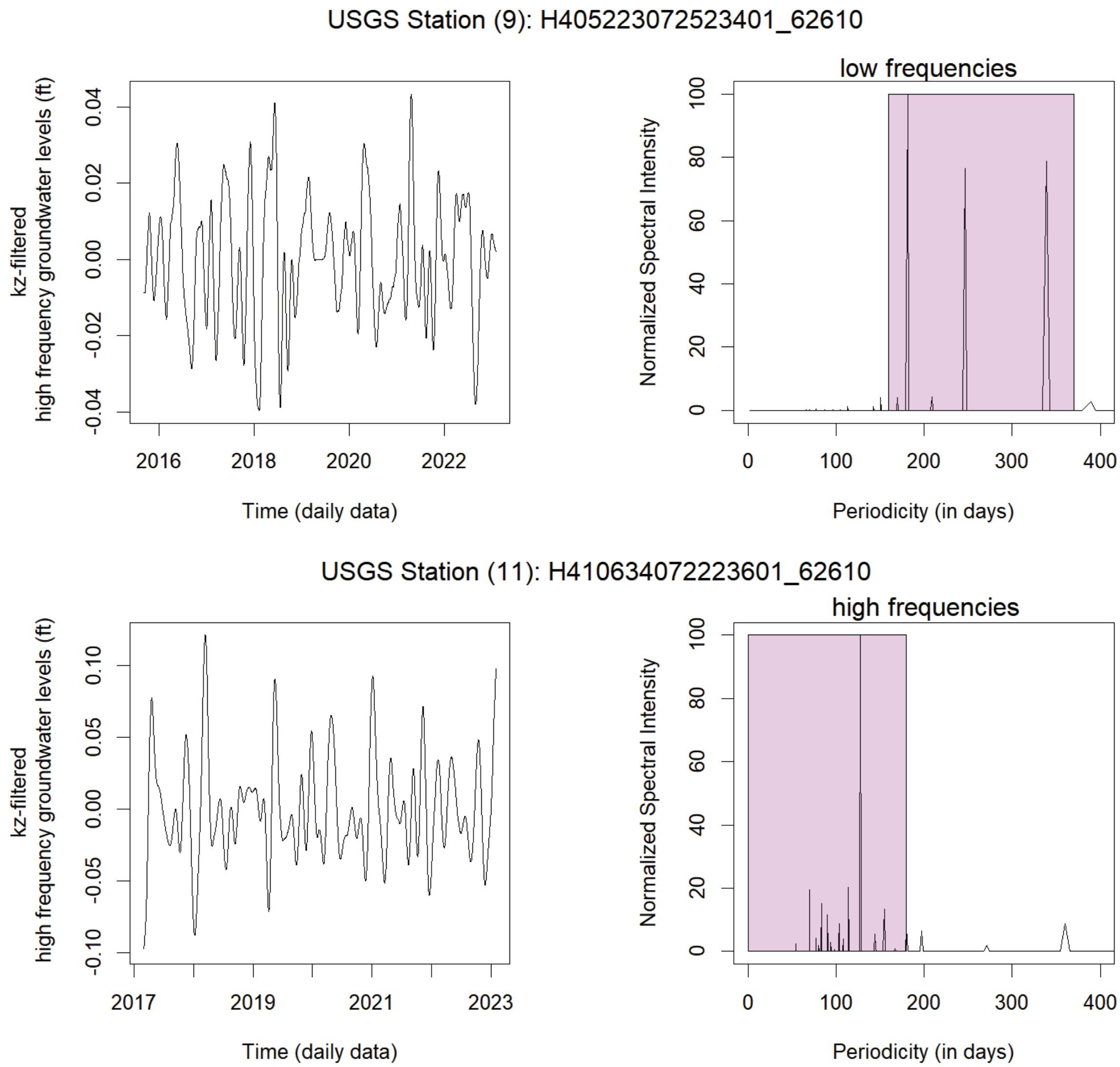

Figure 4: Groundwater Fluctuations and Frequency Levels at Sites 9 and 11. The main peaks in frequency are highlighted in purple.

