Evaluation of the costs and benefits of natural and grey infrastructures for the protection of the Lake Erie shoreline

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ABSTRACT
Approximately 75% of Ohio's Lake Erie shoreline is protected by grey infrastructures (such as seawalls and breakwaters), which can alter natural coastal processes and disrupt coastal ecosystems. Recently, natural infrastructures providing a more natural/sustainable shoreline environment have attracted interest in the coastal engineering community. However, a lack of research-based evidence demonstrating the long-term benefits of using natural infrastructures has limited their use and promotion. This study evaluates costs/benefits for adopting natural versus grey infrastructures to protect Lake Erie shorelines. A cost-benefit analysis comparing three natural infrastructures (vegetated sand dunes, beach nourishment, and living shorelines) and five grey infrastructures (seawalls, breakwaters, groins, bulkheads and revetments) provides a quantitative understanding of the long-term costs/benefits associated with each approach. A survey of local professionals shows the advantages of natural infrastructures in terms of cost savings and environmental/ecological protection.

RÉSUMÉ
Près de 75% du littoral du lac Érié en l'Ohio est protégé par des infrastructures artificielles (telles que digues et môles), qui peut altérer les processus côtiers naturels et agiter les écosystèmes côtiers. L'infrastructures naturelles offrant un environnement côtier durable aient récemment attiré l'attention des ingénieurs du domaine côtier, mais le manque de données factuelles démontrant les avantages à long terme sont limitant leur utilisation et promotion. Cette étude examine les coûts et les avantages de l'adoption d'infrastructures naturelles ou artificielles pour la protection des rives. Une analyse coûts-avantages a été utilisée pour comparer trois infrastructures naturelles (dunes de sable végétalisées, restauration de plages à l'aide de sable, et rivages vivants) et cinq infrastructures artificielles (digues, môles, murets, cloisons et revêtements) afin de fournir une compréhension quantitative des coûts et des avantages à long terme de l'utilisation de ces techniques. Une enquête auprès de professionnels locaux montre les avantages de l'utilisation des infrastructures naturelles en termes de réduction des coûts et de protection de l'environnement.

1 INTRODUCTION

Shoreline erosion affects the entire 500 km of shoreline on the Ohio side of Lake Erie and results in damage and economic loss to both public and private lands, utilities, and infrastructure (Farm and Dairy 2011). Shoreline protection infrastructures can be categorized into two broad types: grey infrastructures and natural infrastructures.

Grey infrastructures — which involve construction of a solid structure using steel, concrete, rock or wood — are more familiar to professionals and the general public. Common grey infrastructures include structures such as jetties (piers or structures built perpendicular to the shoreline to protect a harbor or the mouth of a channel), groins (rigid structures built perpendicular to the shoreline to interrupt the flow of water and restrict the movement of sediment), breakwaters (barriers constructed parallel to the shoreline to protect the coastline from wave-induced erosion by blocking or dissipating wave energy), seawalls (vertical or nearly vertical walls built at the edge of the sea to prevent reflect waves and wave energy away from the coast to prevent erosion), revetments (sloped retaining walls that are placed parallel to the shoreline to dissipate low-energy waves), and bulkheads (a vertical wall built parallel to the shoreline in a bay, port, or harbor to prevent upland fill or concrete from eroding into the water in areas with low-energy waves). However, grey infrastructures may not stop flooding or storm surges (van Rijn 2013, Coastal Systems International [undated]) can be prone to scouring or increase the rate of erosion of a shoreline (Kraus and McDougal 1996) and are known to have irreversible adverse consequences for nearshore environments and ecosystems. The use of materials that are impervious and/or artificial can induce a rise in manufacturing, transport, and construction related carbon emissions and can disrupt ecological cycles such as those involving the movement of larval fish. Once a grey infrastructure has been installed, it can be difficult to restore the shoreline to nature-based condition.

