ES612 Project Report - Natural Drivers of Coastal Erosion

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Abstract

This report investigates the primary natural drivers of coastal erosion, including wave dynamics, tidal patterns, storm impacts, sea-level rise, sediment transport, and geological factors. Through exploratory data analysis and machine learning techniques, we examine the relationships between these factors and develop a predictive model to forecast erosion rates. Our findings reveal the complex, multifaceted nature of coastal erosion processes, with wave energy, sediment transport, and sea-level rise emerging as significant contributors. The Random Forest Regressor model demonstrates the potential for predicting erosion rates based on natural drivers, providing a foundation for coastal management strategies and erosion risk assessment. This study highlights the importance of comprehensive approaches to understanding coastal erosion in the context of climate change and increasing coastal vulnerability.

1. Introduction

Coastal erosion is a serious issue affecting coastal communities around the world. It damages infrastructure, ecosystems, and livelihoods. This process happens when waves, tides, water currents, or strong winds gradually wear away the land and carry off sand from beaches or dunes. About 70% of the world's beaches are currently eroding, with rates accelerating due to climate change and human activities.

Through this report we will try to:

- Examine the natural drivers of coastal erosion
- Analyze the relationships between these drivers
- Develop and evaluate a predictive model for coastal erosion rates
- Provide insights for coastal management and erosion mitigation strategies

Understanding these processes is crucial for developing effective coastal management strategies and adaptation measures, particularly as climate change intensifies many erosion drivers.

2. Literature Review

2.1 Wave Dynamics

Wave energy plays a key role in driving coastal erosion. Studies have shown that wave characteristics, such as height, period, and the angle at which waves approach the shore, have a strong impact on erosion patterns. Waves contribute to coastal erosion through processes like hydraulic action, abrasion, attrition, and solution. Research indicates that destructive waves, which have shorter periods and steeper fronts, tend to cause more erosion compared to constructive waves with longer periods. Furthermore, wave refraction and diffraction focus wave energy on headlands and spread it out in bays, leading to varied erosion patterns along the coast. [1][2][3]

2.2 Tidal Patterns

Tidal variations play an important role in shaping coastal landforms by influencing the vertical extent where wave activity takes place. Coasts with large tidal ranges (macro-tidal, >4 meters) show different erosion patterns compared to those with small tidal ranges (micro-tidal, <2 meters). Strong tidal currents can move large amounts of sediment, gradually altering the shape of the coastline. Studies have also found that tidal asymmetry affects the overall direction of sediment movement, coastal areas where flood tides dominate tend to see sediment moved landward, while ebb-dominant systems usually experience sediment being transported seaward. [4][2]

2.3 Storm Impacts

Storms greatly increase the rate of coastal erosion by causing storm surges, stronger wave energy, and coastal flooding. Research has recorded significant shoreline retreat during single storm events (for example, Hurricane Katrina led to over 1 kilometer of beach erosion in some areas of Louisiana). Studies also suggest that when storms occur close together in time, their combined effects on erosion can be greater than the impact of each storm on its own. This is because the coast often does not have enough time to recover between storms. [4]

2.4 Sea-Level Rise and Climate Change

Sea-level rise worsens coastal erosion by causing submergence, increasing the impact of wave activity, and making coastal flooding more frequent. According to the Bruun Rule, which has certain limitations, sandy shorelines may retreat 50 to 100 times the amount of sea-level rise. Climate change projections indicate that erosion risks are likely to increase significantly, with some estimates suggesting up to an 84% rise in erosion by the end of the 21st century under high-emission scenarios such as RCP8.5. [5][6][7]

2.5 Sediment Transport

Sediment transport plays a key role in shaping whether a coastline erodes or builds up over time. Sediment can move in two main ways: cross-shore transport carries it in and out from the shoreline, while longshore transport moves it along the coast. Studies have shown that when these natural movements are disrupted either by natural events or human activities, it can lead to noticeable changes in erosion patterns further down the coast. Maintaining a balance between the amount of sediment being added and removed is important for keeping coastlines stable. [2][8]

2.6 Geological Factors

The geological composition of coastlines affects how easily it erodes. Studies have shown that different rock types erode at different rates, leading to the formation of unique coastal features. For example, softer rocks like clay wear away much faster than harder rocks like granite, which can result in landforms such as sea stacks, arches, and caves. Research has also found that the shape of the sea floor (known as bathymetry) affects how waves bend as they approach the shore, which in turn affects how and where erosion happens. [1][3]

3. Methodology

3.1 Data Collection

This report used simulated data representing key coastal erosion drivers, including:

