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Assessment of Wave Impacts on Highway Embankments due to Hurricanes/Tropical Storms in Coastal Louisiana

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16. Abstract
This study focuses on the analysis of wave pressure analyses and development of wave pressure envelopes that can be used for the design of coastal embankment as well as for assessing vulnerability of existing embankment to hurricanes along Louisiana's coastline due to adverse weather events. The research integrates the Generalized Extreme Value (GEV) analysis with Ordinary Kriging Interpolation, producing a comprehensive spatial representation of wave height for return periods of 2, 5, 10, and 20 years. This innovative approach enables more accurate predictions of wave height variability across the Louisiana coastline, identifying regions that are most vulnerable to extreme weather impacts. Wave height data were collected from an expanded network of monitoring stations, incorporating historical hurricane data to simulate extreme conditions. The study employs empirical formulas, including the Minikin and Blackmore-Hewson methods, to calculate hydrodynamic pressures and forces on embankments. Detailed pressure distribution diagrams were developed to illustrate the combined effects of hydrodynamic and hydrostatic forces, aiding in the optimization of embankment designs. The outcome of this study underscores the critical importance of designing region-specific coastal embankments that account for spatial variability in wave impacts. The methodology outlined in this report offers a practical solution for predicting wave heights and calculating wave-induced forces on embankments, supporting disaster risk management and coastal engineering applications. The research findings will be implemented by the Coastal Protection and Restoration Authority (CPRA) in dike design practices for coastal marsh creation projects, contributing to the prevention of wetland loss in coastal Louisiana.

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ASSESSMENT OF WAVE IMPACT ON HIGHWAY EMBANKMENT DUE TO HURRICANES/TROPICAL STORMS IN COASTAL LOUISIANA

FINAL REPORT
SPTC Project Number: CY1-LTU-03

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The authors are also deeply appreciative of the Louisiana Department of Transportation and Development (LADOTD), the National Oceanic and Atmospheric Administration (NOAA), and the Coastal Protection and Restoration Authority of Louisiana for providing the essential data and resources that formed the foundation of this analysis. Their comprehensive records of wave and hurricane data significantly enhanced the findings of this report.

Table of Contents

List of Tables

List of Figures

List of Equations

List of Abbreviations and Acronyms

C_b	Celerity of waves in the breaking zone.
d_s	Depth of water at structure toe.
D	Depth of water one wavelength in front of the wall.
H_b	Height of breaking zone.
H_s	Significant wave height
L_D	Wavelength in depth equal to D, we can find it using table C-1 of SPM.
NAVD88	North American Vertical Datum of 1988.
NOAA	National Oceanic and Atmospheric Administration
P_{max}	Maximum dynamic pressure at SWL.
P_p	Maximum dynamic pressure by Blackmore & Hewson Formula.
P_s	Hydrostatic pressure
R_s	Hydrostatic force
R_m	Hydrodynamic force
R_t	Total force
SWL	.Still water level
T_p, T	Peak period
USGS	United States Geological Survey
W =	Average weight of water = 64 lbs/ft^3

Executive Summary

Coastal embankments are vital for safeguarding Louisiana's hurricane-prone regions, serving as barriers against flooding and storm surges while supporting critical infrastructure such as evacuation routes and disaster response pathways. The state's coastline is increasingly at risk due to persistent challenges, including extensive land loss, rising sea levels, and the intensifying impacts of hurricanes. Major storms like Katrina (2005), Laura (2020), and Ida (2021) have highlighted the destructive potential of extreme weather events, emphasizing the need for embankments designed to withstand both routine wave forces and the extreme conditions generated during hurricanes.

This study focuses on evaluating wave hydrodynamic forces on coastal embankments along Louisiana's coastline, addressing gaps in traditional methodologies for wave height prediction and force estimation. Conventional approaches, such as Generalized Extreme Value (GEV) analysis, often rely on single-point data, which fails to capture the spatial variability in wave height across a region. To overcome this limitation, the study integrates GEV analysis with Ordinary Kriging interpolation, producing a comprehensive spatial representation of wave heights for return periods of 2, 5, 10, and 20 years. This innovative approach enables more accurate predictions of wave height variability across Louisiana's coastline, identifying regions that are most vulnerable to extreme weather impacts.

Wave height data were collected from an expanded network of monitoring stations, incorporating historical hurricane data to simulate extreme conditions. The study employs empirical formulas, including the Minikin and Blackmore-Hewson methods, to calculate hydrodynamic pressures and forces on embankments. These formulas consider key parameters such as wave height, period, and water depth, providing reliable estimates of the pressures and forces that embankments must endure. For this analysis, a representative highway embankment with a height of 9 feet and a 4:1 slope was chosen, reflecting typical design standards in Louisiana. The results highlight significant variability in wave-induced pressures, with maximum hydrodynamic pressures exceeding 2,800 lbs/ft² in some regions. Detailed pressure distribution diagrams were developed to illustrate the combined effects of hydrodynamic and hydrostatic forces, aiding in the optimization of embankment designs.

The findings of this study underscore the critical importance of designing region-specific coastal embankments that account for spatial variability in wave impacts. The integration of statistical modeling, spatial interpolation, and empirical calculations provides a robust framework for assessing hydrodynamic forces on embankments, offering actionable insights for enhancing resilience against extreme weather events. This methodology not only addresses the flood protection function of embankments but also reinforces their role in supporting critical infrastructure, ensuring their stability under shifting weather pattern challenges. By presenting a practical approach that combines advanced statistical techniques and empirical methods, this study contributes to the development of optimal coastal defenses and improved infrastructure resilience.

The methodology outlined in this report offers a practical solution for predicting wave heights and calculating wave-induced forces on embankments, supporting disaster risk management and coastal engineering applications. By incorporating spatially distributed data and advanced analytical techniques, the approach enhances the ability to design embankments that withstand the combined pressures of hydrodynamic forces and structural demands. Through its detailed analysis and practical recommendations, this study represents a significant contribution to coastal engineering and the ongoing effort to protect Louisiana's communities and infrastructure from the impacts of adverse weather events.

Chapter 1. Introduction

The stability and resilience of coastal embankments are essential for flood protection regions susceptible to extreme weather events, especially along the hurricane-prone Louisiana coast (Seed et al., 2008). These embankments are exposed to persistent wave activity and the intensified conditions generated by hurricanes, which significantly increase the hydrodynamic forces impacting these structures (Tiwari & Wang, 2024, 389-398). As weather patterns shift, marked by rising sea levels and more intense storms, the need for robust embankment design has become increasingly critical. In Louisiana, coastal embankment serves not only as a barrier against flooding but also as essential support for critical infrastructure, including evacuation routes and disaster response pathways. Over the past century, Louisiana's coastline has faced extensive land loss, with 1,800 square miles disappearing since 1932 due to erosion, subsidence, and severe weather (Barnes et al., 2017). Major hurricanes, such as Katrina (2005), Rita (2005), and Isaac (2012), have demonstrated the destructive potential of storm surges and hurricane-driven waves, underscoring the necessity for embankments that withstand both routine wave force and extreme storm conditions.

A fundamental aspect of designing resilient embankments is the accurate prediction of wave height, which provides a foundation for assessing wave-induced forces. Traditional methods, such as Generalized Extreme Value (GEV) analysis, are commonly used to forecast wave heights for different return periods (e.g., 1, 2, 5, 10, and 20 years), offering valuable data to anticipate the intensity of wave forces during extreme events (Caires, 2011, 1-33). However, these methods often focus on single-point data from individual monitoring stations, which may not capture the spatial variability of wave height across the Louisiana coast. In this study, we enhance the prediction methodology by incorporating Ordinary Kriging interpolation, which allows for a regionally comprehensive estimation of wave heights across multiple locations (Buhmann, 2003). By using Kriging interpolation on 20–year return period wave data from various coastal monitoring stations, we generate a continuous wave height map for Louisiana's coastal region, thereby providing a more detailed and accurate assessment of wave exposure along the coast.

This interpolated wave height data, coupled with GEV analysis, serves as the foundation for calculating hydrodynamic forces on coastal embankments. Empirical formulas, including The Minikin formula (Coastal Engineering Research Center (U.S.), 1975) and the Blackmore & Hewson formula (Blackmore and Hewson, 1984,331-346), are then applied to estimate wave forces on embankments. These calculations consider wave height, wave period, and water depth, yielding reliable estimates of the hydrodynamic pressure that embankments must endure. Additionally, these results will be illustrated through a detailed pressure distribution diagram, offering an intuitive understanding of pressure profiles, and aiding in embankment design optimization for enhanced resilience against wave-induced forces.

This report outlines a novel methodology for predicting wave heights and calculating hydrodynamic forces on embankments along Louisiana's coast. Using Kriging spatial interpolation and GEV analysis, wave heights are estimated for various return periods, empirical formulas are applied to calculate forces exerted by waves under both regular and hurricane conditions, also the pressure distributional diagrams are plotted. This approach not only addresses the flood protection function of embankments but also reinforces their role as stable bases for critical infrastructure, ensuring resilience against the combined challenges of hydrodynamic forces and structural demands in the face of severe weather events.

Chapter 2. Literature Review

Coastal infrastructure, including highway embankments, plays a crucial role in mitigating flooding, storm surges, essential supports for evacuation routes and disaster response pathways, particularly in hurricane–prone regions like Louisiana. The unique challenges posed by Louisiana's coastline, such as extensive land loss, rising sea levels and severe hurricanes, demand innovative engineering solutions. This literature review synthesizes advancements in wave dynamics calculations, and coastal embankment designs, highlighting their contributions to resilient infrastructure development.

