A 20-year systematic review of wave dissipation by soft and hybrid nature-based solutions (NbS)

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Abstract

A systematic review of 20 years of studies was conducted to understand wave dissipation trends of hybrid and natural (soft) coastal features, collectively referred to as nature-based solutions (NbS). Of 13,451 studies identified and 470 studies reviewed; only 50 studies consistently reported the basic parameters required to compare wave height dissipation. These studies were used to create a basic understanding of wave dissipation across soft and hybrid features along different cross-shore widths. More specific implementation guidance for NbS is limited due to the lack of consistent monitoring practices and protocol within and between soft and hybrid features. This disparity is greatest between soft and hybrid NbS. To fully understand best practices for the wide variety of soft and hybrid NbS, more uniform monitoring data is needed to assess and more fully define wave dissipation performance. Based on the findings of this review, eight parameters to measure the wave dissipation effectiveness of NbS features are proposed. These findings will inform the development and application of evaluation protocols for future NbS projects.

Keywords

nature-based solutions, wave height dissipation, natural and nature-based features, living shorelines, hybrid shoreline protection

Introduction

Reducing erosion and wave-induced flooding is often an engineering goal of both traditional and nature-based coastal infrastructure features. This goal is commonly achieved through the installation or enhancement of features that dissipate waves and success is often evaluated as the reduction of incoming wave height by the feature. In the United States, shoreline retreat averages up to 1.8 m/y and 0.9 m/y on the Gulf Coast and Atlantic Coast, respectively; between 1984 and 2015 there was almost 28,000 km^2 of permanent land loss globally in coastal areas (Beatley et al., 2002; Mentaschi et al., 2018). Application of shoreline protection that both utilizes and enhances ecological systems, also known as natural and nature-based features (NNBFs), nature-based solutions (NbS), or living shorelines, has substantially risen in popularity in the past 15-20 years (Cohn et al., 2022; O'Donnell, 2017; Preti et al., 2022). Additionally, nature based solutions can include techniques specific to urban environments, however this was not covered in this review (Su et al., 2024; Wang et al., 2024). While the adoption of NbS has accelerated over the past decades, with several projects situated on fetch-limited coastlines in temperate regions, limited guidance on feature suitability is one barrier to effective and widespread implementation (Bridges et al., 2021). Current guidance often recommends design choices based on qualitative metrics with limited quantitative decision-making tools available (Morris et al., 2020, 2019; Schoonees et al., 2019). With over 20 years of NbS research and implementation, quantitative recommendations for wave height dissipation capacity can be drawn through a systematic review of NbS features.

NbS can be categorized into soft, hybrid, and eco-engineered hard features (Moosavi, 2017; Morris et al., 2020; Schoonees et al., 2019). Soft features solely rely on habitat conservation or restoration and include submerged aquatic vegetation (SAV) beds or salt marshes. Soft NbS can have tremendous coastal protection capacity; however, coastal protection benefits largely depend on the surface area of the habitat, creating limitations of application (Narayan et al., 2017). Hybrid features use a combination of

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built structures and habitat restoration, such as a rubble mound sill or a constructed oyster reef (COR) seaward of salt marsh vegetation. Hybrid NbS can be applied in a wider range of environmental conditions compared to soft NbS; such as a more energetic wave climate caused by boat wakes, changing conditions brought on through climate change, stricter space constraints, or sediment supply issues (Palinkas et al., 2022). Hard methods aim to ecologically enhance a more traditional engineering structure (*e.g.,* through the addition of microhabitats), although ecologically enhanced traditional infrastructure is often categorized separately from soft and hybrid features (*i.e.,* hard features are not considered living shorelines) (Bilkovic et al., 2016; Strain et al., 2018).

NbS features have been employed worldwide (Morris et al., 2024; University of Oxford, 2024; U.S Army Corps of Engineers (USACE), 2024). However, projects are rarely monitored for engineering effectiveness, and when they are, the methods and reporting are inconsistent. This deficiency of robust monitoring data creates a lack of understanding of NbS performance in different wave climates and conditions, preventing consistent and effective NbS implementation. There is a recognized need to understand when to use different NbS features (Morris et al., 2020). Multiple attempts at categorizing site suitability for different features exist; however, most of these methods are qualitative and typically classify solely between soft or hybrid, not the specific NbS feature (Miller *et al.*, 2015; Woods Hole Group, 2017; Harte Research Institute, 2020; Morris, Boxshall and Swearer, 2020; Nelson, 2022; Bredes *et al.*, 2023; Young *et al.*, 2023; Virginia Institute of Marine Science (VIMS), National Oceanic and Atmospheric Administration (NOAA) and Troy University, 2024). In most qualitative guidance, wave energy is positively correlated with hardness (amount of rock or concrete) of a solution; the higher the wave energy, the harder the feature recommended (*e.g.*, taller and broader rock sills in higher energy environments). However, this recommendation is often not quantitively verified, reducing the robustness of resulting designs.