Natural infrastructures are approaches that mitigate erosion without the installation of a permanent artificial structure. Examples of natural infrastructures include nature-based shore-lines (where vegetation, edging, and sills are installed at the shoreline), beach nourishment (where sand is added to a beach to offset the effects of erosion), living shorelines, vegetated sand dunes (where vegetation is used to trap wind-blown sand), and shore stabilization using erosion-control mats or blankets. Natural infrastructures have many advantages: 1) coastal engineering benefits such as absorption of water during storm surges and floods, reductions in the impacts of wave energy at areas seaward of the shoreline, and the capture of sand to help rebuild eroded shorelines or maintain the current shoreline; 2) environment benefits such as filtration of excess nutrients or pollutants, formation of carbon sinks (which help to mitigate climate change), and maintenance of natural shoreline dynamics and sand movement; 3) ecological benefits such as providing or enhancing important shoreline habitat; and 4) economic benefits such as maintaining beach and intertidal areas that the public can access to wade, fish, and walk, as well as reducing costs for stabilization needed for bulkheads, rip rap, and other grey infrastructures (Cunniff and Schwartz 2015). Admittedly, natural shorelines do have their limitations: they may not be suitable for shorelines where much of the area is already hardened, and they may not provide adequate protection of shorelines in high-energy environments. In addition, a natural shoreline is more difficult to design and install than traditional approaches that employ a grey infrastructure. Moreover, the availability of information on the effectiveness of living shorelines for different types of shorelines as well as for shorelines having different energy regimes and storm conditions is limited.

The overall objective of this project was to perform a cost-benefit evaluation of natural and grey infrastructures for Lake Erie shoreline protection in Ohio. This was achieved through a two-part program: 1) a comparison of benefits and costs for three natural shoreline protection methods (vegetated sand dunes, beach nourishment and living shorelines) and five grey shoreline protection techniques (seawalls, breakwaters, groins, bulkheads and revetments) based on collected cost data and 2) a comparison of benefits and costs for various natural and grey shoreline protection techniques based on a comprehensive survey of local professionals in Ohio.

2 METHODOLOGY

The following subsections describe the approach used in the two parts of this study.

2.1 Cost Analysis Approach

In order to compare the long-term costs and benefits of various natural and grey shoreline protection approaches, a review of the literature and historical projects was conducted and a thorough online search on the state of the practice for shoreline protections from a number of agencies was performed. This search included agencies such as the Ohio Sea Grant, Wisconsin Sea Grant, Mississippi-Alabama Sea Grant, US Army Corps of Engineers, National Oceanic and Atmospheric Administration, Hudson River Estuary Research Reserve, Governors' South Atlantic Alliance, National Park Service, European Climate Adaption Platform, and various government websites related to coastal management. Based on the information compiled from these sources, four cost categories were itemized in this study for each shoreline protection approach:

1) Initial construction cost, which is considered to be the cost for a shoreline solution technique in terms of materials and labor involved in construction, is considered as a one-time cost. Information on initial construction costs was obtained from NOAA (2015), Trembanis and Pilkey (1998), City of Norfolk (2015), Hudson et al. (2015), Governors' South Atlantic Alliance (2016), Peek et al. (2016), Town of North Topsail Beach (2009), North Carolina Department of Environmental Quality (2010), Cunniff and Schwartz (2015), and County of Monterey (2018). It is noted that the initial cost data excludes costs for design, permitting (including the time waiting for a permit), and demolition. For most grey infrastructures, the design fee, time cost to receive a permit, labor fee and equipment fee will typically cost much more than those associated with the implementation of natural infrastructures. As such, the initial construction costs for grey infrastructures in the cost analysis in this study are considered to under-estimate the full costs of implementation.
2) Maintenance cost, which mainly refers to the cost associated with monitoring, inspection, re-vegetation, dredging and repair of normal wear and minor structural damage. Information on maintenance costs was obtained from the State of Massachusetts (2013), Peek et al. (2016), North Carolina Department of Environmental Quality (2010), European Climate Adaptation Platform (2015), Cunniff and Schwartz (2015), NOAA (2015), Governors' South Atlantic Alliance (2016), Reston Association (2006). In this study, most of the collected cost data for maintenance was lumped into an annual maintenance cost that covers all maintenance activities. The 25-year cost was calculated by multiplying the annual costs by 25.
3) Damage cost, which refers to the cost associated with the removal of damaged structures after a major failure due to a storm event. Information regarding damage costs was obtained from NOAA (2015), City of Norfolk (2015), Trembanis and Pilkey (1998), Hudson et al. (2015), North Carolina Department of Environmental Quality (2010), Rella and Miller (2012), City of Seattle (2015), and the Governors' South Atlantic Alliance (2016). Natural shorelines, such as vegetation and sand dunes, can be significantly damaged during a strong storm and thus, damage costs can occur with some frequency in the long-term cost analysis. Although grey shorelines can perform better during a strong storm, a portion of the structure may be subject to failure during the design life. Considering the materials, labor, equipment and permitting expenses for repairs of grey infrastructures, the damage costs for grey infrastructures can be massive. In this study, the damage cost for beach nourishment is presumed to be the same as the initial construction cost, based on a very conservative assumption that the entire beach requires re-nourishment after a major storm.