2.1. Wave Dynamics and Coastal Interactions

Wave dynamics govern the behavior of waves as they interact with the coast, influencing coastal erosion, sediment transport, and design of protective structures. Coastal Louisiana, known for its low–lying marshlands and exposure to frequent hurricanes, faces significant challenges due to wave forces amplified by shallow bathymetry and storm surges (Spalding et al., 2014, 50-57). As waves propagate across the water surface, their energy transfer is influenced by wind speed, fetch length, and duration. Upon approaching shallow regions, processes like wave shoaling, refraction, and diffraction alter their behavior, often leading to breaking waves that exert concentrated forces on coastal infrastructure (Goda, 1974, 100).

The interaction of waves with Louisiana's marshlands and built structures is further complicated by the region's geomorphology. Breaking waves in shallow areas exert significant pressures that vary based on breaker height, type, and local bathymetry (Wienke and Oumeraci, 2005, 435-462). Louisiana's unique conditions, including extensive marsh loss, amplify these interactions, making region-specific design approaches critical (Barnes et al., 2017) emphasized the economic implications of coastal land loss in Louisiana, noting how reduced marshland buffers have increased wave impact severity. Similarly, (CPRA, 2017) highlighted the necessity of integrating wave dynamics into coastal protection strategies to safeguard infrastructure and mitigate erosion.

The design of coastal structures in Louisiana must address both routine and extreme wave impacts. Geosynthetic reinforcements and specially designed concrete block systems have been used to improve resilience under such conditions. (Nagai, 1960, 659-673) and (Yamini et al., 2017, 184-202) conducted experimental studies demonstrating how articulated concrete blocks and geosynthetic materials effectively dissipate wave energy and prevent structural erosion. These systems provide cost-effective solutions for mitigating the effects of breaking waves, making them vital for the region's embankments and dikes.

2.2. Empirical and Statistical Methods for Force Estimation

Accurate estimation of wave–induced forces on coastal infrastructure is essential for designing highway embankments. Over the decades, several empirical and statistical methods have been developed and validated through experimental, numerical, and field studies. These methods aim to provide practical and reliable estimates of wave forces under both routine and extreme conditions, making them indispensable for engineering applications in hurricane-prone regions like coastal Louisiana.

One of the foundational empirical approaches is the Minikin Method (1963), which calculates dynamic wave pressures using a parabolic pressure distribution model (Coastal Engineering Research Center (U.S.), 1975). This method is particularly suited for initial designs due to its simplicity but often provides conservative estimates, which may overstate actual forces under specific conditions. The Blackmore and Hewson Method (1984) builds on these principles, incorporating factors like aeration effects and foreshore roughness to provide accurate predictions for breaking waves (Blackmore & Hewson, 1984, 331-346).

In addition to these empirical approaches, Extreme Value Analysis (EVA) is a widely used statistical method for estimating wave heights and forces associated with rare, high-impact events. EVA fits probabilistic distributions, such as the Generalized Extreme Value (GEV) distribution, to historical wave data, enabling the prediction of extreme conditions with specified return periods (Caires and Sofia, 2011, 1-33). For example, this study utilizes EVA to estimate wave forces for return periods of 2, 5, 10, and 20 years, ensuring that the design of embankments incorporates safety margins for extreme scenarios.

The integration of statistical methods with field data enhances the accuracy and applicability of wave force predictions. Studies by (Parker, 2014, 1-75) and (CPRA BA-0194, 2020) emphasized the importance of combining empirical formulas with historical wave records to account for region-specific conditions. Louisiana's marshland dynamics, hurricane tracks, and tidal characteristics introduce unique challenges that necessitate tailored solutions. The ability to generate wave pressure envelopes, reflecting maximum forces for specific hurricanes and storm surges, has proven invaluable in optimizing design strategies for coastal infrastructure.

2.3. Advancements in Numerical Modeling Techniques

Numerical modeling has emerged as a cornerstone in advancing the understanding of wave dynamics and their impact on coastal structures. By leveraging computational approaches, engineers can simulate complex interactions between waves and infrastructure with high precision. These models provide insights into hydrodynamic pressures, wave overtopping behavior, and breaking wave forces under extreme weather conditions.

One of the earliest contributions to numerical modeling was made by (Ren & Wang, 1999, 562-566), who investigated variations in wave impact pressure on structural surfaces. Their work highlighted critical factors such as maximum impact pressures and pressure distribution characteristics, forming the basis for future research. (Lin and Liu, 1999, 213-240) advanced this approach by utilizing the Volume of Fluid (VOF) method to solve the Navier-Stokes (N-S) equations, incorporating nonlinear Reynolds stress models and turbulence closure schemes. This study enabled accurate simulations of wave breaking processes and energy dissipation.

In the early 2000s, (Peregrine et al., 2005, 4005-4017) explored the effects of breaking wave shapes and topography on structural pressures using two-dimensional simulations. Concurrently, (Park et al., 2001, 70-82) conducted three-dimensional numerical simulations to analyze nonlinear wave interactions with vertical structures. These efforts established a deeper understanding of the localized effects of wave forces.

Advancements in Smoothed Particle Hydrodynamics (SPH) modeling have significantly enhanced the ability to capture complex wave-structure interactions. (Gómez-Gesteira et al., 2005, 223-238) applied SPH to simulate wave overtopping, providing insights into fluid dynamics in scenarios involving highly nonlinear waves. (Dang et al., 2021, 111349) extended SPH applications by using open-source codes to model breaking and non-breaking waves, demonstrating their utility in coastal engineering design.

Further developments in numerical modeling focused on dynamic wave loading on infrastructure. (Huang & Xiao, 2009, 164-175) evaluated wave forces on bridge decks during hurricane conditions, employing models to simulate varying water depths and storm surge effects. (Kamath et al., 2016, 105-115) adopted the REEF-3D numerical model to study the response of vertical cylinders to breaking wave impacts, offering critical insights into dynamic structural stability.

OpenFOAM, an open-source computational framework, has been widely used for modeling focused wave impacts. (Bredmose et al., 2013, 10) utilized OpenFOAM to simulate breaking wave forces on offshore wind turbine foundations, highlighting its effectiveness for offshore applications. Similarly, (Xu & Cai, 2015, 04014150) developed finite volume-based numerical simulations to evaluate the impact of solitary waves on ribbed bridge decks, addressing parameters like wave height and deck configuration.

Despite the accuracy of numerical models, computational costs remain a significant limitation. For practical applications, engineers often integrate numerical simulations with empirical methods to balance precision and efficiency. For example, (Chang et al., 2018, 344-351) demonstrated that combining focused wave theories with validated numerical flume experiments significantly enhances the reliability of structural designs.

2.4. Historical Context and Lesson Learned

The evolution of coastal engineering practices has been shaped by the lessons learned from significant historical events and the corresponding advancements in scientific understanding. Louisiana’s extensive history of hurricanes and coastal land loss offers valuable insights into the challenges of designing resilient infrastructure in hurricane-prone regions.

One of the most impactful events in recent history was Hurricane Katrina (2005), which caused widespread devastation due to storm surges, levee failures, and inland flooding. Studies, such as those by (Seed et al., 2008, 701-717), highlighted critical design flaws in levees and floodwalls, including underestimation of storm surge levels, inadequate geotechnical assessments, and lack of redundancy in protective systems. These findings emphasized the importance of integrating probabilistic approaches in wave pressure and storm surge estimation to address uncertainties inherent in extreme weather conditions.

Hurricane Rita (2005) further demonstrated the role of marshlands in mitigating wave energy and reducing storm surge impacts. (Spalding et al., 2014, 50-57) Illustrated how coastal vegetation acts as a natural buffer, dissipating wave energy and protecting inland areas from severe erosion. However, the accelerated loss of marshlands in Louisiana, compounded by subsidence and rising sea levels, has diminished this natural defense, necessitating greater reliance on engineered solutions, such as geosynthetic-reinforced embankments.

Historical analyses have also underscored the need for region-specific design standards. (Parker et al., 2009, 206-220) revisited the failures observed during Hurricane Katrina and recommended that future designs account for Louisiana's unique geophysical conditions, including its soft soils, shallow bathymetry, and frequent storm activity. This shift toward localized design criteria was echoed in CPRA's Coastal Master Plan 2017 (CPRA, 2017), which emphasized a balance between hard infrastructure (e.g., levees and embankments) and natural solutions, such as marshland restoration.

The lessons learned from historical failures and successes have significantly influenced modern design practices, emphasizing the importance of resilience and adaptability. This study builds on these lessons by integrating empirical and statistical methods to develop wave pressure envelopes for embankment design. By addressing the unique challenges of Louisiana’s coastal conditions, the research aims to contribute to the development of infrastructure capable of withstanding future extreme events.

Chapter 3. Methodology

3.1. Data Collection

To analyze wave hydrodynamic forces on embankments along the Louisiana coast, wave data were collected from an expanded network of monitoring stations, covering the period from 2004 to 2024. Figure 1 shows the location of these monitoring stations, visualized using Google Earth imagery.