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Wave dissipation is often quantitatively assessed using wave height as a representation of wave energy. Wave heights are typically measured with pressure or capacitance gauges on the leeward (transmitted) and seaward (incident) sides of a feature within the study area. In engineering studies, the ratio of the transmitted, H_t, to incident, H_i, wave height is typically used to quantify the effectiveness in reducing wave height, and is called the transmission coefficient, K_t (Jefferys, 1944):

$$K_t = \frac{H_t}{H_i} \tag{1}$$

Smaller values of K_t reflect greater reduction in wave height; higher values of K_t indicate less dissipation, with $K_t > 1$ indicating an increase of wave heights. Wave height dissipation by a structure is a function of the geometry and material characteristics of that structure. Freeboard, F, structure crest width, B, still water depth, d, structure crest height above the bottom, h_c, and the incident wave length, L_i, are identified controlling parameters (Goda et al., 1967):

$$K_t = f\left(\frac{F}{H_i}, \frac{B}{d}, \frac{h_c}{d}, \frac{d}{L_i}, \frac{H_i}{d}\right) \tag{2}$$

Many equations have been proposed to assess the ability of submerged and partially submerged breakwaters to dissipate waves, although few of these equations are specific to NbS designs (Bredes et al., 2022). These equations typically rely on the same parameters identified by Goda et al. (1967) (Ahrens, 1987; Buccino and Calabrese, 2007; d'Angremond et al., 1996; Friebel and Harris, 2003; Seabrook and Hall, 1998; Van Der Meer et al., 2005).

Understanding the wave height dissipation capability of NbS is important to further understand the performance of these projects with respect to shore protection and coastal flood hazard mitigation. Reducing erosion from both natural and anthropogenic systems is often a project goal achieved through wave dissipation. The amount of wave dissipation required to reduce erosion will be dependent on project goals and local site conditions. Numerous studies of both soft and hybrid NbS, including many

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found in this review, report minimal wave height dissipation, which may be considered as a metric with which to assess reduction of wave energy or other performance requirements. Conversely, there is a risk of “overpromising” performance based on studies with specific conditions where wave height dissipation was high, for example from a few observations of wave height dissipation by reefs on open coasts (Christianen et al., 2013; Morris et al., 2021; Wang et al., 2021). These inconsistences result in a lack of quantitative guidance which consequently reduces the ability to evaluate of NbS project outcomes. Others have identified these gaps and lack of guidance, with the majority of criticism focused on the difficulty of achieving both ecological and engineering goals and the lack of quantified engineering guidelines for NbS (Firth et al., 2020; Morris et al., 2019; Ostrow et al., 2022; Strain et al., 2019, 2018).

With a focus on the parameters in formula (2), a systematic review of current peer-reviewed scientific manuscripts, academic theses, and reports from government organizations was completed on the breadth of soft through hybrid NbS features on fetch-limited coastlines in temperate regions to gain a greater understanding of the wave height dissipation capacity of these features in different wave climates and under different site constraints. The data collated in this review provide an opportunity to quantitatively understand trends in wave height dissipation through different soft and hybrid NbS depending on submergence, width, transmission coefficient, and incident wave height. Through the collection of this data, this study aims to (1) use the data extracted from the literature to create a quantitative understanding of wave height dissipation by a variety of NbS, and (2) create guidance for monitoring based on the available data to ensure high quality quantitative guidance can be created in the future.

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Methods

Literature Search and Data Extraction

This systematic review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method to synthesize data from field measurements of wave height reduction in coastal

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habitats. A literature search was performed using Web of Science, SCOPUS, and Google Scholar databases through July 2023 for studies that describe measurements of wave height reduction in coastal habitats. Search strings used the format: <habitat type> + <wave reduction type>, where <habitat type> is either “coir log”, “breakwater”, “sill”, “reef ball”, “oyster castle”, “COR”, “marsh”, “wetland”, oyster reef”, “seagrass” or “kelp,” and <wave reduction type> is (“wave height” AND “reduction” OR ”dissipation” OR “attenuation” OR ”spending” OR ”mitigation”). The search for “marsh”, “wetland”, “oyster reef”, “seagrass” or “kelp” was conducted for post-2016 publications only. For pre-2016 data, the database from Narayan et al. (2016) was used, which was compiled using the same literature search method. The search for “coir log”, “breakwater”, “sill”, “reef ball”, “oyster castle”, “COR” includes pre-2016 and post-2016 search results.

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To be included in the database, papers had to be English-language and primary literature (no conceptual papers, meta-analyses, *etc*.). Peer reviewed literature, dissertations, theses, and technical government reports were included. Studies were excluded if reported data were collected in modelling or laboratory studies, and if studies were completed in non-temperate climates, as this study focused on temperate systems only. Temperate features assessed included salt marsh, seagrass, kelp, COR, breakwaters, sills, biodegradable breakwaters, and coir logs. The inclusion criteria are studies that (1) where data is not collected during storm conditions, (2) not collected along open coasts rather than fetch-limited coastlines, and (3) reported the necessary parameters. The necessary parameters wereincident and transmitted wave height or transmission coefficient and incident wave height across an included NbS feature, water depth, freeboard, or percent time submerged throughout the tidal cycle of the NbS feature and total cross-shore width of the NbS feature. Wave period was rarely reported; therefore, exclusion criteria were selected for conditions where similar wave periods and incident wave climate could be assumed (*i.e.*, estuarine environments). Waves in closed bodies of water will generally be fetch limited, creating upper bounds on period and height (Karimpour et al., 2017). The initial search across all

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11 features yielded 13,451 studies. Duplicate papers and irrelevant papers were removed, leaving 6,876 papers. Of these, titles and abstracts were screened for eligibility in detail using exclusion criteria. At this stage, the number of studies was reduced to 479 and full-text studies were reviewed for inclusion criteria. Of those, 50 studies met all three inclusion criteria needed for this analysis (Figure 1).