4) Environmental degradation cost, which mainly results from the depletion of resources such as water (e.g., when using impermeable structures) and soils (e.g., soil erosion in front of the structure), destruction of ecosystems, loss of habitat, extinction of wildlife, increased pollution, and increased carbon emissions. While environmental degradation is not a factor that will be obvious to the general public during the selection phase for a shoreline protection approach, it can be devastating over the course of a number of years. Costs due to environmental degradation have seldom been reported or quantified in previous studies on shoreline management, mainly due to the difficulty in quantifying negative impacts to the environment. In fact, the cost of environmental degradation is difficult to quantify. Since it is site-specific, it can involve multiple variables, and there may be a lack of quantitative data. In this study, for the sake of simplicity, the costs reported by the U.K. Environment Agency and Scottish Natural Heritage (as published in Hudson et al. 2015) are adopted as objective indices for the cost of environmental degradation.

The total cost for each shoreline solution is the sum of the cost for the four itemized categories listed above. Cost data collected from the literature, which was considered as objective evidence, was adopted in this study to provide a rational basis for calculating the long-term cost for each shoreline protection approach. The following criteria and assumptions were used in the cost analysis:

- The total cost for 25-year service for each shoreline protection approach is considered;
- All the raw cost data published in various periods are converted to US dollars in 2018;
- An inflation rate of 4% was used for projecting the published cost data in a given year to 2018;
- The unit cost per linear foot for each approach is calculated;
- The frequency of a strong storm that may cause severe damage to natural infrastructures is presumed to be five years;
- For any cost where a range of values is reported, the average value is used; and
- In the cost comparison, an underestimation of costs is used for grey infrastructures, while an overestimation is used for natural infrastructures.

2.2 Survey of Local Stakeholders

To further investigate the benefits and costs for various natural and grey shoreline protection techniques, a survey of was conducted to solicit information from local professionals in the shoreline engineering community in Ohio. Based on discussions with and additional input from our agency adviser at the Ohio Department of Natural Resources (ODNR), the research team prepared a survey form that included three natural shoreline protection approaches (vegetated dunes, beach nourishment and living shorelines) and five grey shoreline protection approaches (groins, break-waters, seawalls, bulkheads and revetments). Other potential approaches for shoreline protection (such as slope cutting) were also indicated on the survey form, and respondents were encouraged to indicate any additional approaches they may use for shoreline protection.

For each shoreline solution, respondents were asked to consider five aspects: construction cost, maintenance cost, maintenance frequency, damage cost, and environmental cost. For each aspect, the respondents were asked to provide a rating on a scale of 1 to 10, where 1 indicates the lowest cost or frequency and 10 indicates the highest cost or frequency. The survey form also included three questions:

1. *Do you recommend natural infrastructures? If yes what types?*
2. *Is there any monitoring difference between natural and grey infrastructures?*
3. *Do you know cost information for any solutions?*

ODNR provided the research team with a list of local stakeholders, which included professionals in 167 state and local shoreline jurisdictions, 36 coastal practitioners or design engineers, and 162 general contractors and consultants. The respondents included a variety of agencies and firms at local and national level, including ODNR, National Oceanic and Atmospheric Administration (NOAA), the US Army Corps of Engineers (USACE), Erie Metroparks, Cleveland Metroparks, the City of Lakewood, Black Swamp Conservancy, Coldwater Consulting and the engineering firm AECOM. The research team distributed the survey form to local stakeholders in June, 2018.