Data sources included the National Oceanic and Atmospheric Administration (NOAA, n.d.) and the United States Geological Survey (USGS, n.d.). The primary monitoring stations used in this study are New Canal (Station ID: 8761927), Shell Beach (Station ID: 8761305), Amerada Pass (Station ID: 8764227), Berwick (Station ID: 8764044), Calcasieu Pass (Station ID: 8768094), Freshwater Canal (Station ID: 8766072), Lake Charles (Station ID: 8767816), and Rigolets (Station ID: 301001089442600). Additional stations incorporated into the analysis include Grand Isle (Station ID: 8761724), Pilots Station East (Station ID: 8760922), Pilottown (Station ID: 8760721), Port Fourchon (Station ID: 8762075), and West Bank 1 (Station ID: 8762482).

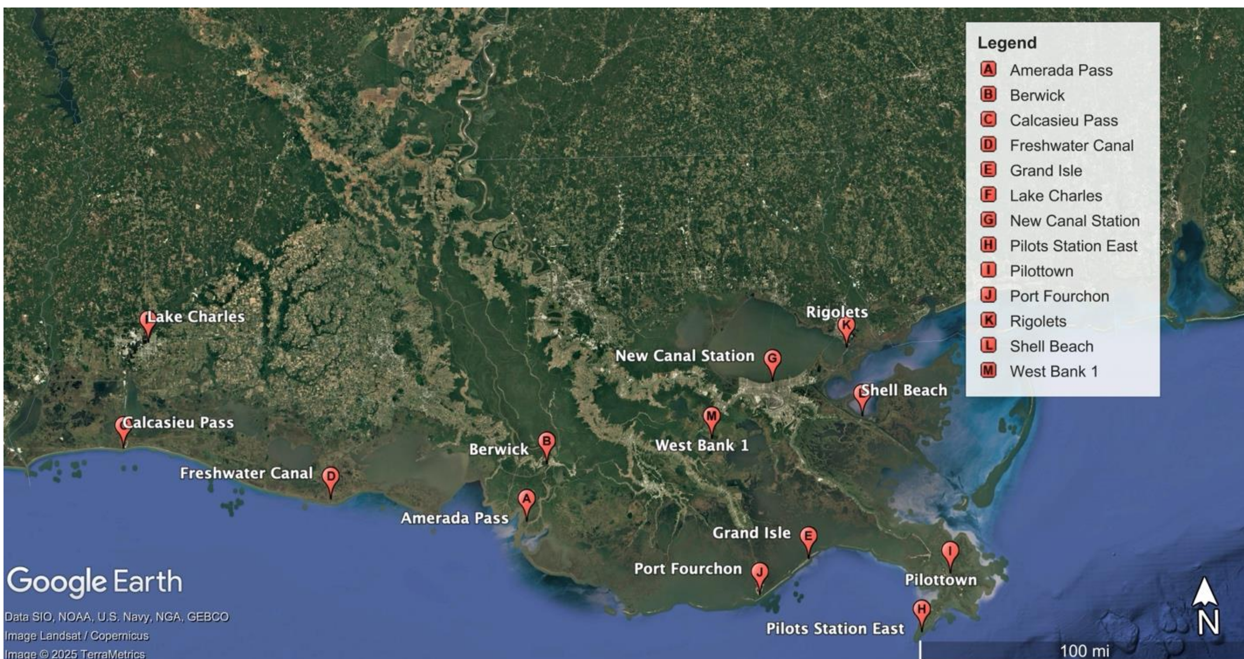

Figure 1. Wave Station Location Via Google Earth Image

The maximum wave height recorded at each station during the study period is presented in Figure 2, which displays the highest observed wave height at each station from 2004 to 2024.

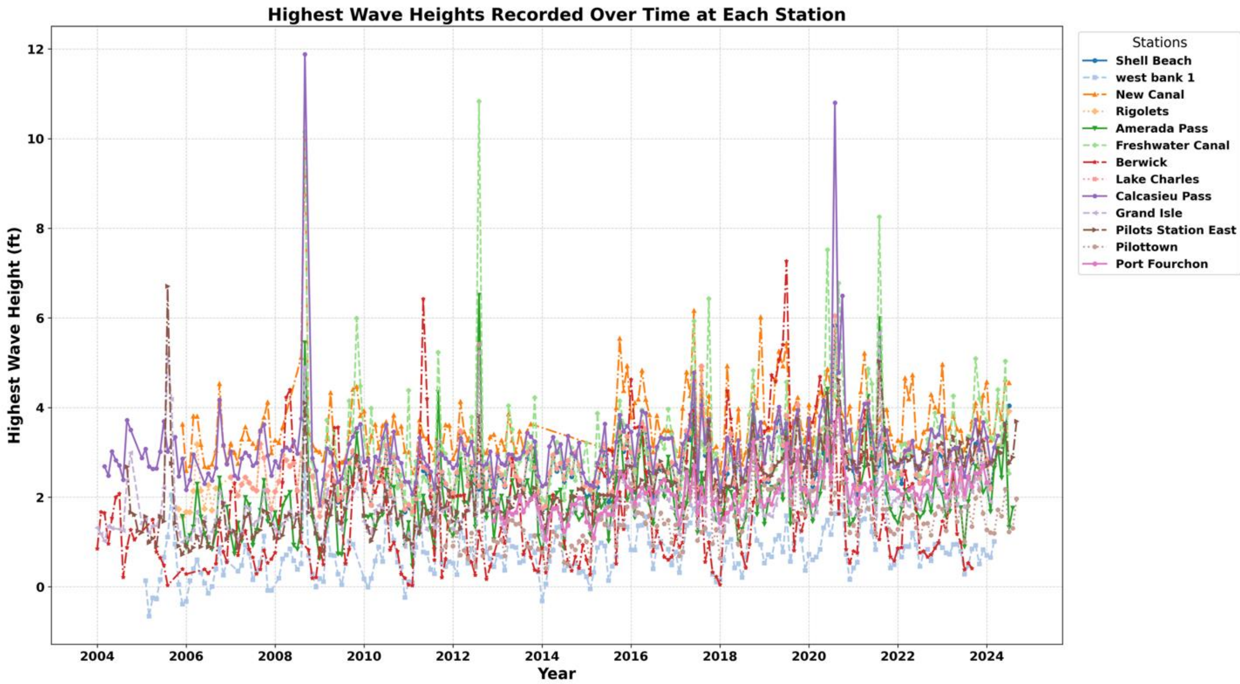

Figure 2. Highest Wave Height Recorded at Each Station

In addition to wave data, historical hurricane data measured near the Louisiana coast were integrated into the study. This dataset includes information on past hurricanes and wave conditions during these events. Figure 3 summarizes the High-Water Marks (HWMs) observed during selected hurricanes to highlight the potential impact of extreme conditions on embankment structures. Further details, including the source and a link to historical wave data, are provided in Appendix A.

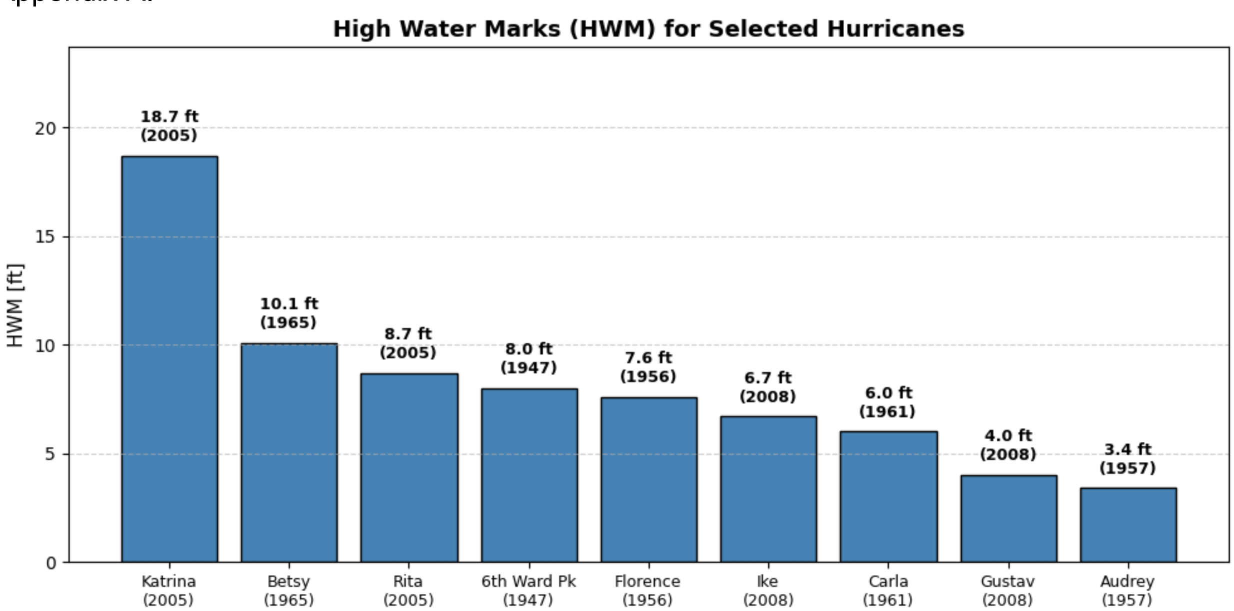

Figure 3. High Water Marks (HWM) for Selected Hurricanes

3.2. Statistical Analysis

To predict wave heights accurately along coastal Louisiana, a comprehensive statistical approach was employed. This process combined Extreme Value Analysis (EVA) to estimate wave heights associated with different return periods, reflecting the probability of extreme wave events over specific time intervals, with spatial interpolation techniques to model and distribute wave heights across the study area. Together, these methods provided a detailed understanding of wave behavior under both normal and extreme conditions. The analysis generated critical data for evaluating the hydrodynamic forces acting on embankments, which is essential for designing structures capable of withstanding such forces. A more detailed explanation of the methodology and process is provided in Appendix B.