For each of the 102 study sites observed within the 50 studies, 6 parameters were extracted: transmission coefficient, incident wave height, submergence, shore perpendicular width, feature class (soft or hybrid), and feature category. Soft feature categories include salt marsh, seagrass, and kelp. Mangroves and coral were excluded due to tropical climates and habitats having large differences from the other soft features studied. Hybrid feature categories included COR, breakwaters, sills, biodegradable breakwaters, and coir logs. Of the studies assessed, 26 and 24 were hybrid and soft NbS, respectively. The Matlab 2021 function Grabit (Doke, 2024) was used to accurately extract data from figures, and averages were calculated for all numeric parameters when not reported directly. Of the selected metrics, transmission coefficient, incident wave height, and shore perpendicular width were collected numerically; due to inconsistent reporting, submergence was collected categorically. Some studies reported percentage submerged throughout the tidal cycle, while others reported freeboard or position within the tidal cycle. Therefore, data on submergence was collected as percentage submerged in three categories by time submerged: not submerged (<25%), partially submerged (25-75%), and fully submerged (>75%). Average H_i in each feature category was used as an estimate of incident wave climate.

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For studies reporting multiple observations over the same site (*e.g.* a summer observation and winter observation), observations were averaged to collapse data into one observation per site to avoid placing greater weight on studies with multiple same-site observations. For the cases in which multiple observations over the same site did not follow the same field methods (*e.g.,* different widths between gauges), observations were not averaged, and instead the observation representing a greater length of

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time was chosen. For multiple observations of the same length of time but with different field methods, one single observation was selected at random. Thess collapsed data were only used to evaluate study effects, not for the entire study.

Statistical and Classification Analysis

All 6 collected parameters(transmission coefficient, incident wave height, submergence, shore perpendicular width, feature class (soft or hybrid), and feature category) were used as predictors of what? Transmission coefficient?. Akaike information criterion (AIC) (Akaike, 1973) is a parameter used to select the best fit model to test study effects (Feng, 2021). The importance of each parameter was tested using AIC, however due to the limited parameter space, linear models were only used to evaluate study effects and not additional trends in the data. To test for study effects, an ordinary linear regression model was created using a reduced number of studies with [insert parameter] as the response and [insert parameters] as predictor variables. When a study was added at random, the AIC did not change, indicating that study effects are negligible. Due to the limited parameter space available, further analysis was conducted with other methods as described in the following paragraph.

Mean and standard deviations were calculated for shore-perpendicular X, K_t, H_i, and submergence from the data collected for every feature reviewed. Additionally, a decay coefficient was created by normalizing percent dissipation by unit width, α. A Principal Components Analysis (PCA) was conducted to understand the importance of the collected parameters in predicting NbS class (soft or hybrid). This is represented in an importance factor; the higher the importance factor, the more influence it has on the other components. The PCA was conducted using built in MATLAB functions. A classification analysis was also used to identify and assign categories within a given dataset (Géron, 2017). Support vector machine, or SVM, is a type of classification machine learning algorithm approach which focuses on finding the optimal separation boundary between datapoints that have different classifications and is typically used to classify small complex datasets (Géron, 2017). SVM is modified to fit nonlinear datasets using

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different kernels. A radial basis function (RBF) kernel is typically used for fitting datasets with nonlinear boundaries between classes that fit a Gaussian distribution, such as the one collected in this analysis (Géron, 2017). The rate at which the kernel decays is governed by gamma (G), where a higher gamma indicates more rapid decay. The other parameter within SVM is cost (C). Cost is essentially the penalty associated with making an error. Typically, the higher the cost, the less likely a misclassification, although this may cause overfitting. When determining the optimal values for gamma and cost, a standard random 80-20 train-test data split was used (Géron, 2017). The e1071 package in R was used to run SVM analysis (Meyer et al., 2023). This package includes a function called "tune.svm" for optimizing cost and gamma parameters. This function was used to evaluate the most accurate combinations of gamma and cost parameters for the model. Three combinations (G=0.1 C=100, G=0.1 C=1000, G=0.2 C=100) were found to be the best fits, all with a train dataset accuracy of 0.952 and a test dataset accuracy of 0.905. After visually reviewing each combination, G=0.2 C=100 was chosen as it was the least overfit. Soft margins were used to indicate the range of uncertainty in the category boundary.

Results

Trends in Soft and Hybrid NbS

Studies that met the criteria for evaluating wave dissipation were found in North America, Europe, Asia, and Australia, with the highest concentration of studies in North America (63%), and the majority of hybrid studies in the United States. Globally documented coastal NbS projects by two large networks, Engineering With Nature and Oxford, showed 76% of documented projects in North America, this bias is likely amplified by reporting, research funding availability, and research interest (University of Oxford, 2024; U.S Army Corps of Engineers (USACE), 2024).

