NatuReturn: An Environmental Management Tool

by

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Executive Summary

The explosive growth in data analytics driven by software and computing innovation enables powerful tools for environmental managers who plan, execute, and monitor projects. In the past costly and frequently protracted impact studies were necessary as part of the initial planning for projects. In this study, a prototype tool was developed that assists environmental managers by predicting a project's return-on-investment (ROI) and providing a risk assessment using historical and current environmental data. By synthesizing this information, potential projects can be evaluated and compared giving stakeholders a quantitative ability to set priorities and determine where to allocate limited funds. The tool does not eliminate impact studies. It may lower costs by reducing the number of impact studies needed and focus the existing effort to the most relevant issues in the proposed projects.

The goal of this feasibility study was the completion of a prototype tool that builds on the existing methods of ecosystem service modeling by adding cost, schedule (time), and risk. This comprehensive view is a form of benefit-cost modeling that focuses on the most relevant benefits for the stakeholders rather than all services provided. The tool might be useful to:

- government agencies – allocating limited funds for greatest effectiveness
- funders of environmental projects – evaluating and sorting project impacts
- conservancies – in requests for funding, allocating funds
- researchers – grant requests, applied research

By using oyster reef restoration as an example, the complexity of the tool, the difficulty of assembling relevant and accurate data, the database management challenges, the usefulness of the tool in general environmental projects, and the tool's scalability are examined.

Methods

After choosing oyster reef restoration as the prototype application, the study area chosen was the prime oyster habitat in Texas bays south of Houston and north of Corpus Christi. Three locations and three types of oyster reefs each with different benefits were investigated. A GIS-based model with analysis capability was developed incorporating relevant benefit measures, cost, schedule and risk factors. Data was collected from various government agencies, researchers, conservancies, and engineering firms. The method of storage, data management, and data accessibility were noted during the process. Reef locations were proposed with targeted

benefits, and the model was used to synthesize current and historical projects to predict the ROI for each project. Challenges were noted and recommendations assembled for next steps.

Summary of findings

Constructing the top-level model that incorporated benefit, cost, schedule, and risk was straightforward. The project quickly became focused on findng and retrieving the needed data. Environmental projects frequently involve multiple agencies and entities, each responsible and concerned separately about funding, impact, permitting, and science. Each entity stores data in different formats and has different goals. Models required modification to adjust for the type of data available, and the accuracy constraints. A judgement on practical feasibility includes cost, and the frequent iterative and manual requests for information will discourage some stakeholders from using the tool until there is more general acceptance and ease-of-use progresses. For the three reef benefits emphasized: oyster harvest, shoreline protection, and recreational angling, the complexity of the prototype was manageable for oyster harvest and shoreline protection. Adding additional social dynamics modeling to the recreational angling model would provide more accuracy.

A view to the future

The continued use of data analytics coupled with automated search technologies have already changed the financial and health industries where ROI drives for-profit competitive advantages. Environmental projects funded by government or charity may not drive innovation, but they can benefit from the technology developments. Next steps:

1) Early adopters of this type of tool need to estimate costs of relevant data assembly
2) Adopting standard method of data storage for environmental project planning, construction, and monitoring will lower costs
3) Data curation and management by agencies can be implemented now in anticipation of automated searches and artificial intelligence methods.
4) Data accessibility can be improved by using secure public portals, and this will also lower tool usage cost.
5) The modeling technique scales to larger areas because results are easily aggregated, and the method can be applied to general environmental projects.

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Finally, this project is dedicated to the memory of John Diehl, my dive buddy who died in a scuba accident in the middle of the Gulf of Mexico less than a week before I started at the Nicholas School. A friend and business partner for a decade, he enthusiastically supported my mission to bring technology to the environmental space. Although I started the DEL-MEM program grieving, the memories of the two of us venting and inventing over beers at Uncle Billie's Brewery, and the 10PM dives in Barton Springs perfecting underwater 360 video technology for the nighttime coral spawn are still inspirational. I miss him terribly. His joyous spirit of adventure and the memory of his smirk as we encountered uncertainty and obstacles are helping me in the drive to make a difference. This is for you John.