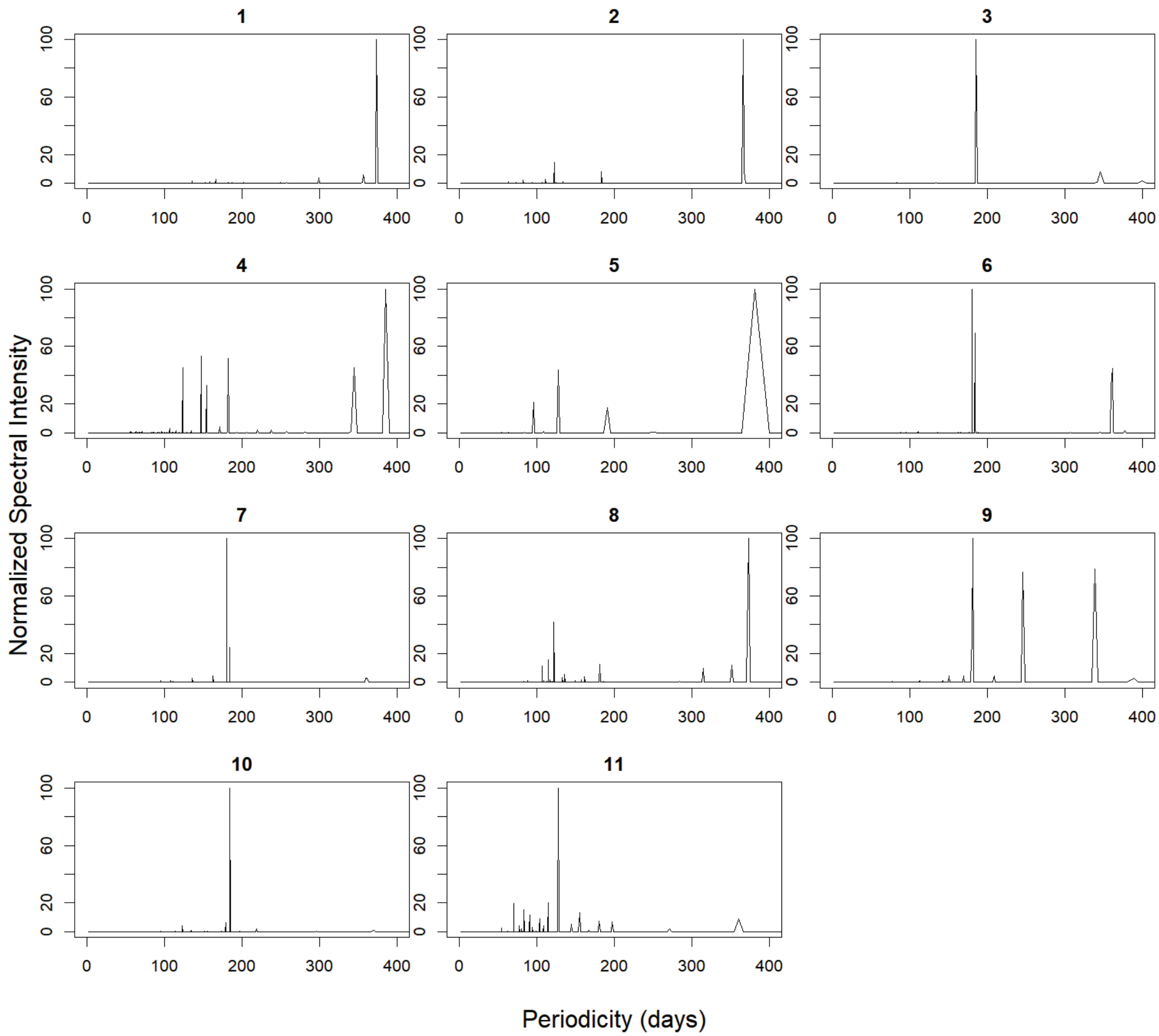

Figure 5: Spectral analysis (periodograms) of groundwater frequencies at stations 1 through 11. Spectral analysis of the frequency of groundwater fluctuations in 11 USGS sites across Long Island, NY at the frequency domain of 1-400 days.

Discussion

As we know, the sites that experience a spike in groundwater annually are at an increased risk of a landslide occurring. Long Island's north shore is known for high property value and beaches which are now vulnerable to erosion due to increased precipitation from climate change. The results from Figure 1 display the closest possible active sites for groundwater data near Long Island's north shore since the sites directly within the region of landslide occurrences provided no available data or with very large time-gaps. Landslides commonly occur along the north shore of Long Island where there are steeper elevations of land. The path profile shown in Figure 2 is a graphical representation of the terrain along a specified line. The line was drawn from west to east, along Long Island's north shore using Global Mapper. This path profile confirmed that the elevation of the north shore varies, and in places with steep slopes, comprising both low and high terrain. Higher terrain present on the north shore are prime sites for landslides because the elevations are formed by loose glacial till which is highly susceptible to erosion as well as changes to groundwater level fluctuation.

The formula presented in Figure 3 shows that the moving average of the groundwater being subtracted from the raw groundwater to remove noise from low-frequency annual cycles. A moving average window of 27 days is chosen because it represents the moon cycles and was performed for a total of 3 times. The subtraction of periodicities higher than 27 days, such as moon cycles or other monthly or annual cycles, does not entirely eliminate them from the raw data; rather, it enables the revelation of higher frequencies that may be obscured by long-term trends. High-frequency water fluctuations can lead to more underground erosion. The formula was used to lessen the noise seen within the datasets. The rapid movements of these fluctuations then allow the sediment to become loose and based on the steepness and high level of elevation the sediments are stationed at, it will begin to slide down the hill pushing other small pieces of sediment along with it, thus forming landslides.

The groundwater fluctuations and frequencies (Fig. 4) emphasize on the lowest and highest frequencies comparing all the sites 1 through 11. Station 9 shows the low-frequency levels that occur annually over 365 days. Station 11 shows high-frequency levels that occur daily under 365 days. Station 7 and the others that follow its trend generally occur in areas with larger populations, so it is within reason to say that overconsumption of groundwater accounts for the lack of the annual cycle peak on the graphs.

Conclusion

As the groundwater levels fluctuate more frequently during less than the annual time it creates stress on the sediments and minerals at higher elevations by rapid vibration movements which then break apart these minerals leading to potential landslides. Not much research has been conducted like this experiment to study the effects that groundwater levels have on landslide occurrences. Past research has described the destruction caused to private properties due to landslides. There are various sites throughout Long Island's north shore containing no or unavailable groundwater data, which led to the reconstruction of new sites with available data that is used in this experiment. This study encourages the need for more data on groundwater levels around the areas of Long Island, especially where there are high elevations. This research can not only encourage Long Island researchers but also researchers from different states like Oregon, California, and Washington that experience major landslide impacts.

Credit Authorship Contribution Statement

Badger, T.: editing, literature, Rstudio coding, Figure 4, Figure 5, writing- Results, Discussion; Parag, A: Literature, editing, writing- Global Mapper, Google Earth, Abstract, Results- figure 1, Methods, Discussion; Pelletier, A.: references, literature, editing, writing - Introduction, Discussion; DeRocchis, S.: figures, editing, USGS Graphs, Global Mapper, writing - Methods, Discussion; Marsellos, A.E.: supervision, Rstudio coding, guidance, editing; Tsakiri, K.G.: Rstudio coding.

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