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Averages and standard deviations collected for each of the parameters (*e.g.,* H_i, K_t, X, and submergence) were found to be very different across different types of ecosystems, with wave dissipation influenced by frequency of submergence (Table 1). As previously mentioned, wave period was underreported within

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studies, so it was not included in the collected data. Therefore, average H_i in each feature category was used as an estimate of incident wave climate. H_i was equivalent in magnitude between most categories (13cm, 35.5 cm, 18.1 cm, 12.3cm, 22.3cm, 27.7cm for biodegradable breakwaters, breakwaters, coir logs, CORs, salt marsh, and seagrass, respectively). H_i for rock sills (3.5cm) and kelp (87cm) had the largest difference from the other features; this is likely due to the small sample size of rock sill data (4 observations) and the deeper water depth of kelp habitat. The features with the highest transmission coefficients (*i.e.*, least effective at wave dissipation) were associated with more frequent submergence during the tidal cycle. In general, hybrid features outperformed soft features, with the exception of salt marshes, which outperformed all other features with an average K_t of 0.3 (Figure 2).

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Submergence varied more greatly within each feature for hybrid features than soft features. Of the hybrid NbS, 33 were submergent, 20 were partially submergent, and 12 were emergent, with the most emergent hybrid NbS being breakwaters. Of the soft NbS, every observation of kelp and seagrass were submergent and every observation of salt marshes were partially submerged. Shore perpendicular width, *X*, is a large differentiator between soft and hybrid features, with X of soft features one or two magnitudes larger (97.4-417.6 m) than X (0.5-8.3 m) of hybrid features. The natural width of salt marshes, SAV beds, and kelp are often on the order of hundreds of meters or more, consistent with the average width of studies reviewed (97.4m, 417.6m, and 250m on average for salt marsh, SAV, and kelp, respectively), while breakwaters and sills in the studies reviewed were often several orders of magnitude smaller in width, and rarely included the width of any marsh or vegetation behind the structures (2.0m, 0.5m, 8.3m, 0.6m, and 3.6m on average for rock sills, biodegradable breakwaters, breakwaters, coir logs, and COR, respectively). It should also be noted that widths of soft features had larger standard deviations than widths of hybrid features (Table 1).

Dissipation and Width Relationship

Width of feature was significantly more important than K_t, H_i, and submergence in predicting the feature category (soft or hybrid), with an importance factor of 0.013. The next closest parameter, H_i, had an importance factor of 0.002, as calculated with a PCA.

Using a decay coefficient, α, the wave dissipation capacity of different features over variable widths was explored (Figure 3). α was found to be significantly different between soft and hybrid NbS, with soft features never dissipating more than 10% of wave height per meter. Hybrid features at times dissipated more than 90% of wave height per meter. Differences in α are also correlated with submergence. Submerged hybrid structures outperformed submerged soft solutions, with an average α for hybrid and soft solutions of 0.28 m^{-1} and 0.02 m^{-1}, respectively. Submerged hybrid structures consistently dissipated wave heights less than partially submerged and non-submerged hybrid structures, with an average α for submerged, partially submerged, and non-submerged hybrid features of 0.08 m^{-1}, 0.47 m^{-1}, and 0.51 m^{-1}, respectively. While hybrid structures are rarely analyzed using a decay coefficient, this result is consistent with existing analytical models for wave height dissipation through vegetation (Mendez and Losada, 2004).

Non-submerged hybrid structures achieved the highest wave height dissipation per meter; however, they were typically deployed within the same incident wave heights (on the order of 10 cm), making this portion of the dataset too small and uniform to draw conclusions. Incident significant wave height for soft structures showed two distinct clusters for submerged and partially submerged soft NbS due to habitat differences for those features; salt marsh has lower H_i and kelp and SAV have higher H_i due to level of submergence (Table 1).

Discussion

Effect of NbS Width and Submergence

Results of this systematic review and analysis quantitatively support what many qualitative analyses and practitioners assert; hybrid NbS provide more efficient wave height dissipation than soft features for smaller available shore perpendicular widths, while soft NbS are better suited to larger available widths assuming other ecological and biological parameters are suitable for these solutions (Morris et al., 2020).

These findings indicate that soft NbS use more space than hybrid NbS to provide the same wave height dissipation, and that increased submergence decreases wave height dissipation, trends that are expected based on analytical and theoretical understanding of wave propagation through vegetation. Averages and standard deviations calculated in this review, as well as the normalized wave height dissipation per meter values, showed consistent wave height dissipation trends with the majority of literature on hybrid and soft features (Bilkovic et al., 2016; Harte Research Institute, 2020; Moosavi, 2017; Nelson, 2022; O'Donnell, 2017; Safak et al., 2020; Woods Hole Group, 2017; Young et al., 2023). Despite this theoretical knowledge, there still exists a lack of practical guidance for new NbS projects on the widths necessary to achieve specified levels of wave dissipation. These results validate many current practices and assumptions; however, robust design guidance is still needed. Thus, below are suggestions on conditions for the application of soft or hybrid NbS, as well as monitoring metrics for future data collection to inform construction and monitoring of NbS.

Choosing Appropriate NbS Widths

The PCA analysis of the parameters extracted from this review suggested the importance of width in wave dissipation capacity. This relationship suggests that hybrid features may be more appropriate in situations where available space is limited. A SVM analysis was deployed to further explore that relationship and create a tool for understanding, given shore perpendicular width, *X*, and desired wave

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height dissipation outcome, whether a soft or hybrid NbS is the best choice. While this SVM model is multivariate and incorporates all collected parameters, it is plotted as K_t vs X (m) for ease of interpretation given the importance of shore perpendicular width (Figure 4). The SVM analysis suggests that to meet wave dissipation goals below a K_t of 0.6, hybrid NbS should be used when X is below ~65 m. When only minimal wave dissipation is required (K_t > 0.8) or when more shore perpendicular space is available (X > 400m) the use of soft NbS is recommended when ecologically appropriate, as indicated by the "soft" margins depicted in Figure 4 with dashed lines. Cases between these margins are within the "Best Judgement Zone" where practitioners are encouraged to use their expertise to determine the best combination/selection of soft and hybrid features to achieve desired wave dissipation goals. These margins are determined through the soft margins along the decision boundary within the SVM model.