3 RESULTS

3.1 Cost Analysis Results

The cost analysis results for the 16 scenarios considered in this study are presented in Figure 1. For each scenario, the total 25-year cost is the summation of the initial construction cost, the 25-year maintenance cost, the damage cost, and the environmental degradation cost. The total 25-year costs for each of the three natural infrastructures were calculated under two different scenarios (frequent storms and rare storms). In the calculation for the costs of grey infrastructures, storm frequency was not considered; however, separate costs were calculated when a given grey infrastructures could be constructed using more than one material.

The highest cost for a grey shoreline protection approach was for groins constructed using concrete and steel, with a cost of 50,970 USD per linear foot parallel to the shoreline, followed by breakwaters, with a cost of $35,288 USD per linear foot. The least costly scenario for a grey infrastructure was revetments comprised of riprap, with a cost of $3,238 USD per linear foot. The cost per linear foot for the other grey infrastructure scenarios ranged from just under $10,000 USD to just over $20,000 USD. For natural shoreline protection approaches, the highest cost for a solution under a frequent storm scenario was beach nourishment, with a cost of $16,582 USD per linear foot, while the costs for nature-based shorelines and vegetated dunes were somewhat lower ($9,382 USD and $9,131 USD per linear foot, respectively).

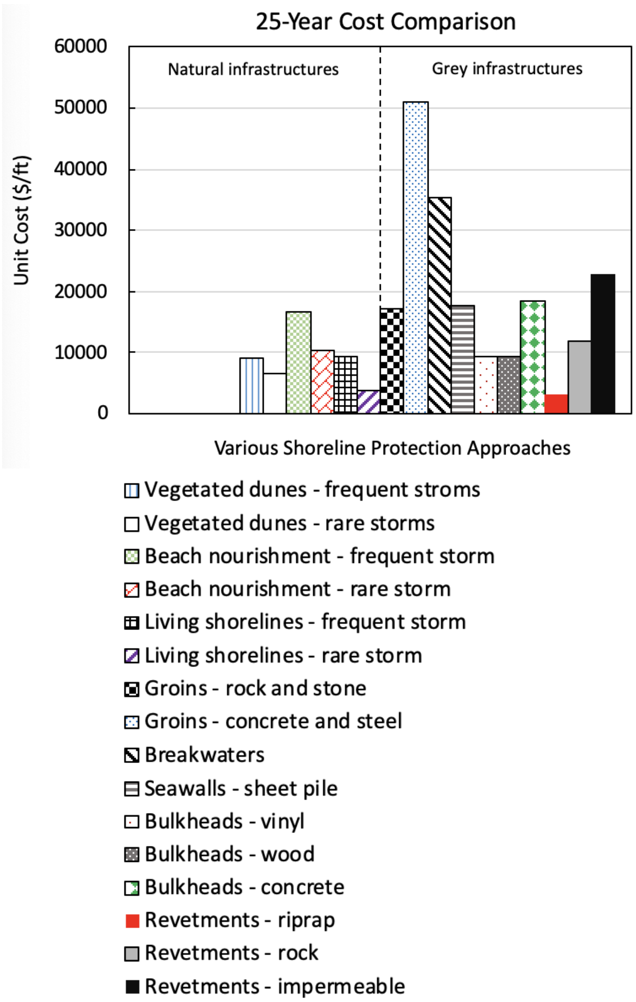

Figure 1: Total 25-yr cost comparison of natural approaches vs. grey approaches when including environmental degradation cost (Source: Luo 2018).

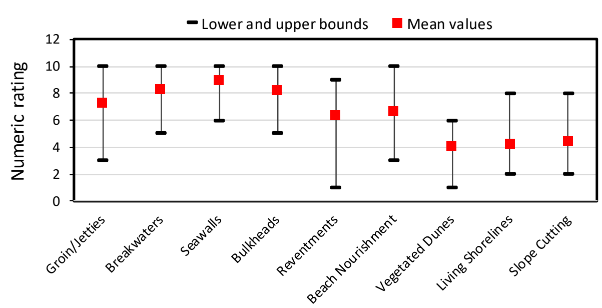

Figure 2: Initial construction cost ratings for various grey and natural shoreline protection approaches (Note: a larger number indicates a higher cost; Source: Luo 2018).