3.2.1. Extreme Value Analysis

In this study, Extreme Value Analysis (EVA) was used to estimate the likelihood of extreme wave heights occurring along the Louisiana coastline. Python scripts were developed to process and analyze annual maximum wave height data recorded at multiple wave gauge stations. These stations provided valuable data for understanding wave behavior under extreme conditions, ensuring robust spatial coverage for analysis.

The analysis employed the Generalized Extreme Value (GEV) distribution, a statistical model specifically designed for analyzing extreme events. Using Python's `SciPy` library for statistical fitting and `pandas` for data handling, the scripts efficiently processed the data. The Maximum Likelihood Estimation (MLE) method was used to fit the GEV distribution to the data, allowing the estimation of critical parameters that characterize the behavior of extreme wave heights. These parameters include the central tendency, variability, and likelihood of extreme values, which were then used to calculate wave heights for specific return periods, such as 2, 5, 10, and 20 years.

Wave heights corresponding to these return periods were derived using the quantile function of the GEV distribution. The results, including predicted wave heights, were compiled into a dataset and saved as a CSV file for further spatial analysis. To provide a visual representation, Figure 4 illustrates the relationship between return periods and wave heights for each wave gauge station, offering a clear understanding of the risks associated with extreme wave events.

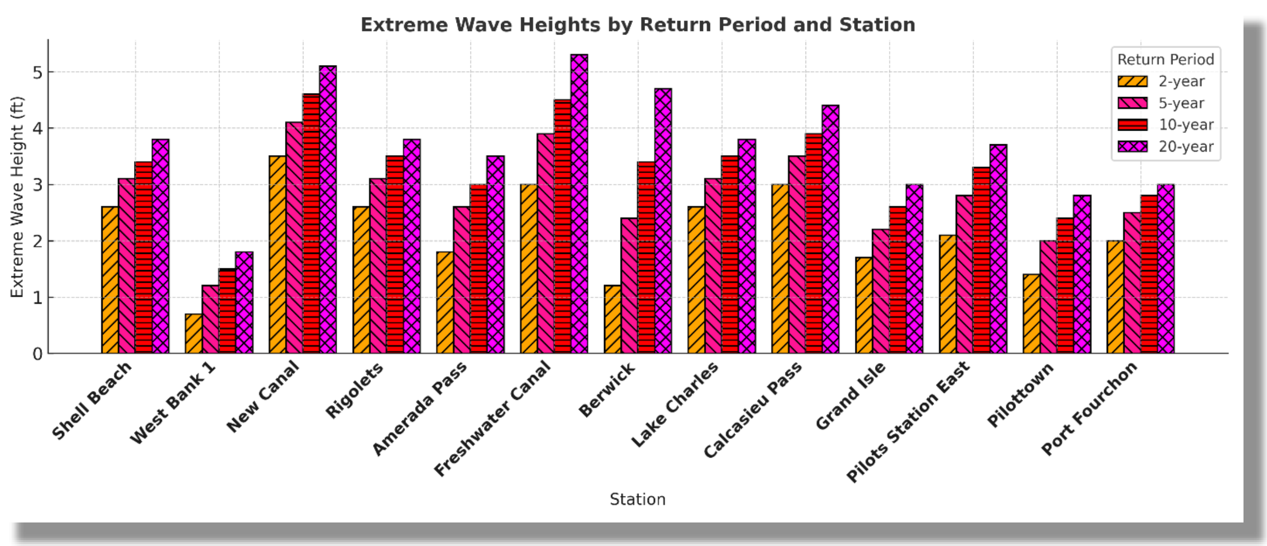

Figure 4. Return Period Wave Height for Each Station

The Python scripts used for this analysis are detailed in Appendix B, providing full transparency and ensuring reproducibility of the methodology. This rigorous approach offers crucial insights for embankment design, enabling engineers to assess and accommodate the forces exerted by extreme waves.

3.2.2. Spatial Interpolation Using Kriging Statical Approach

To extend wave height predictions beyond the specific locations of wave gauge stations and create a continuous spatial map, spatial interpolation of the GEV parameters was performed using a geostatistical method known as Ordinary Kriging. This approach enables the estimation of wave heights at any point within the study area by considering the spatial arrangement and statistical variability of the available data. The process was implemented using Python scripts, which utilized the `pykrige` library to execute the Kriging interpolation.

The outputs from this process were saved in multiple formats for further use. The interpolated GEV parameters and calculated wave heights were stored as `NumPy` arrays, which are efficient for computational tasks. Additionally, the results were exported as GeoTIFF files, a widely used format for geospatial data visualization. For further analysis and ease of use, a CSV file containing longitude, latitude, and interpolated wave heights was also generated.

To visualize the results, the interpolated wave height data was mapped onto a Louisiana coastline map using QGIS**,** an open-source Geographic Information System (GIS) software. This software allows for the creation of detailed visual representations of the data, making it easier to interpret and analyze. For instance, Figure 5 shows the spatial distribution of 20-year return period wave heights, illustrating how extreme wave heights vary across the study area. This map effectively highlights regions that are most at risk from extreme wave events, providing critical information for disaster preparedness and coastal engineering.

The interpolated wave height data was visualized on a Louisiana coastline map using QGIS, an open-source geographic information system software widely used for spatial data analysis and visualization. Figure 5 presents the spatial distribution of the 20-year return period wave heights, effectively illustrating the variability in extreme wave heights across the study area and highlighting regions most susceptible to extreme events. Techniques such as Inverse Distance Weighting (IDW) and Triangulated Irregular Network (TIN) were also explored to validate and enhance the interpretability of the spatial distribution.

The integration of Python libraries, including `NumPy`, `matplotlib`, and `pykrige`, alongside QGIS for visualization, ensured accurate and efficient mapping of wave height distributions. This robust workflow supports disaster risk management and coastal engineering applications by providing critical insights into wave height variability across the Louisiana coastline.

However, it is important to acknowledge the limitations of the kriging approach used. Ordinary Kriging assumes spatial stationarity and isotropy in the statistical properties of the field and relies solely on the spatial distribution of observation points. It does not directly incorporate physical factors that may significantly influence wave heights. For instance, stations located inland near canals or smaller lakes may experience markedly different wave behavior than coastal stations, despite being at similar distances from the storm center.

Storm-specific dynamics, such as hurricane path, counterclockwise wind rotation, and whether a station lies on the windward or leeward side, can also strongly influence local wave responses but are not captured by the interpolation process. A clear example is the observed difference in wave heights between New Canal and Rigolets Stations: although geographically close, New

Canal located along Lake Pontchartrain with a large 41-mile fetch, shows significantly higher wave heights than Rigolets, which is adjacent to Lake Catherine, having a fetch of only 4.4 miles. Similarly, stations like Calcasieu Pass and Freshwater Canal experience elevated wave heights due to their direct exposure to the Gulf of America (Gulf of Mexico) and the recording of more recent intense hurricanes.

To improve the physical realism and accuracy of wave height interpolation, future work could explore the use of co-kriging or physics-informed geostatistical models. These approaches would allow the integration of auxiliary variables such as wind direction, storm trajectory, local topography, and water body type, providing more context-aware and event-specific wave height predictions especially during extreme weather events.

It is noteworthy that most of the spatial interpolations of wave heights recorded at different monitoring stations were not conducted for a single tropical storm or hurricane, but rather for multiple events. The results are therefore presented statistically in terms of 5-, 10-, 15-, or 20-year return period hurricanes. Consequently, errors related to wind direction, storm trajectory, and other storm-specific factors are not cumulative; instead, they tend to offset each other to some extent.