At NbS sites where shore-perpendicular space is limited, this analysis concluded that hybrid structures may be more appropriate than soft NbS to achieve wave dissipation goals. The lowest NbS width in this review that achieved non-negligible wave dissipation for waves above 10 cm was 0.5m, with a biodegradable breakwater (Table 2). At a point where space is very limited, NbS may not be suitable and traditional hard infrastructure could be more appropriate; however, the data collected in this review did not include traditional infrastructure, making this threshold difficult to quantify. In the cases where soft or hybrid NbS cannot be used, ecological enhancement of the system may be incorporated as part of the structure given the limited space available for restoration outside the structure. Features to ecologically enhance hybrid and grey infrastructure may include CORs, stone structures using a wide variety of rock sizes and textures to create a variety of niches, the use of novel materials, and other creative ecological features (Strain et al., 2018).

The "Best Judgement Zone" (Figure 4) also provides unique opportunities for practitioner creativity. Within this zone, shore perpendicular width is large enough to incorporate some soft features, while likely still requiring use of hard structures. In widths above the "Best Judgement Zone", soft features should be adequate to meet wave dissipation goals. This does not indicate that those features will not experience erosive forces, but behind those features, wave dissipation goals should be met. This characterization model quantitatively agrees with the conceptual model posited in Morris et al. (2020) and supports previous theoretical studies that posit the availability of space as a key factor in determining the suitability of soft NbS projects (Van Hespen et al., 2023).

Best Practice Recommendations For Monitoring

Based on insights from this review regarding current practice in monitoring wave dissipation across soft and hybrid NbS, recommendations are provided for 1.) what to monitor – i.e., key metrics to monitor to evaluate wave dissipation and 2.) how to consistently monitor these metrics (Table 2). These metrics are categorized as either critical, important or useful to be able to effectively evaluate the wave dissipation and collect data on implemented NbS projects to create a deeper understanding of how different site conditions effect project outcomes.

1.) Metrics to monitor to evaluate wave dissipation: This review revealed that important metrics directly related to wave dissipation, such as wave period, freeboard, bathymetry, turbidity, and colonized organism density, were rarely reported. Owing to the lack of studies meeting the minimal inclusion criteria selected for this analysis, small sample size and lack of detailed data reduced the ability to conduct detailed statistical analyses. Critically important metrics for such analyses include significant wave height and wave period. Information on wave period helps create an understanding of how parameters such as steepness or breaking, change when interacting with a structure or feature. Wave steepness is related to erosion, and is important to understand the impact of structures (Kana, 1977; King and Williams, 1949; Lemke and Miller, 2020; Masselink et al., 2010). While difficult and expensive to collect, bathymetry is also important. When bathymetry cannot be gathered offshore, a manual onshore/tidal zone survey at low tide around, offshore, and onshore of structures can be conducted, offering a cost-effective alternative. These data are important because depth controls how waves transform though a site. Wave breaking can cause wave height dissipation, so at some sites, bathymetry may be causing breaking and driving K_t values. Conversely, if bathymetry is causing wave shoaling, wave height dissipation and shoaling may have competing effects. Bathymetry effects are especially important in areas where the targeted NbS is submerged for the majority of the tidal cycle or in areas with large tidal cycles where the effects of bathymetry on wave dissipation may change dramatically throughout the cycle.

When using natural features for wave dissipation, it is critical that engineering and ecological approaches for monitoring are integrated well (Van Wesenbeeck et al., 2016). Due to the natural component of NbS, metrics not directly related to wave dissipation, such as turbidity and organism density, provide information important to the ecology of features. Turbidity measurements can serve as proxy for sediment supply in the system, which can contextualize the wave dissipation data to erosive or accretional potential at the study site and is important for understanding the ability of a marsh to maintain pace with sea level rise (FitzGerald and Hughes, 2019; Thorne et al., 2021). In lieu of turbidity monitoring, a sediment budget can also be performed. Organism density, whether reef building shellfish or flora such as SAV or marsh grass helps contextualize the data to understand frictional effects for wave dissipation as well (Chen et al., 2018).

2.) Consistent monitoring of metrics: In addition to the lack of reported data, this review also revealed heterogeneity in the way in which metrics are reported. This heterogeneous data collection led to a limited parameter space and reduced suitable studies (0.4% of studies that matched search criteria and 10.6% of studies fully reviewed) for this analysis. For example, some studies report significant wave height, while others report maximum or average wave heights, locations of gauges are not standardized in spacing or distances from structures when they exist (Everett et al., 2019; Wiberg et al., 2019).

Inconsistencies add artificial complexity to comparing already heterogeneous sites and features, making it nearly impossible to create robust engineering guidance on specific feature application and suitability.