Introduction

The need for determining the value of ecosystem services grew over the past three decades as policy makers, economists, agency leaders, philanthropists, and environmentalists faced decisions for allocating government and private funds (Peterson 1975; Porter 1982). Although detailed ecosystem service benefit models for restoration projects are developed based on scientific research, the costs and risk assessment of these projects, which could be useful in setting restoration priorities, are given less emphasis (Viglizzo et al. 2012; Yu et al. 2018). This project can be considered a part of bridging the science-practice gap (Cabin 2011: 155–172) by integrating benefits, costs, and risk into a GIS-based software tool that systematically spans the scientific and socio-economic boundaries and synthesizes information for environmental restoration practitioners, researchers, and decision makers. This feasibility study investigates the usefulness of a prototype tool by focusing on oyster reef restoration along the Gulf Coast. A set of examples highlights the model's predictive possibilities and may inspire the reader to imagine the power and potential uses of such a tool as low-cost sensors and data analytics further inform and revolutionize environmental management.

Investing in Nature

The historical progression of models like those proposed in this project are rooted in the mid-1900's ecosystem valuation research performed without the benefit of today's sophisticated sensors and computers. In a 1946 Yale study on the benefits of forests in watershed management, only the marketable timber is discussed as a benefit with financial return (Hawley 1946). Added ecosystem services that benefit the watershed like soil permeability, water filtration, and flow regulation are identified in Hawley's study but not emphasized or quantified. There was awareness of impacts to habitat loss, human enjoyment, and carbon sequestration but these were not considered.

By the 1980's, research began on broader ecosystem services valuation. Researchers modeled societal impacts in monetary terms using an expanded set of benefits that included provisional, regulating, supporting, and cultural services. (Farber and Costanza 1987; Costanza and Daly 1992; Bengston 1994).

A decade after the first papers on broad ecosystem services valuation were written, a controversial effort by a large group of researchers attempted to set a value on the global ecosystem services and suggested a conservative $33 trillion dollars which at the time was

slightly larger than the aggregate gross domestic product (GDP) of all nations (Costanza et al. 1997). The controversy developed around the methods used in valuing large categories of global ecosystems when value has contextual meaning that is frequently local, temporal, and cultural (Toman 1998; Turner et al. 1998). In spite of the fact that the controversy was about the errors inherent in valuation of broad and global ecosystems, many environmentalists took issue with setting monetary values on nature and contrasted utility with intrinsic value (McCauley 2006). Perhaps lost in the aggregation argument was the utility of using quantified valuation of ecosystem services backed by science as part of a broader decision-making process for funding decisions critical for environmental restoration projects at a smaller scale.

U.S. Government investing in nature

An example showing the need for tools that can quantify ecosystems service value, costs, and risks is found in severe storm resiliency. Because of the large investments associated with improving resiliency, the federal government is interested in seeking a return through investments in natural systems. While environmentalists debated setting monetary value on comprehensive ecosystem services within the context of broader service definitions, coastal cities in the US were experiencing increasing catastrophic property loss from hurricanes and storms. Twenty-seven years ago, Hurricane Andrew, a "super-hurricane", destroyed $50 billion in property and killed 65 people in Florida. It was the costliest storm to date (NCEI 2018).

Since then, the National Oceanic and Atmospheric Administration (NOAA) data shows storm damage estimates (consumer price index adjusted), spiraling upward. In 25 years, the aggregate damage was nearly a half-trillion dollars from five storms shown in Table 1.

Table 1 Recent severe hurricane damage and death estimates (NCEI 2018)

Year	Hurricane Name	Damage ($billions)	Deaths
1992	Andrew	50	65
2005	Katrina	>150	1250
2012	Sandy	71	233
2017	Harvey	70	68
2017	Maria	90	disputed

The size of the monetary damages from catastrophic storms led to demands for greater resiliency in U.S. coastal cities and communities. The high level of investment required for "hardened" or man-made infrastructure protection has created an awareness that natural systems, (Taylor et al. 2015) or hybrid systems (Sutton-Grier et al. 2015) might be used cost-effectively for resiliency.

Following Hurricane Sandy, the $50 billion Disaster Relief Appropriations Act required that all federal rebuilding projects using this fund consider the use of natural systems where appropriate for enhanced resiliency (Sutton-Grier et al. 2015). Natural systems provide multiple benefits and co-benefits that create greater complexity in decision-making and the need for accurate modeling of impacts during the coastal project planning phase. When comparing the societal benefits of natural systems to man-made systems, project planners need cost and risk information along with the ecosystem service valuation. This is especially needed along the coast where the population continues to grow, exacerbating the financial exposure (Crosett et al. 2013).