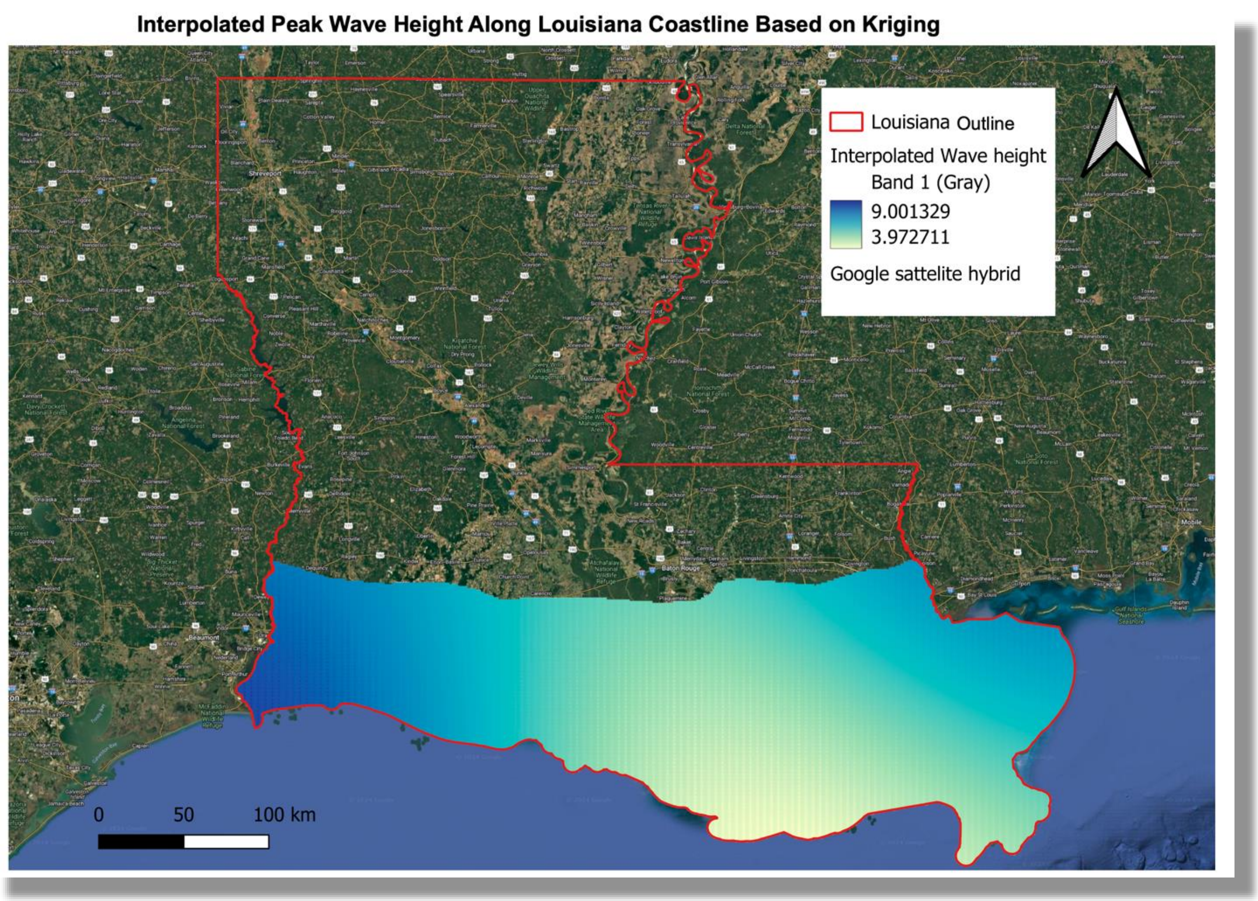

Figure 5. Spatial Distribution of 20-Year Return Period Wave Heights Along the Louisiana Coastline

3.3. Wave Force Calculation

The calculation of wave forces acting on embankments is a critical component of this study, focusing on breaking wave conditions. These calculations are essential for understanding the hydrodynamic pressures that embankments must withstand during extreme weather events, particularly hurricanes.

3.3.1. Breaking Wave Condition

For breaking waves, the study employs two widely recognized empirical formulas: the Minikin formula and the Blackmore and Hewson formula. The Minikin formula estimates the dynamic pressure exerted by breaking waves on vertical structures. It is defined as:

$$P_m = 101\, w \frac{H_b}{L_D} \frac{d_s}{D} (D + d_s)$$

Equation 1. Maximum Hydrodynamic Pressure at SWL by Minikin Formula

$$R_m = P_m \times \frac{H_b}{3}$$

Equation 2. Maximum Hydrodynamic Force by Minikin Formula

$$R_t = R_m + \frac{w\left(d_s + \frac{H_b}{2}\right)^2}{2} = R_m + R_s$$

Equation 3. Total Force Calculation by Minikin Formula

Where P_m is the maximum dynamic pressure, w is the specific weight of water, H_b is the breaker height, d_s is the depth at toe of the wall, D is the depth one wavelength in front of wall, L_D is the wavelength in water depth D, Rm is the dynamic force, Rs is the hydrostatic force and Rt is the total force (Coastal Engineering Research Center (U.S.), 1975). The Blackmore and Hewson formula is also applied to estimate the impact pressure on coastal defenses. This formula is expressed as:

$$P_p = \beth T C_b^2$$

Equation 4. Maximum Hydrodynamic Pressure at SWL by Blackmore & Hewson Formula

Where, P_p is the dynamic pressure, ב is the aeration factor (0.25 for sandy beach and 0.5 for rocky beach), T and C_b are related to the characteristic length. The dynamic pressure, P_p was assumed to act uniformly over the impact area, and it is added to the hydrostatic pressure to give the total force per meter (Blackmore & Hewson, 1984, 331-346).

The formula is applicable to structures that have either nearly vertical or sloping walls. In cases where the wall slopes backward, the horizontal component of the dynamic force resulting from wave breaking must be decreased by $\sin^2\theta$ (Coastal Engineering Research Center (U.S.), 1975). This adjustment is necessary because the force calculated using the original formula assumes a vertical wall, providing a perpendicular force direction. For a sloped wall, it is essential to consider the perpendicular wave pressure component along the slope, which alters the original horizontal component. Consequently, this original horizontal pressure component is adjusted by $\sin^2\theta$.

Furthermore, when converting the resultant force from a perpendicular orientation to a horizontal one, it is necessary to further reduce it by $\sin^2 \theta$ (Tiwari & Wang, 2024, 389-398).

Chapter 4. Results

The results of this study provide valuable insights into the wave heights, forces, and pressures acting on coastal embankments under both breaking wave conditions and overtopping scenarios. The analysis integrates statistical findings with empirical calculations to assess the potential impact of extreme weather events, particularly hurricanes, on coastal infrastructure.

4.1. Wave Height Predication

The Generalized Extreme Value (GEV) analysis yielded significant parameter estimates for wave heights. These parameters indicate a strong correlation between historical data and predicted extreme wave heights for various return periods (2, 5, 10, and 20 years) illustrated in Table 1.

Table 1. Estimated Significant Wave Heights for Return Periods

Station Name	2-yr Return Period Wave Height (ft)	Wave Period (Sec)	5-yr Return Period Wave Height (ft)	Wave Period (Sec)	10-yr Return Period Wave Height (ft)	Wave Period (Sec)	20-yr Return Period Wave Height (ft)	Wave Period (Sec)
Shell Beach	2.6	3.2	3.1	3.5	3.4	3.5	3.8	3.7
West Bank 1	0.7	1.2	1.2	1.5	1.5	1.7	1.8	2.1
New Canal	3.5	3.9	4.1	4.0	4.6	4.2	5.1	5.2
Rigolets	2.6	3.2	3.1	3.5	3.5	3.7	3.8	3.7
Amerada Pass	1.8	2.2	2.6	3.2	3.0	3.4	3.5	3.7
Freshwater Canal	3.0	3.4	3.9	3.8	4.5	4.1	5.3	5.2
Berwick	1.2	1.6	2.4	2.6	3.4	3.7	4.7	4.5
Lake Charles	3.6	3.9	4.3	4.1	4.6	4.2	5.8	5.5
Calcasieu Pass	3.0	3.4	3.5	3.9	3.9	4.0	4.4	5.3
Grand Isle	1.7	1.9	2.2	2.5	2.6	3.1	3.0	3.3
Pilots Station East	2.1	2	2.8	3.3	3.3	3.5	3.7	3.8
Pilottown	1.4	1.7	2.0	2.2	2.4	3.1	2.8	3.3
Port Fourchon	2.0	2.2	2.5	3.0	2.8	3.3	3.0	3.3

The hurricane highest watermarks recorded along the coastal areas of Louisiana, presented in Table 2 and Figure 3, were derived from the NOAA (NOAA, n.d.) and the Coastal Protection and

Restoration Authority (CPRA) Louisiana Report (Coastal Protection and Restoration Authority PO-0169, 2018). This dataset is integral for calculating wave hydrodynamic forces on embankments under storm surge conditions.

Table 2. Major Hurricane Data Recorded Along Coastal Louisiana

Hurricane	HWM (ft)	Year	Long.	Lat.	Wind Speed (Knot)
Katrina	18.70	2005	-89.80	30.06	150
Issac	10.10	2012	-89.76	30.11	70
Rita	8.70	2005	-90.08	30.36	155
6th Hurr FL	8.00	1947	-89.79	30.06	100
Flossy	7.60	1956	-89.88	30.05	90
Ike	6.70	2008	-90.07	30.35	125
Carla	6.00	1961	-90.06	30.36	150
Gustav	4.80	2008	-90.12	30.02	95
Audrey	3.40	1957	-90.06	30.34	125

4.2. Calculated Breaking Wave Hydrodynamic Force on Embankment

For this study, a highway embankment height of 9 feet with a 4:1 slope was chosen to evaluate the wave impact in coastal Louisiana during hurricanes and tropical storms. This selection aligns with typical embankment design standards provided by the Louisiana Department of Transportation and Development (LADOTD). According to LADOTD guidelines, embankments with slopes of 4:1 are commonly employed beyond the clear zone, providing stability and accommodating drainage needs. The 9-foot height reflects the range observed in coastal highway embankments designed to mitigate storm impacts. These parameters enable accurate calculation of wave height and pressure distribution during extreme weather events, aiding in the analysis of highway resilience under storm surge conditions (Louisiana Department of Transportation and Development, 2019).