As a guide for future NbS projects interested in evaluating wave dissipation performance, a concise list of engineering monitoring metrics has been developed based on the needs of common engineering and ecological wave dissipation equations (Table 2), and categorized as either critical, important or useful for evaluation of wave dissipation by NbS features. Collection of these data are important not just for monitoring NbS performance but also for modeling future performance of NbS projects under different ecological, water level or wave height scenarios. Recommended metrics include: incident significant wave height, transmitted significant wave height, wave period, feature dimensions, tide/ water level, bathymetry/ elevations, turbidity, and organism density, when applicable. When budget and time are limited, priority should be taken to the most critical metrics: incident significant wave height, transmitted significant wave height, wave period, feature dimensions, tide/ water level; then to important metrics: bathymetry/ elevations; and finally, to useful metrics: turbidity, and organism density. These metrics allow engineers to further study and understand the conditions at which NbS are dissipating waves through many of the principles of wave dissipation (Goda et al., 1967). As studies become more standardized, future work will focus on synthesizing ecological and engineering metrics for better project planning and adaptive management.

Conclusions

This extensive PRSIMA systematic review of the wave dissipation of soft and hybrid NbS features in temperate regions produced several important results and conclusions:

- Wave height dissipation varied between different features and their associated parameters; NbS that were submerged during the majority of the tidal cycle were the least dissipative, and hybrid NbS had greater dissipation than soft NbS overall. Salt marsh was the most dissipative feature in this study. The largest differentiator between soft and hybrid NbS was shore perpendicular width, with the largest widths associated with salt marshes.

- When wave height dissipation is normalized by cross-shore width of the feature, creating a decay coefficient, the best performing hybrid NbS dissipated 90% of wave heights per meter, while soft NbS only attenuated 10% of wave heights per meter. Submerged hybrid NbS dissipated less energy per meter than emergent hybrid NbS.
- A classification model using SVM was created to provide guidance for practitioners demonstrating that hybrid NbS should be deployed when shore perpendicular width is limited and wave dissipation needs are high, and soft NbS can be relied on when width is large and available, ecological conditions are appropriate, and/or wave dissipation needs are minimal. However, there is no clear threshold between soft and hybrid NbS usage, therefore a "Best Judgement Zone" has been developed for cases when the determination between soft or hybrid is less clear (Figure 4).
- A small body of existing literature (50/13,451 or 0.4%) that appeared in search results met the inclusion criteria necessary for analyzing wave height dissipation. The size of this dataset relative to the body of literature is due to a lack of clear monitoring metrics and procedures. Therefore, critical, important, and useful monitoring metrics and the associated methods are proposed (Table 2).

The use of NbS is increasing, but until standardized data is collected to better inform technical guidance, the uncertainty in the level of risk reduction will remain a barrier to broader implementation. Additionally, increasing understanding of the interdisciplinary metrics needed to evaluate engineering and ecological goals present in NbS projects will help to ensure both priorities are optimized in future projects.

Figures

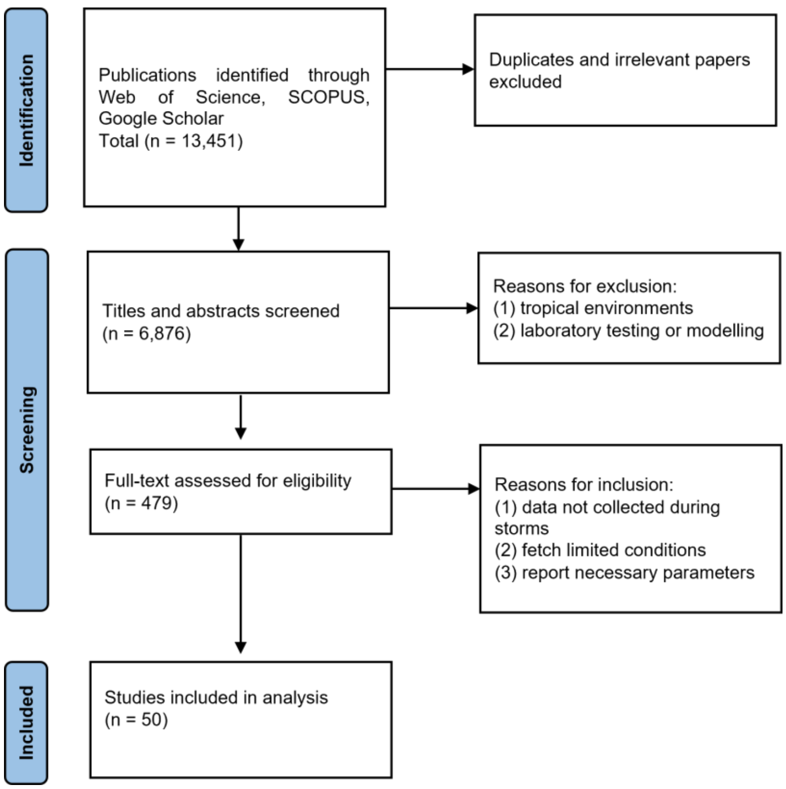

Figure 1. This systematic review was completed using PRISMA. As publications were screened and excluded or included based on criteria, the number of identified publications decreased from 13,451 to 6,876 to 470, to a final 50 studies for use in this analysis.