Tools for scenario analysis

Municipalities and regions face alternative methods to achieve environmental goals that include resiliency, water quality, responsible resource management and tourism. Lists of potential projects include natural system preservation, enhancement, restoration, and creation (PERC). The geographic scale for these potential projects ranges from smaller than an acre to large regions that are hundreds of miles long like the Texas Coastal Bend.

Environmental managers consider the prioritization or selection of alternative PERC or infrastructure projects as "scenario analysis", and regional assessments of ecosystem service valuation as "green accounting"(National Ecosystem Services Partnership 2016). Sustainability, PERC, or resiliency projects involve a complex web of interacting systems including human systems. New planning software tools such as IMPLAN assist in assessing impacts in complex socio-economic systems and assist in planning and priority processes by synthesizing large quantities of data (Santos et al. 2016; Parajuli et al. 2018).

Predictive tools needed at project level

Historically, natural system restoration was driven by conservation and preservation organizations with limited funding ability. The increased focus of local, state, and federal governments on storm resiliency requires investment at unprecedented levels. Along the Gulf and Atlantic coasts, there are numerous resiliency projects at various stages of planning that include natural, (i.e. living shorelines), and hardened structure (i.e. concrete seawalls). In a $2 million initiative funded by NOAA, the Texas General Land Office (GLO) developed a Coastal Resiliency Master Plan that lists projects and sets priorities (Texas General Land Office 2017). The resiliency priorities are established based on science, available funds, and perceived benefits by the stakeholders along the coast. Assessment of economic and social value for restored natural ecosystems used for resiliency is difficult and standards for reporting are still evolving (Olander et al. 2018).

What is missing from the planning process is an accessible tool that reports the socio-economic benefits of the ecosystems, risk assessments for the projects, and cost estimates in the project proposal phase. Typically, impact, scope, risk, and resource needs for an individual project are estimated by environmental consulting engineers through studies using proprietary data and methods that may take weeks or months to develop and assemble.

Many tools focus on benefits

Software tools and databases, many of them GIS-based (visual), are used for setting resiliency project priorities by state and federal organizations. For example, NatureServe's Vista tool provides scenario-based assessments for land management (Bagstad et al. 2013). However, the tools lack some economic attributes needed for a comprehensive priority assessment

including costs, benefits, and risks. A state agency that might use TNC's Coastal Resiliency Toolkit can use the proposed tool and methods (The Nature Conservancy 2013 Oct 17), for example, to provide more project details during the early stages of a resiliency planning process.

One further limitation of tools is resolution. An example is Earth Economics' proprietary tool, Ecosystem Valuation Toolkit (Bagstad et al. 2013), that focuses on economic impacts of natural systems worldwide. The scale of this toolkit, based on website information, indicates a focus on large regional estimates that may not be applicable or accurate at the local level. Further, this tool is not focused on individual project impact and does not include risk assessment, resource requirements, or schedule assessments for natural system PERC projects.

An additional example, the Harte Research Institute (HRI) in the Gulf of Mexico initiated a searchable database called GecoServe (Plantier-Santos et al. 2012) for valuing various ecosystem services based on economic data found in literature searches for Gulf projects and studies. In this database the geographic scale varies from local projects to regional projections, and lists publications, the method used for valuation (i.e. willingness to pay), and general location. This tool is targeted at valuing ecosystem services and doesn't address project-specific decisions.

Benefit relevance and costs

Are all the services provided by an ecosystem part of the benefit value in the investment return? An organization that attempts an answer to this question, the National Ecosystem Service Partnership (NESP), describes the ecosystem service causal chain using the conceptual diagram in Figure 1 (Olander et al. 2017). The first red box shows that ecosystem health can be measured with ecological indicators that might consist of physical instrumentation measures or population counts for example. The second red box connects the ecosystem to human needs by measuring benefit relevant indicators (BRIs) which connect the ecosystem to societal needs or value. Consider the top row of boxes in the diagram to be a progression of benefits in general to societal value. Most ecosystems provide more than one service that society may or may not value in a specific place and time. Stakeholders making decisions on environmental projects may consider just one service important or valuable. It may be useful to catalog all services provided at a given time and focus on the value of one or a few services when setting priorities for projects. This study adds to the Olander et al. causal chain by including the green shapes in