3.2 Survey Results

The fourteen (14) valid survey forms received included responses from 11 state/local shoreline jurisdictions, one coastal practitioner, one general consultant and one education intern. Figures 2 through 6 present a summary of ratings in each of the five categories (initial construction cost, maintenance cost, maintenance frequency, damage cost, and environmental degradation cost). In this survey, the estimated cost for various infrastructures ranges from 1 to 10, with a larger numeric value indicate a higher cost, e.g., 10 is the most expensive.

When asked if they recommend natural infrastructures for public and private land with shorelines, nine of the surveyed individuals indicated that they do so. The solutions they recommend suggest the incorporation of vegetation (including trees), dune restoration and vegetated dunes, beach nourishment, living shorelines, wetland restoration, the regrading and vegetation of slopes, drainage improvements, offshore breakwaters, low sills, and locked logs. One respondent recommended coir mats: *Fabrication of coir (a natural fiber extracted from the husk of coconut) mats into large envelopes and bags which are then filled with locally compatible beach sand and constructed into terraces extending up the face of the coastal bank. These natural materials absorb wave and surf impacts, help encourage sand to build up or accrete naturally and fosters reduced wave reflection*.

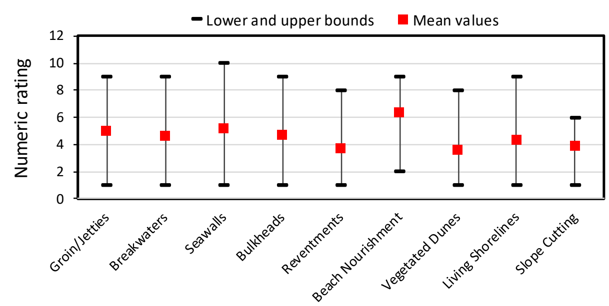

Figure 3: Maintenance cost ratings for various grey and natural shoreline protection approaches (Note: a larger number indicates a higher cost; Source: Luo 2018).

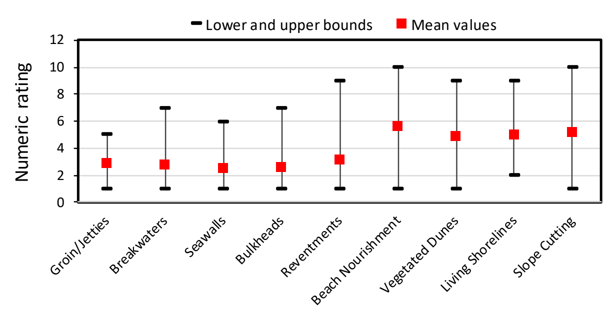

Figure 4: Maintenance frequency ratings for various grey and natural shoreline protection approaches (Note: a larger number indicates a higher frequency; Source: Luo 2018).

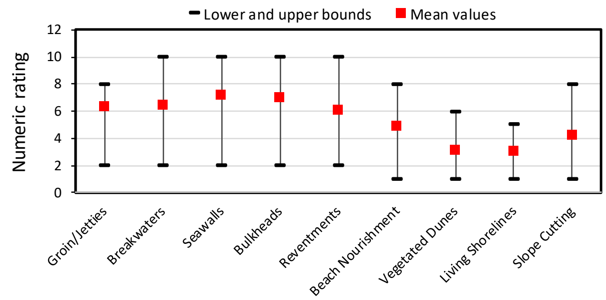

Figure 5: Damage cost ratings for various grey and natural shoreline protection approaches (Note: a larger number indicates a higher cost; Source: Luo 2018).

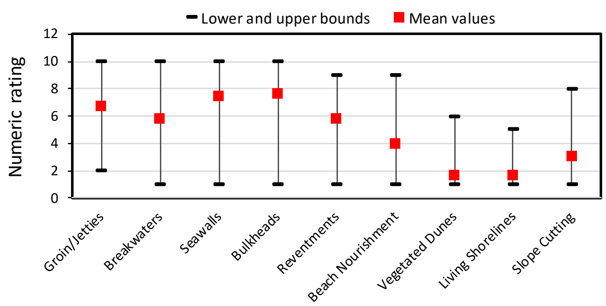

Figure 6: Environmental degradation cost ratings for various grey and natural shoreline protection approaches (Note: a larger number indicates a higher cost; Source: Luo 2018).