Table 3. Breaking Wave Pressure on Embankment by Minikin Formula

Station Name	20-yr Return Period Wave Height (ft)	T_P (Sec)	D (ft)	L_D (ft)	P_{max} (lbs/ft^2)	R_t (lbs/ft)	Total Force on Embankment (4:1)
Shell Beach	3.8	3.7	4.15	48	1854	2213	536.87
West Bank 1	1.8	2.1	3.35	29	1515	1931	468.46
New Canal	5.1	5.2	5.89	56	2456	2743	665.45
Rigolets	3.8	3.7	4.15	50	1902	2347	569.38
Amerada Pass	3.5	3.7	4.05	46	1763	2142	519.65
Freshwater Canal	5.3	5.2	5.67	53	2526	2832	687.04
Berwick	4.7	4.5	5.12	51	2231	2562	621.54
Lake Charles	5.8	5.5	6.05	59	2802	3043	738.14
Calcasieu Pass	4.4	4.3	4.89	51	2160	2478	601.16
Grand Isle	3.0	3.3	3.89	42	1680	2078	504.12
Pilots Station East	3.7	3.8	4.12	48	1817	2198	533.23
Pilottown	2.8	3.3	3.21	36	1589	1987	482.04
Port Fourchon	3.0	3.3	3.89	39	1672	1972	478.41

Table 3 and Figure 6 present the breaking wave pressure, which combines the hydrodynamic pressure exerted by wave breaking on the embankment with the hydrostatic pressure by Minikin formula. Table 4 and Figure 7 provide the wave pressure calculated using the Blackmore & Hewson formula.

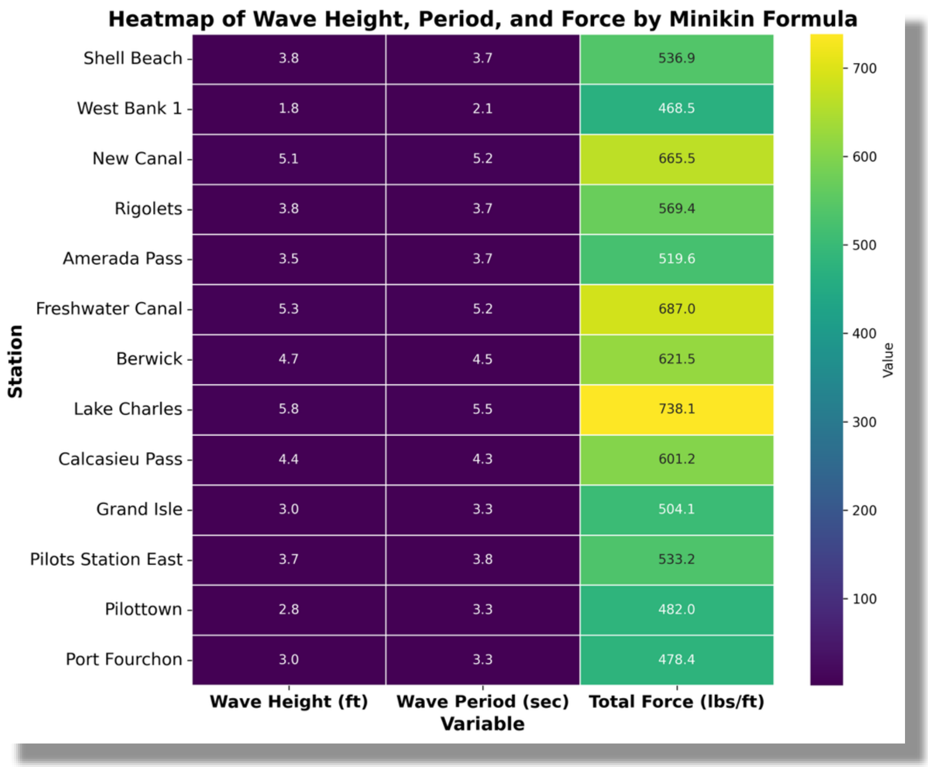

Figure 6. Heatmap of Wave Height, Wave Period, and Total Force on Embankment by Minikin Formula

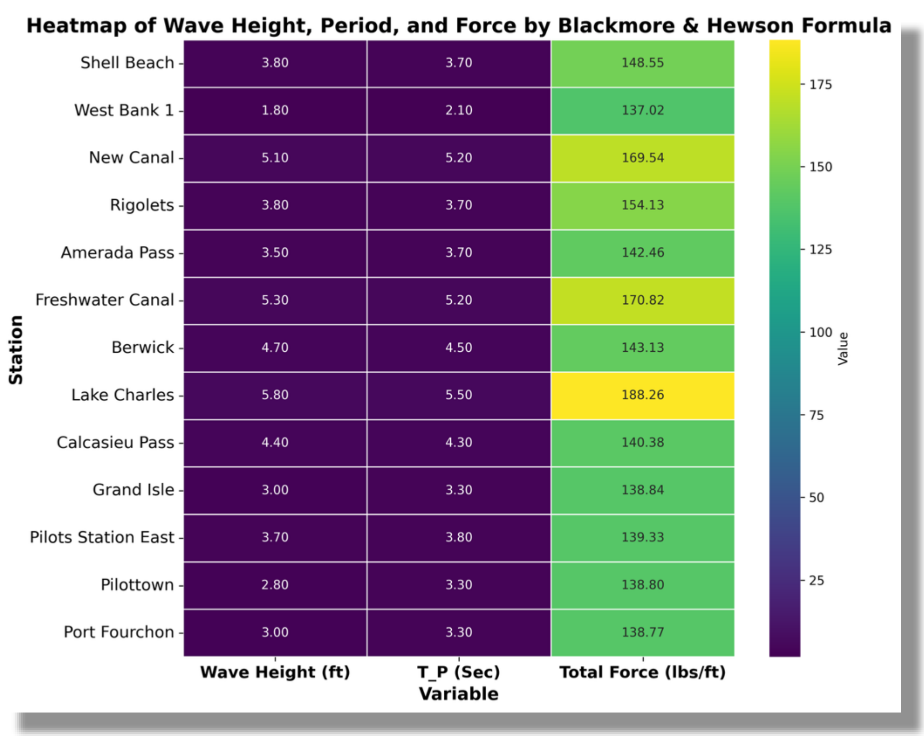

Figure 7. Heatmap of Wave Height, Wave Period, and Total Force on Embankment by Blackmore & Hewson Formula

Table 4. Breaking Wave Force Calculation by Blackmore & Hewson Formula

Station Name	20-yr Return Period Wave Height (ft)	T_P (Sec)	C_b (ft/sec)	P_p (lbs/ft^2)	R_m (lbs/ft)	R_t (lbs/ft)	Total Force on Embankment (4:1)
Shell Beach	3.8	3.7	8.15	92.30	182.70	612.34	148.55
West Bank 1	1.8	2.1	6.83	82.45	169.45	564.78	137.02
New Canal	5.1	5.2	9.34	102.70	208.76	698.86	169.54
Rigolets	3.8	3.7	8.15	92.34	183.45	635.32	154.13
Amerada Pass	3.5	3.7	8.15	91.76	179.87	587.21	142.46
Freshwater Canal	5.3	5.2	9.34	102.85	210.12	704.12	170.82
Berwick	4.7	4.5	8.45	96.70	189.67	589.98	143.13
Lake Charles	5.8	5.5	9.67	99.29	215.78	776.39	188.26
Calcasieu Pass	4.4	4.3	8.39	94.86	185.24	578.67	140.38
Grand Isle	3.0	3.3	7.85	87.94	176.83	572.31	138.84
Pilots Station East	3.7	3.8	8.13	91.21	178.92	574.32	139.33
Pilottown	2.8	3.3	7.85	86.33	175.67	572.12	138.80
Port Fourchon	3.0	3.3	7.85	86.72	176.39	572.02	138.77

4.3. Pressure Distribution Diagram

The pressure distribution diagrams illustrate the hydrodynamic pressures exerted on coastal embankments near two critical locations: New Canal Station in the New Orleans area and Lake Charles Station. These locations were selected for their strategic importance and proximity to major infrastructure.

Near New Canal Station, situated within the New Orleans metropolitan area, the embankments provide critical protection to nearby highways, including U.S. Highway 90, which serves as a vital transportation corridor for local and regional traffic. The pressure distribution diagrams for this location demonstrate the combined hydrodynamic and hydrostatic forces calculated using both the Minikin and Blackmore & Hewson formulas, highlighting the intense pressures these embankments endure during extreme wave events.

At Lake Charles Station, the embankments protect essential infrastructure near Interstate I-10, a major east-west transportation route connecting Louisiana to neighboring states. This location is particularly vulnerable to hurricane impacts, given its proximity to the Gulf Coast. The pressure distribution diagrams for Lake Charles illustrates the pressures acting on embankments with a 9-foot height and a 4:1 slope under breaking wave conditions, derived from both the Minikin and Blackmore & Hewson methods.