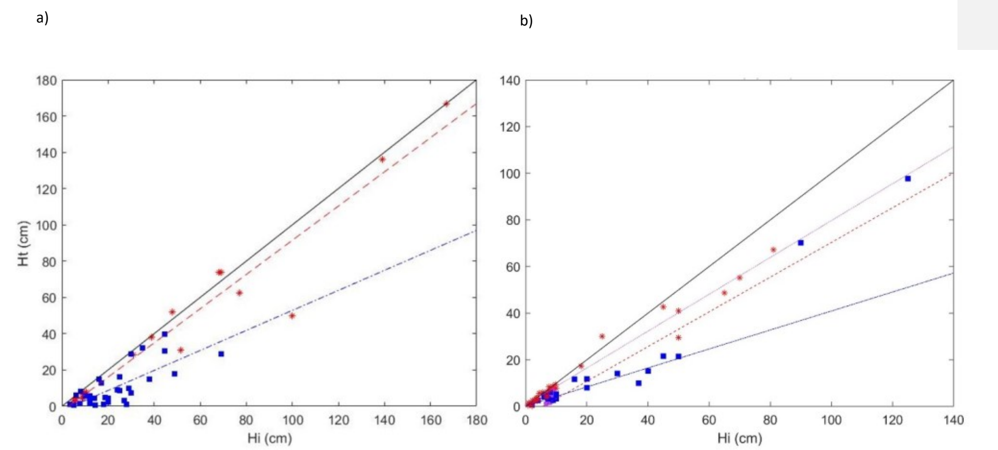

Figure 2. Transmitted wave height (cm) vs. incident wave height (cm) for soft (a) and hybrid (b) features, demonstrating the effect of submergence for both soft and hybrid features. Both soft and hybrid features that are submerged more than 75% (indicated by the red stars) of the tidal cycle have reduced performance (closer to 1:1 line) than partially (blue squares) or non-submerged (purple circles) features.

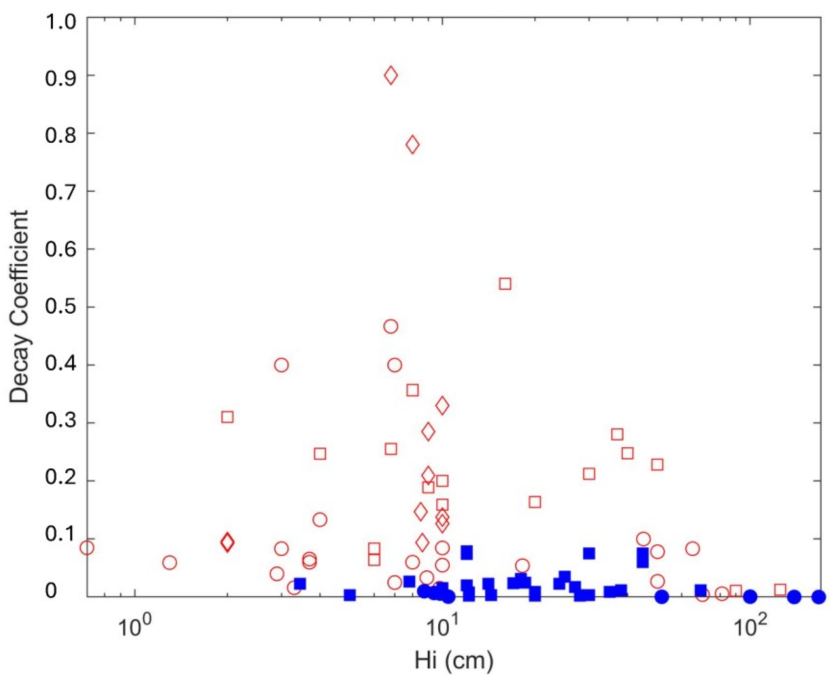

Figure 3. Decay coefficient (percent dissipation by shore perpendicular width (m)) plotted against incident wave height. Red empty symbols and blue filled-in symbols represent hybrid features and soft features, respectively. Diamond, square, and circle symbols represent submerged, partially submerged, and non-submerged conditions, respectively.