In response to the second survey question, which inquired if there are any differences in monitoring for grey and natural infrastructures, the majority agreed that there are indeed some differences. One respondent suggested, *Yes, manmade structures tend to be … monitored more because they reflect wave energy and this causes more damage to their structure,* while another suggested, *Generally, grey infrastructures (if well designed and built) require fewer inspections during the year but all structures require some level of annual monitoring*. On respondent specifically pointed out that *groins and breakwaters require yearly sand volume monitoring*. For natural infrastructures, one respondent suggested that *monitoring of natural infrastructures should incorporate ecological monitoring of habitat to watch for invasive species and presence of important species*. A few respondents mentioned that they had no experience with monitoring of nature-based shorelines or did not use these natural infrastructures. One respondent replied that there are no differences between grey and natural infrastructures in terms of ecological monitoring.

A third question asked about costs for any grey or natural infrastructures, and very few respondents were able to provide specific cost information. One respondent noted, *In general, grey infrastructures such as steel, vinyl or concrete seawall and bulkheads can run anywhere from $200.00 – $1,000 per linear foot*, while another respondent estimated the cost for a revetment to be around $1,300 per linear foot.

4 DISCUSSION

The benefit and cost analysis based on collected cost data clearly demonstrated that, given that life-cycle cost is the major consideration in the selection of a shoreline protection solution, natural infrastructures are generally superior to grey infrastructures. For example, the 25-yr life-cycle cost estimates for vegetated sand dunes, beach nourishment and living shorelines under rare storm impacts are approximately $6,553 USD, $10,446 USD and $3,803 USD per linear foot, respectively, which are significantly less than the 25-yr life-cycle cost of most grey infrastructures ($35,288/ft USD for breakwaters, $17,741/ft USD for sheet pile seawalls, $18,383/ft USD for concrete bulkheads, $11,872/ft USD for rock revetments and $22,775/ft USD for impermeable revetments).

The comprehensive survey study based on numeric ratings shows the advantages of using natural shoreline infrastructures versus grey infrastructures in terms of cost savings and environmental/ecological protection. For example, the mean values of numeric ratings on the initial construction cost for the grey infrastructures are all greater than 5, while the mean ratings for the natural infrastructures are all less than 5, with a larger value indicating a higher cost. Similarly, the mean ratings on the environmental degradation cost for the grey infrastructures are all greater than 4, while the mean ratings for the natural infrastructures are all less than 3, showing the benefits of using natural infrastructures.

5 CONCLUSIONS

The numeric ratings provided by various local professionals further confirm the advantages of using natural shoreline infrastructures, both in terms of environmental/ecological protection. The conclusions based on the survey are nearly identical to those based on the cost data analysis. As indicated by the survey responses, the final decision should also be based on other factors such as wave energy level, site geology, space and infrastructure to be protected. The cost benefit analysis conducted as part of this study was based on currently available cost information and focused on only three natural infrastructures and five grey infrastructures; as such, it should be considered as a preliminary study. Future research would include a more comprehensive analysis of additional natural and grey shoreline infrastructures (e.g., slope cutting) and would consider additional factors such as the on-site geology, anticipated wave energy, and the type and size of infrastructure to be protected.

As noted by some professionals in their survey responses, natural infrastructures may not be appropriate for all sites, especially when considering open-coast locations subject to high wave energy and winter ice conditions. It should be noted that several important factors — recreational value and effects on nearby private property, as well as the effects of wave energy, on-site geology and space — are not included in the cost analysis in this study. An ongoing research project funded by Ohio Sea Grant is studying the economic benefit of a beach on the local economy. The local economic benefit and other additional factors can be readily implemented in the cost comparison framework employed in this study.

The responses to the survey conducted as part of this study indicate that most professionals in Ohio are not familiar with the use of natural infrastructures for shoreline stabilization. More effort is needed to promote green natural shoreline solutions, develop design standards or guidelines for their implementation, and implement demonstration (pilot) projects to promote their wider use. Research-based evidence will be useful to develop engineering guidance and design criteria, training programs for shoreline management, and promotional materials encouraging the use of natural infrastructures where appropriate.

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