Figure 1 – costs, risk, and schedule and determine net economic benefit to society or ROI, and since investment decisions are measured in net present value, project schedule is critical. This path provides additional information for policy and project management decisions.
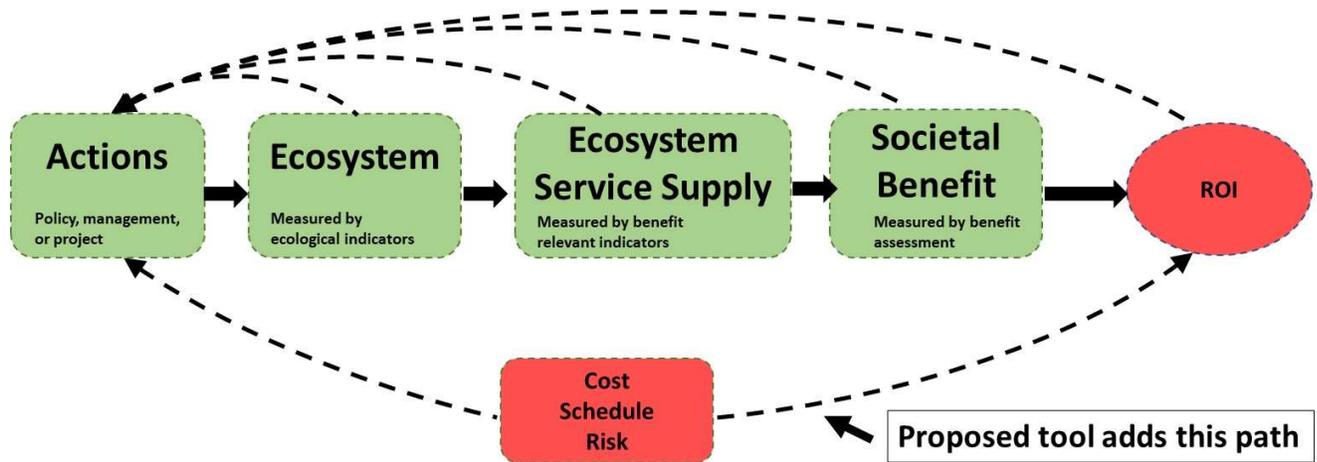
Figure 1 Ecosystem service causal chain (Olander et al. 2017) - with cost, schedule, risk, and ROI added

Is a local GIS-based ROI tool useful?

Can a GIS-based tool be constructed that predicts a regional return on investment for proposed projects at the local level? Further, could such a tool be used to aggregate local project data for use in regional scale projects by state or federal environmental managers?

The proposed GIS-based database tool synthesizes historical project, research, and monitoring data in a systemic context that synthesizes environmental, economic, and social impacts. In the feasibility study, the available data from restored reefs in the same bay is included. There is a focus on predictive return-on-investment (ROI) for proposed reef projects using a cost/benefit analysis and assessment of project risks using data collected from historical projects. This tool may be useful in planning and priority processes performed by environmental managers with a goal of reducing the planning time and cost for local projects. For state or national managers, even though the tool assesses local scenarios it could be used to aggregate predicted results of smaller projects for larger scale planning initiatives through map-based reports.

Tool ownership and maintenance

For this type of tool, a motivated entity needs to own the tool improvements, maintenance, and database management. A state agency like the Texas General Land Office owns the intertidal regions and maintains surface leases on the bays but funding priorities might make owning the tool maintenance unlikely, and agencies might be best at managing the data. A tool owner might be private, or a collaborative of interested stakeholders.

Databases and tools that are useful across federal or state agencies, municipalities, conservancies, and research institutions are sometimes managed through networks that sponsor the development, data updates, and long-term maintenance. One example is the National Ecosystems Services Partnership (NESP) that published the Federal Resource Management and Ecosystem Services Guidebook (Nicholas Institute for Environmental Policy Solutions 2018). Although targeted specifically at interconnected federal agencies, this guidebook is used for decision-making and planning at regional and local scales.

Another example of a collaborative with nationwide reach is the Fire Learning Network (Goldstein et al. 2010). This collaborative brings together agencies and project owners who are engaged in maintaining landscapes that require fire for sustainability. Management techniques and funding are shared, so it's conceivable that a similar network could be used to maintain a tool and curate data like the one proposed in this study.