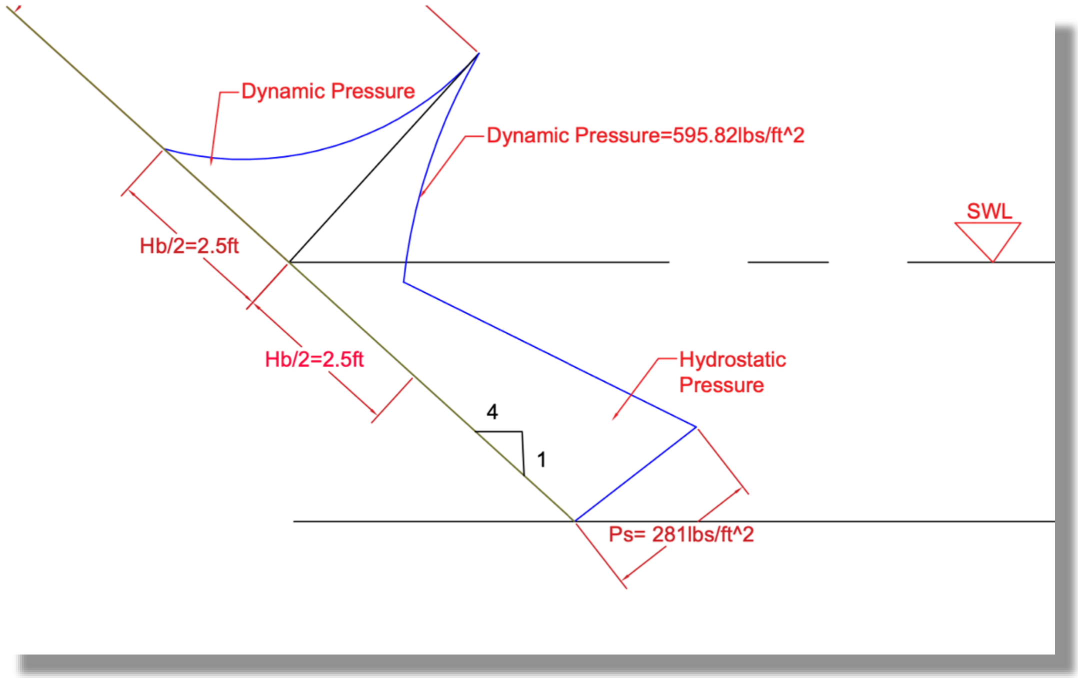

Figure 8. Modified 20-yr return period Minikin wave pressure distribution on a virtual embankment near New Canal Station.

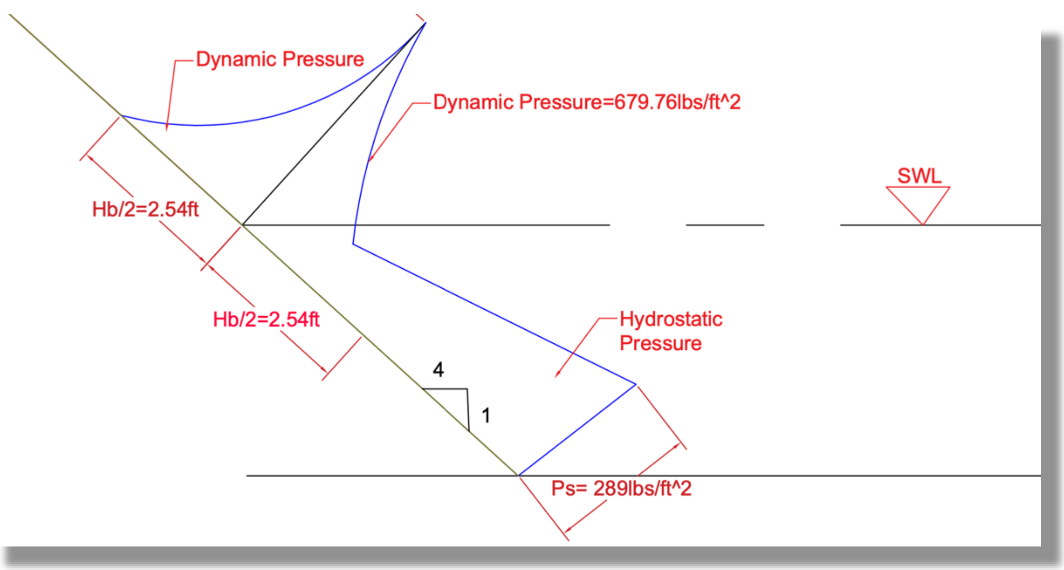

Figure 9. Modified 20-yr return period Minikin wave pressure distribution on a virtual embankment near Lake Charles Station.

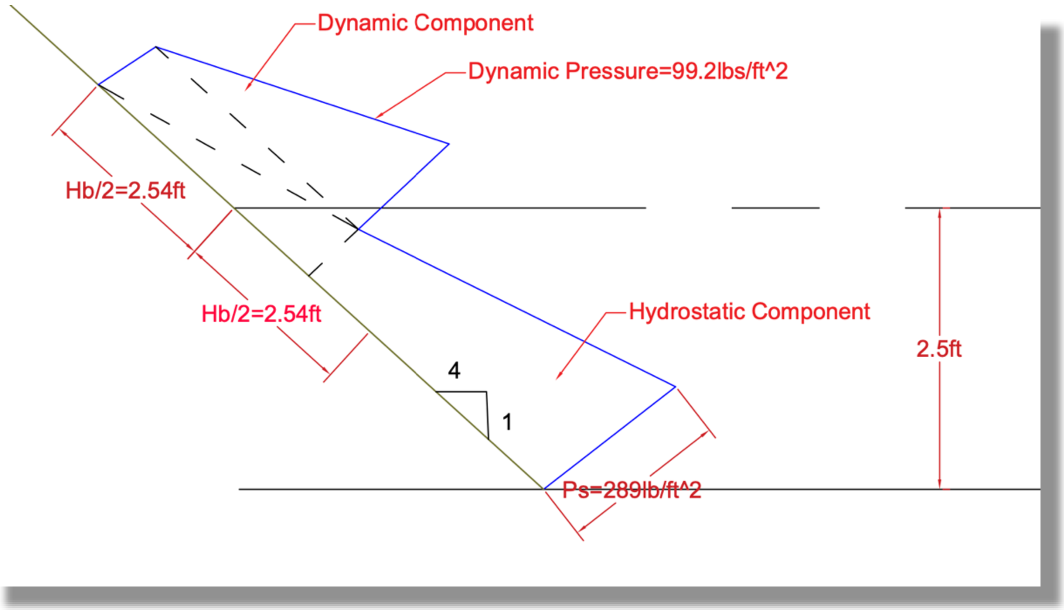

Figure 10. Modified 20-yr return period Blackmore & Hewson wave pressure distribution on a virtual embankment near New Canal Station.

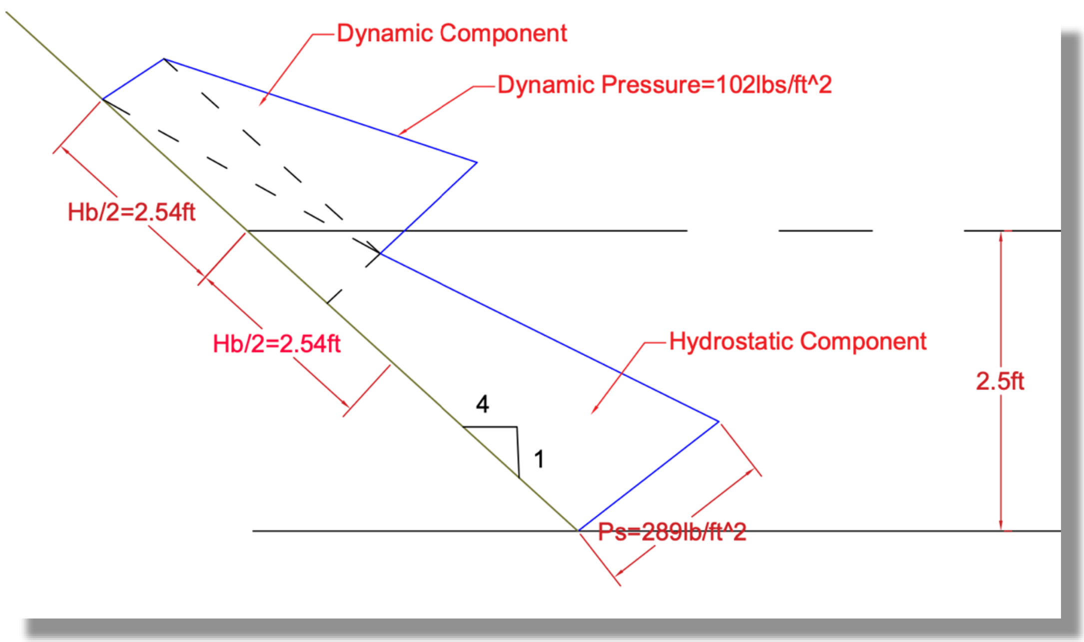

Figure 11. Modified 20-yr return period Blackmore & Hewson wave pressure distribution on a virtual embankment near Lake Charles Station.

Chapter 5. Conclusion

This study addressed the critical challenge of designing geosynthetic-reinforced highway embankments capable of withstanding extreme wave pressures along Louisiana's hurricane-prone coastline. The research successfully integrated statistical wave height prediction methods, spatial interpolation techniques, and empirical formulas to provide practical solutions for embankment design and resilience.

Wave height data from multiple monitoring stations, combined with historical hurricane records, were analyzed using the Generalized Extreme Value (GEV) distribution and Ordinary Kriging interpolation. These methods produced a spatially continuous representation of wave heights for return periods of 2, 5, 10, and 20 years, capturing regional variability. The analysis revealed that embankments near Lake Charles face significantly higher pressures compared to those near New Orleans, primarily due to the frequent and intense impact of hurricanes.

Using empirical formulas such as Minikin and Blackmore-Hewson, hydrodynamic forces on embankments were calculated under breaking wave conditions. The developed wave pressure envelopes, based on analyses of different hurricane categories, offer standardized design guidelines for embankments. These envelopes were specifically recommended to the Louisiana Department of Transportation and Development (LADOTD) for future design applications, addressing practical needs. As a co-sponsor of the research, the CPRA is "*eager to apply the results of your important study in the implementation of our restoration projects".*

Key achievements of this study include the generation of pressure distribution diagrams that provide engineers with actionable tools to optimize embankment designs. These diagrams enable the identification of high-risk zones and the implementation of region-specific design strategies, ensuring embankment resilience under extreme weather conditions. The research outcomes contribute directly to advancing coastal infrastructure design practices, fulfilling the goals set forth in the Cycle One proposal.