- Wave energy (0.5-5.0 kW/m, Gamma distribution (shape=2.0) simulating typical wave energy distributions)
- Tidal range (1.0-10.0 m, Lognormal distribution matching global tidal patterns)
- Sediment transport rate (0.1-2.0 units)
- Sea-level rise rate (0.01-0.1 m/year, Beta distribution (α=2, β=10) emphasizing gradual rise)
- Storm frequency (1-20 events/year, Poisson distribution (λ=5) for discrete extreme events)
- Erosion rate (0.1-5.0 m/year, Non-linear erosion calculation formula combining drivers)

While simulated, these ranges were selected to reflect realistic values based on existing literature. For real-world applications, several comprehensive datasets are available, including:

- *GeoCoast Premium:* Provides detailed geological and geomorphological data
- *State-wise Coastal Erosion Data:* Contains historical erosion rates (1990-2018)
- *Global Coastline Dataset (GCL_FCS30):* Offers high-resolution coastline classification

3.2 Exploratory Data Analysis

I did exploratory data analysis to find relationships between variables. This included:

- Correlation analysis to assess linear relationships
- Distribution analysis of individual variables
- Visualization of bivariate relationships through scatter plots

3.3 Model Development

I implemented a Random Forest Regressor model to predict erosion rates based on natural drivers. The Random Forest algorithm was selected for its ability to:

- Capture non-linear relationships
- Handle feature interactions
- Provide feature importance metrics
- Reduce overfitting through ensemble learning

The dataset (10000 samples) was split into training (80%) and testing (20%) sets. The model was trained with 100 decision trees, using default hyperparameters other than max_depth which was set to 10.

Here is the [notebook]() containing the code for the model.

4. Results

4.1 Exploratory Data Analysis

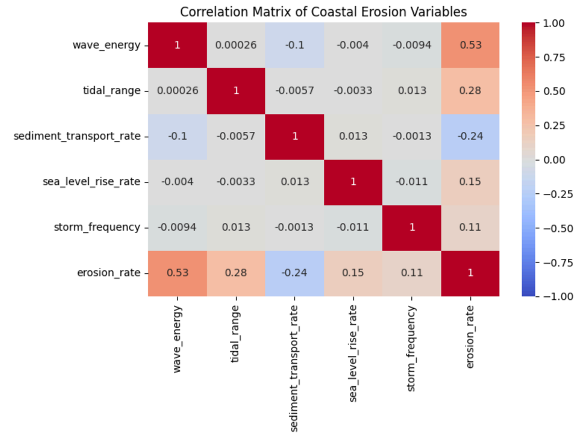

Figure 1: *Correlation matrix of natural drivers of coastal erosion.*

The correlation matrix (Figure 1) reveals interesting relationships between erosion drivers. Most strikingly, the correlation coefficients between individual drivers and erosion rate are relatively weak:

- Wave energy and erosion rate: 0.53
- Tidal range and erosion rate: 0.28
- Sediment transport rate and erosion rate: -0.24
- Sea-level rise rate and erosion rate: 0.15
- Storm frequency and erosion rate: 0.11

These correlations suggest that the relationship between individual drivers and erosion is complex and likely non-linear, highlighting the need for multivariate analysis approaches.

Additionally, the correlations between the drivers themselves are also weak, indicating relative independence among these variables in our dataset.

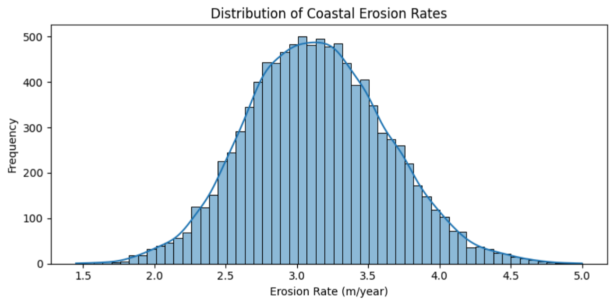

Figure 2: *Distribution of coastal erosion rates (per year)*

The above graph (Figure 2) shows that while erosion rates vary, there is a common range (roughly 1–5 m/year) where most values lie, with a central tendency (mode) around 3 m/year. The smooth shape of the KDE line (Kernel Density Estimate, which gives a smooth approximation of the underlying distribution) further supports the idea that the data might be close to a normal (bell-shaped) distribution.