Objectives

By using oyster reef restoration as an example, this project seeks to demonstrate the feasibility of using a geospatial modeling tool that combines location, costs, benefits, and risks to provide environmental project stakeholders with quantitative and predictive impact measures. Goals of the feasibility study:

- Build a working prototype model that analyzes the impact of three ecosystem services provided by multiple proposed oyster reefs in varying locations along the Texas coast.
- Determine if the necessary data for constructing a database for this decision tool exists.
- Show that a GIS based model can provide feedback on project location choice by calculating benefit-cost impact, and the risk of success.
- Determine the complexity, obstacles, and cost of developing a useful model.
- Determine the scalability for larger regional projects and general environmental projects.

Based on the results, this study will provide guidance for follow-on research and discuss standardization of data records or other methods that may reduce the cost

Based on the results, the usefulness of such models for general environmental projects including terrestrial and marine will be discussed. Example scenarios using the prototype will reveal the power of synthesizing economic, social, and scientific perspectives in a modeling tool. It will also reveal the need for curating and storing the planning, execution, and monitoring data in ways that automated search methods or machine learning algorithms can access and synthesize quickly.

Study Area

The bays of Texas are shallow and marshy with estuaries providing freshwater inflow that creates prime oyster habitat in some of the bays (Legare and Mace 2017). The bays produce 3.5 million pounds of oyster meat per year which is more than 10% of the total U.S. harvest (NOAA Office of Science and Technology 2019). Galveston Bay, prior to Hurricane Harvey in 2017 was producing 2/3 of the oysters harvested in Texas which is remarkable considering this bay is situated 20 miles downstream of the world's largest concentrated petrochemical complex in Houston, and one of the busiest ports (Blackburn 2004: 31). The Gulf Coast oyster reefs are among the healthiest in the world; however, they are threatened by natural disasters like droughts and floods as well as anthropogenic causes such as overharvesting and oil spills (Beck et al. 2011). In this study, Beck, et al. estimate that 85% of the world's oyster reefs have been destroyed over the last century. The services provided by increasingly rare oyster reefs includes fish habitat benefiting recreational and commercial fisheries, storm resiliency, water filtration, denitrification, food production, and shoreline erosion protection (Grabowski et al. 2012). In Texas, multiple organizations have funded or been involved with oyster reef restoration including The Galveston Bay Foundation (Galveston Bay Foundation 2011), The Nature Conservancy (Carlton et al. 2016), US Fish and Wildlife Services (Legare and Mace 2017), U.S. Army Corps of Engineers (Townsend et al. 2014), Texas Parks and Wildlife Department (Legare and Mace 2017), and NOAA (Beseres Pollack et al. 2013).

The area of study for this prototype tool development was the coastal region extending from Galveston Bay near Houston through the center of the Texas Coastal Bend in Matagorda Bay (Figure 2).

Figure 2. Study area along Texas coast is prime oyster habitat

The study area includes two bays that are prime oyster habitat because of depth and freshwater inflow, Galveston Bay and Matagorda Bay. Three sites were proposed for reef restoration, each with one dominant ecosystem service for illustrating the use of the tool. These bays include nearby restored reefs with similar targeted ecosystem services. In this region, stakeholders are interested in the oyster harvest, recreational fishing, and shoreline protection.

East Galveston Bay Reference Reefs

The oyster reefs in this region of the bay provide multiple ecosystem benefit relevant services including oyster harvest for human consumption. Galveston Bay has a mix of natural and restored reefs (Figure 3) and provides most of the Texas oyster harvest. The typical restoration method is using river rock as cultch for the attachment of oyster larvae. Texas is one of the last states that is harvesting oysters from natural reefs, and many of the reefs are located in Galveston Bay (Knapp 2018). One major intent of restoration in this bay is oyster harvest and the river rock substrate allows the use of oyster dredges. The legal shell size for a harvestable oyster

is greater than 3" and this size can be achieved in about 3 years after the larva attaches to a hard surface.