This work lays a foundation for future enhancements, such as incorporating real-time monitoring and advanced simulation techniques. By addressing the unique challenges of Louisiana's coastal conditions, the study provides a robust framework for designing reliable embankments that protect critical infrastructure and mitigate the risks posed by hurricanes and tropical storms.

Chapter 6. Implementation of Project Outputs

At the request of CPRA, the co-sponsor of the research project, an interim report was prepared and submitted in April 2024 to present preliminary findings toward developing a design guideline for coastal dikes (or highway embankments). The report included research on the hydrodynamic wave pressure distribution on dikes and embankments, which captured the interest of several CPRA engineers. After a thorough review by CPRA personnel, the report received positive feedback and constructive suggestions in July 2024. Significant efforts were made to address their questions and incorporate their suggestions, further enhancing the research outcomes.

In their feedback, CPRA highlighted that the newly proposed method for calculating wave pressure could significantly influence future dike (embankment) designs for wetland protection projects. Additionally, the research findings related to wave height, dike crest elevation, and freeboard will contribute to a comprehensive procedure for designing coastal dikes or highway embankments utilizing armored Articulated Concrete Mats and Geosynthetic-Reinforced Slopes.

Once the final research report, including the calculation of hydrodynamic pressure on coastal dikes and embankments, is accepted, these findings will be integrated into dike design practices for coastal marsh creation projects, helping to prevent wetland loss in coastal Louisiana. Discussions about implementation details are anticipated with CPRA personnel in the summer of 2025.

These advancements in dike design practices for Louisiana's coastal marsh creation projects will result in more reliable and efficient engineering solutions. The improvements are expected to contribute significantly to wetland loss prevention and support ongoing restoration efforts, promoting positive progress.

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Appendix A: Historical Wave Data

This appendix provides a summary of the historical wave data collected from NOAA and USGS stations along the Louisiana Coastline. The data spans from 2004-2024 and includes the highest wave height, lowest wave height, mean sea level, and additional parameters recorded at multiple stations. The information forms the basis for the wave height predictions and force calculations presented in the report.

A. 1 Overview of Data Collection

1. Sources of Data:

- Data was retrieved from the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS) and the Coastal Protection and Restoration Authority of Louisiana (CPRA).
- Monitoring Stations covered both inland and coastal regions of Louisiana to provide comprehensive coverage.

2. Parameters Recorded:

- Wave Height (ft): Significant and maximum wave heights recorded over a 20-year period.
- High Water Marks (HWM): Measurements indicating storm surge levels during major hurricanes.

3. Station Distribution:

- A total of 13 stations were included in the study, ranging from New Orleans to Lake Charles. This ensures spatial variability is captured for robust analysis.

4. Data Cleaning and Preprocessing:

- Anomalous reading caused by equipment malfunctions or interferences were filtered out.
- Missing data points were interpolated using linear methods for consistency.

A. 2 Access to Full Dataset

Due to the large size of the dataset, it has been hosted online for accessibility. Reader can download the complete Excel File, from the following link:

https://docs.google.com/spreadsheets/d/1aGoUTRWtnAgUSPKwAx6XAqMGuYmKbhLa/edit?usp=drive_link&ouid=104405051839642247799&rtpof=true&sd=true

This dataset is provided in its raw format to ensure transparency and to allow for further analysis or validation by interested researchers.

A. 3 Disclaimer

The dataset is shared for academic and research purposes only. The authors are not responsible for any misinterpretation or misuse of the data.

Appendix B: Scripts Used in Analysis

This appendix presents the scripts used for statical analysis and spatial interpolation of wave heights. While the wave force calculations were conducted manually using the empirical formulas provided in the main report, the scripts included here demonstrate the analytical steps for data preprocessing, GEV analysis and Kriging interpolation.

B. 1 Generalized Extreme Value (GEV) Analysis

The script fits a Generalized Extreme Value (GEV) distribution to the annual maximum wave height data and calculates return levels for specific periods.

```
import pandas as pd
from scipy.stats import genextreme as gev
# Load Excel file with wave data
file_path = 'path_to_excel_file.xlsx' # your file path
wave_data = pd.ExcelFile(file_path)
# Initialize results storage
results = []
# Return periods to predict wave heights for
return_periods = [2, 5, 10, 20]
probabilities = [1 - 1/rp for rp in return_periods]
# Loop through each sheet (station)
for sheet in wave_data.sheet_names:
    # Load data for the station
    df = wave_data.parse(sheet)
    # Select the column with wave heights (named "Highest")
    wave_heights = df['Highest'].dropna()
    # Fit GEV distribution
    params = gev.fit(wave_heights)
    shape, loc, scale = params
    # Predict return period wave heights
    predicted_heights = gev.ppf(probabilities, shape, loc, scale)
    # Store results
    results.append({
        'Station': sheet,
        'Shape': shape,
        'Location': loc,
        'Scale': scale,
        '2-Year': predicted_heights[0],
```

```
        '5-Year': predicted_heights[1],
        '10-Year': predicted_heights[2],
        '20-Year': predicted_heights[3]
    }
# Convert results to DataFrame
results_df = pd.DataFrame(results)
# Save results to CSV
output_path = 'gev_wave_height_predictions.csv'
results_df.to_csv(output_path, index=False)
print(f"GEV analysis completed. Results saved to '{output_path}'.")
```

B. 2 Kriging Interpolation for Spatial Wave Height Prediction

This script uses the GEV results to interpolate wave heights spatially across the Louisiana coastline for the 20-year return period.

```
from pykrige.ok import OrdinaryKriging
import pandas as pd
import numpy as np
# Load GEV results
gev_data = pd.read_csv('gev_wave_height_predictions.csv')
# Extract coordinates and 20-year return period values
coords = gev_data[['Longitude', 'Latitude']].values
values = gev_data['20-Year']
# Define grid for interpolation
grid_lon = np.linspace(-93, -88, 100)
grid_lat = np.linspace(29, 31, 100)
grid_lon, grid_lat = np.meshgrid(grid_lon, grid_lat)
# Perform Ordinary Kriging
kriging = OrdinaryKriging(coords[:, 0], coords[:, 1], values,
variogram_model='linear')
z, ss = kriging.execute('grid', grid_lon, grid_lat)
# Save results
interpolated_data = {
    'Longitude': grid_lon.flatten(),
    'Latitude': grid_lat.flatten(),
    'Wave_Height': z.flatten()
}
```

```
interpolated_df = pd.DataFrame(interpolated_data)
interpolated_df.to_csv('kriging_results.csv', index=False)
print("Kriging analysis completed. Results saved to 'kriging_results.csv'.")
```

B. 3 Visualizing Results Using QGIS

This section outlines the process of visualizing the Kriging results using QGIS. The spatially interpolated wave height data for the 20-year return period was mapped onto a Louisiana base map to illustrate areas with higher wave heights.

1. Data Preparation

- The kriging results were exported to CSV file, containing Longitude, Latitude and Wave Height columns.

2. Base Map Integration

- A Louisiana Shapefile was added to QGIS to provide the geographical context for the study area.

3. Data Import and Rasterization

- The CSV file was imported as a delimited text layer, and the Rasterize tool was used to create a continuous wave height map.

4. Map Styling

- A gradient color map was applied to represent wave height magnitudes, with green for higher values and red for lower values.

5. Exporting Results

- The styled map was exported as a high-resolution image for inclusion in the report.

Appendix C: Breaking Wave Force Calculation

This appendix provides the step-by-step process for calculating wave forces generated by breaking waves using the formulas referenced in this report. For clarity, calculations for one specific location are presented as an example to guide readers through the methodology. The same process was applied to calculate wave forces at all other stations.

C. 1 Breaking Wave Force Calculation on Embankment using Minikin Formula at New Canal Location

Embankment Hight = 9 ft

Water Depth (d_s) = 2.5 ft

Embankment Slope = 4H:1V (m = 0.25)

Wave Period = 5.2 sec

H = 5.1 ft

$L_0 = \frac{gT^2}{2\pi} = 1.56\ (5.2)^2 = 42.18$ m = 139 ft

$d/L_0 = 2.5/42.18 = 0.01798$

and from table C-1, Appendix C, (Shore Protection Manual Part-2)

d/L = 0.07268

and

$L_d = 13.56$ ft

$D = 2.5 + 13.56 \times (0.25) = 5.89$ ft

And using Table C-1, as above,

$D/L_0 = 0.0423$; $D/L_D = 0.10517$

Hence

$L_D = 56$ft

Using equation 1 of this report to find P_m

$P_m = 2455.83 \approx 2456$ lbs/ft^2

Using equation 3 of this report to find R_t

$R_t = 2743$ lbs/ft

R_t for embankment (4H:1V) = $2743 \times \sin\theta = 665.45$ lbs/ft

C. 2 Breaking Wave Force Calculation on Embankment using Blackmore & Hewson Formula at New Canal Location

Embankment Hight = 9 ft

Wave period = 5.2 sec

$C_b = (gd)^{1/2} = (32.185 \times 2.5)^{1/2} = 8.97$ ft

Using equation 4 of this report to find P_p

$P_p = 0.25 \times 8.97^2 \times 5.2 = 102.70$ lbs/ft^2

R_t = Dynamic force + Static force = 698.86 lbs/ft, embankment (4:1) = $698.86\sin\theta = 169.54$ lbs/ft

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