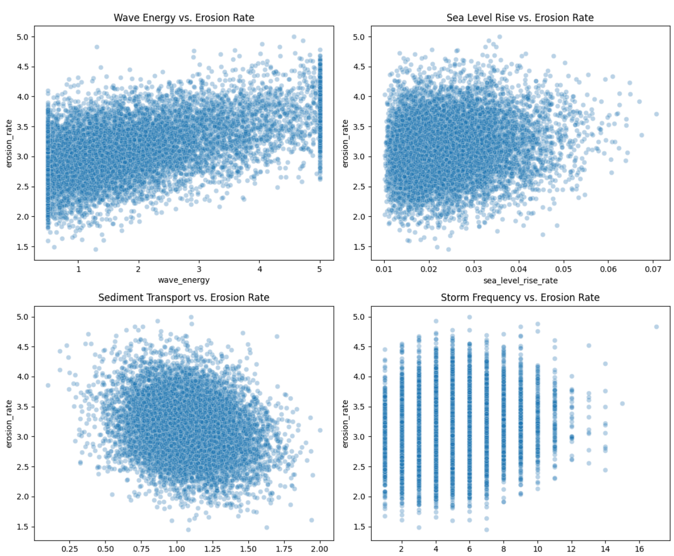

Figure 3: *Scatter plots of key relationships*

In the first graph in Figure 3, wave energy vs erosion rate, we see that as wave energy increases (moving to the right), there is some indication that erosion rates may also increase. However, the relationship does not appear to be strongly linear, instead, it looks more like a scattered cloud. This is evident from their correlation coefficient.

In the second graph of Figure 3, we see that the points are scattered throughout a narrow range of sea level rise rates, making it hard to see a strong trend. However, there might be some tendency for erosion rates to be higher at greater sea-level rise values, but the variance is high.

In the third graph of Figure 3, we see that the data points are spread broadly across the entire plot, with no immediately obvious strong positive or negative trend, but a slight elliptical formation can be seen showing low erosion rates with high sediment transport rates (as higher sediment input typically reduces erosion) and vice versa.

In the fourth graph of Figure 3, storm frequency is a discrete variable. Erosion rates vary at each storm frequency level. Areas with more frequent storms tend to show slightly higher erosion on average but this suggests that just the number of storms isn't enough to predict erosion.

4.2 Model Performance

The Random Forest Regressor model showed decent predictive capability:

- Mean Squared Error: 0.1401
- R^2 Score: 0.4088
- Feature Importances:
  - Wave energy: 49.26%
  - Tidal range: 19.81%
  - Sediment transport rate: 13.97%
  - Sea-level rise rate: 11.83%
  - Storm frequency: 5.13%

Among the input variables, wave energy was the most influential (49.26%), followed by tidal range (19.81%), sediment transport rate (13.97%), and sea-level rise rate (11.83%). Storm frequency had the least impact (5.13%), likely due to its discrete nature and the exclusion of storm intensity and timing.

These findings show the value of using models that can account for complex, non-linear relationships between multiple factors. While wave energy clearly has a strong influence on erosion, other variables also play important roles. Future models could be improved by including more detailed information about storms and coastal landforms.

5. Discussion

5.1 Interpretation of Results

The non-linearity and weak pairwise correlations seen in the EDA are reflected in the model's reliance on multivariate feature interactions, something Random Forest handles well. While intuition might suggest strong correlations between individual drivers and erosion rates, our findings indicate that these relationships are not simply linear. This aligns with existing literature that emphasizes the importance of interaction effects and local contexts in erosion processes.

The feature importance metrics from our Random Forest model provides some more details. The dominance of wave energy shows its primary role in driving erosion, at least in the context of this simulated data. The lower importance of storm frequency and sea-level rise doesn't mean they are insignificant in real-world terms. Again, it may reflect the structure of the simulation. Overall, these factors when paired with more parameters would contribute meaningfully to predicting erosion when considered collectively in a non-linear framework.

5.2 Limitations

Our analysis used simulated data, which may not fully capture the complexities and interactions present in real-world coastal systems.

Temporal variations and seasonal effects were not explicitly modeled.

Human interventions and coastal engineering structures were not considered.

Regional variations in the relative importance of different drivers were not addressed.

5.3 Implications for Coastal Management

Despite these limitations, our findings have several implications for coastal management:

- Detailed approaches that consider multiple erosion drivers are likely more effective than those targeting single factors
- Predictive models can help prioritize areas for intervention based on the presence of multiple risk factors
- The fact that several factors are important suggests that different strategies may be needed to manage coastal erosion effectively.

6. Conclusion

This report examined the natural drivers of coastal erosion and developed a predictive model to forecast erosion rates by generating synthetic data based on real-world scenarios. The findings show the complex nature of coastal erosion processes, with wave energy, sediment transport, tidal range, and sea-level rise all emerging as important contributors to erosion risk.

While individual correlations between drivers and erosion rates were mostly weak (other than for wave energy), their collective consideration in a machine learning framework showed a good prediction capability. This highlights the importance of multivariate, non-linear approaches to understanding and predicting coastal erosion.

Future research perhaps could focus on using real-world datasets, temporal variations, human interventions, and regional differences to enhance model accuracy and applicability. Additionally, integrating remote sensing data and advanced modeling techniques could further improve our understanding of coastal erosion processes and support more effective management strategies.

7. References

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