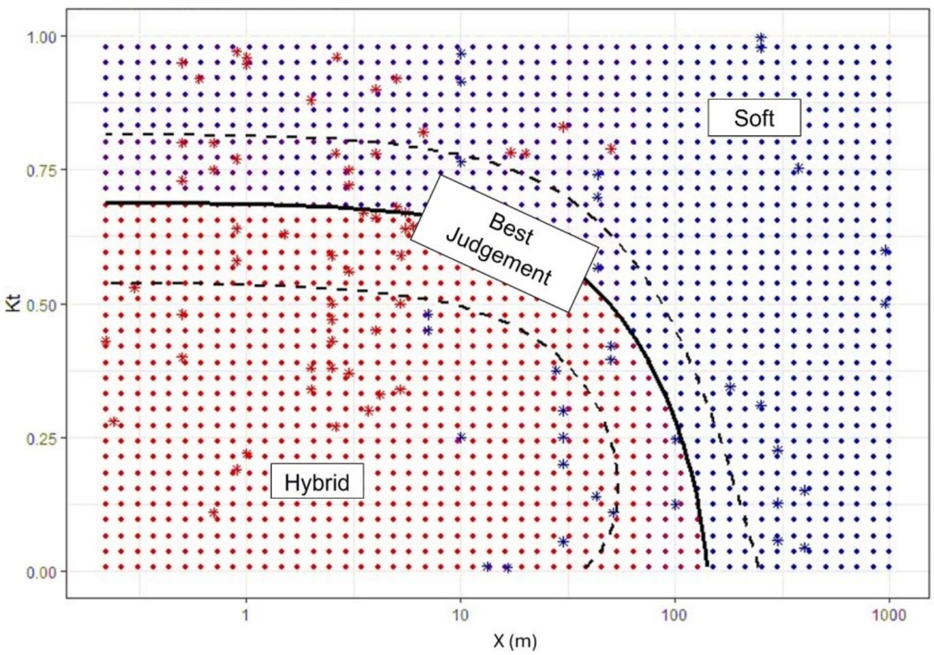

Figure 4. Classification model created using SVM, the blue and red asterisks represent soft and hybrid data points, respectively, from the dataset. In this model, the blue region labeled soft and the red region labeled hybrid represent when each of the respective features are to be implemented according to the model. The region between the dashed lines represents the uncertainty in which feature is the ideal choice, this region is known as the "Best Judgement Zone." It should be noted that this does not mean that erosion or degradation of the selected solution will not happen; these zones simply reflect the requirement to achieve specific wave dissipation goals behind the NbS. It should also be noted that there is a point where space is so limited that traditional hard infrastructure is more appropriate, however the data collected in this review did not include traditional infrastructure, making such a cut-off difficult to quantify.

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Tables

Table 1. Averages and standard deviations for all the numeric parameters (width (X) in meters, transmission coefficient (K_t), and incident wave height (H_i) in centimeters) and occurrences of submergence condition; divided into Yes (submerged over 75% of the time), Partial (submerged 25-75% of the time), and No (submerged <25% of the time).

Feature		X (m)		K_t		H_i (cm)		Submergence		
	# of Data Points	Avg	Std	Avg	Std	Avg	Std	Yes (>75%)	Partial (25-75%)	No (<25%)
Rock Sill	4	2.9	1.6	0.6	0.2	3.5	1.9	0	3	1
Biodegradable Breakwater	3	0.5	0.2	0.6	0.2	13	6.1	0	2	1
Breakwater	14	8.3	13.3	0.5	0.2	35.5	35.1	1	8	5
Coir log	7	0.6	0.3	0.5	0.3	18.1	18.4	2	3	2
COR	37	3.6	4.8	0.8	0.3	12.3	18.5	30	4	3
Kelp	6	250	N/A	0.9	0.1	87	54.7	6	0	0
Saltmarsh	29	97.4	126.3	0.3	0.3	22.3	14.3	0	29	0
Seagrass	8	417.6	376.8	0.7	0.2	27.7	31.6	8	0	0

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Table 2. Suggested metrics for evaluating wave dissipation of nature-based solutions.

Importance	Metric	Equipment	Method	Units	Frequency	Use case
Critical	Incident significant wave height, H_{si}	pressure gauge, capacitance gauge	gauges should be placed offshore of the structure by 1-2m/ feature (before the wave climate is being affected by the NbS), gauges should sample in high frequency (>4 Hz)	m (ft)	Preconstruction and post construction with sufficient time to characterize effects of NbS establishment	This is combined with H_{st} to calculate K_t
	Transmitted significant wave height, H_{st}	pressure gauge, capacitance gauge	gauges should be placed on the inshore side of a hybrid structure by 1-2m, and throughout the soft portion of the NbS every 10 to 20 meters, gauges should sample in high frequency (>4 Hz)	m (ft)	Preconstruction and post construction with sufficient time to characterize effects of NbS establishment	This is combined with H_{si} to calculate K_t
	Period, T	pressure gauge, capacitance gauge	gauges should be placed offshore of the structure/feature (before the wave climate is being affected by the NbS) by 1-2m and on the inshore side of a hybrid structure by 1-2m, and throughout the soft portion of	s	Preconstruction and post construction with sufficient time to characterize effects of NbS establishment	Period is used to understand wave steepness and erosion/ deposition

			the NbS with consistent spacing, gauges should sample in high frequency (>4 Hz)			
	Feature Dimensions	RTK GNSS, drone, tape measure or other measuring device, google earth (if feature is visible)	all measurements should be taken, shore perpendicular width, shore parallel length, height of solution, etc.	m (ft)	Post construction with sufficient time to characterize effects of NbS establishment	Metrics such as freeboard can be calculated, additional calculations can be completed using other dimensions
	Tide / Water level	pressure gauge and RTK GNSS	can calculate from a pressure gauge that is at a known elevation from RTK GNSS	m (ft)	Pre or post construction	Freeboard is calculated using elevation of structure and water level
Important	Bathymetry/ Elevations	RTK GNSS	measure elevation of structures, and measure tidal bathymetry by surveying during low-tide. Boat and jet ski can be used to get further offshore bathymetry	m (ft)	Post construction with sufficient time to characterize effects of NbS establishment	Freeboard is calculated using elevation of structure and water level
Useful	Turbidity	turbidimeter, spectrophotometer, Secchi disk	measure turbidity offshore of structure using the standard procedure for the selected device, measure under different wind and wave	NTU	Pre construction, ideally during different seasons and wave/wind conditions	Turbidity can be used a proxy for suspended sediment concentration using equations found in (Jastram et al., 2010)

			conditions if possible			
	Biologic Growth (when applicable)	quadrats (0.25-meter), calipers, drone, satellite imagery	measure biologic growth and physical dimensions on the feature (i.e. for a COR measure reef building organisms, for a marsh measure density of flora) with standard measurement features for that organism	counts, cm (in)	Pre construction and post construction with sufficient time to characterize effects of NbS establishment	Biologic growth on a feature or resulting in the creation of a feature has implications on wave transmission

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