The reference restored reefs in this bay are fully submerged reefs and constructed using 3"- 4" diameter river rock as cultch, spread evenly across the bottom of the bay. Cultch made of oyster shells is a preferred material but there is limited availability. This bay is heavily harvested. Finfish, crabs, and shrimp frequent this area as well. The dominant ecosystem services of this reef are oyster harvest and recreational angling.
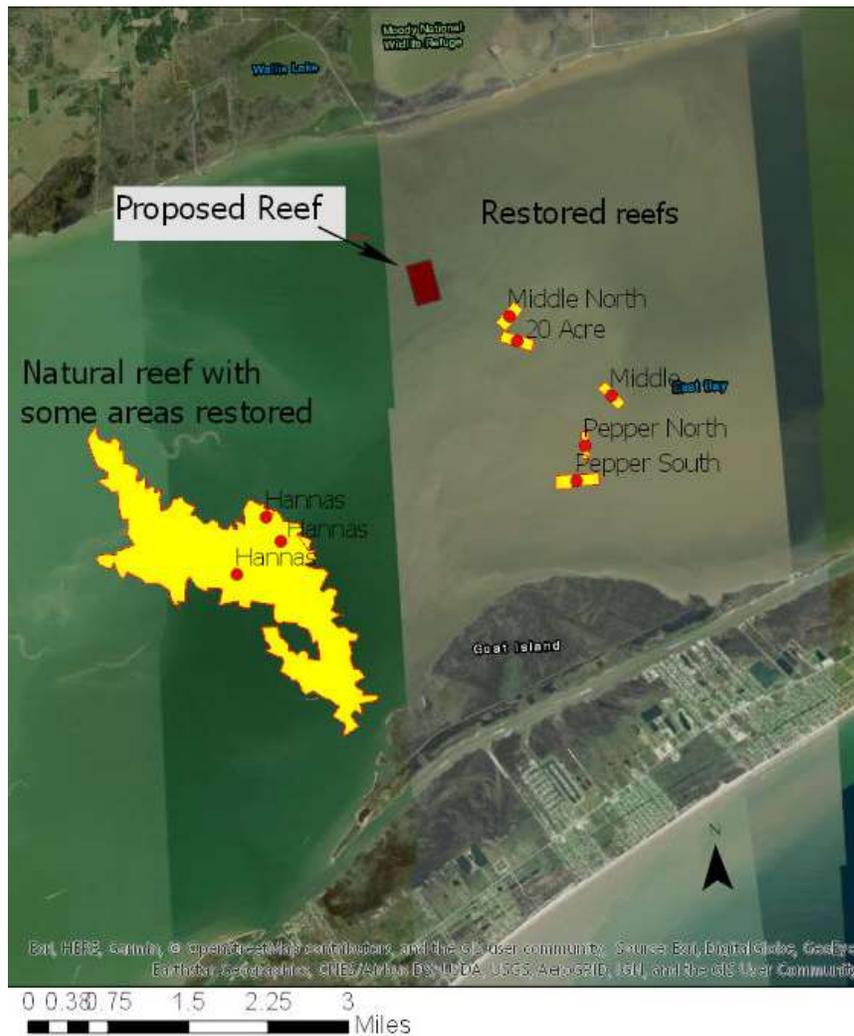
Figure 3 Galveston Bay study area showing nearby restored reefs used as reference

Mad Island Reference Reef

The Mad Island restored oyster reef is used as a reference and was constructed for soil erosion protection near the edge of the intracoastal waterway as it enters Matagorda Bay. The reef base was constructed of interlocking cages filled with mesh bags of oyster shells, using a low-cost method pioneered by Coastal Environments, Inc. in a product they call ReefBlock ™ (Figure 4). This technique is being used in other reef construction projects around Mobile Bay in Alabama for coastal shoreline protection which is a dominant ecosystem service.

Figure 4 Mad Island interlockable Reefblocks^{TM} ready for placement (picture courtesy of Coastal Environments Inc (Randy Sunde)

Half-Moon Reference Reef

     A socio-economic study done by Texas Sea Grant and The Nature Conservancy focused on recreational angling as an ecosystem service for this reference reef known as Half-Moon Reef. This is a submerged restored oyster reef that was constructed in a bay that is a nursery for finfish, shrimp, and crabs. The finfish in Matagorda Bay include species that are desired by recreational anglers and include spotted seatrout, red drum, black drum and flounder. These fish tend to feed on or near the concentration of oyster shells that house small marine organisms. A dominant ecosystem service benefit for this reef is the recreational angling. The reef is constructed from two different cultch materials – limestone rock and recycled concrete. Instead of a continuous distribution of cultch material across the muddy bottom, the cultch was mounded (Figure 5). The roughness of the cultch and the contour will not allow the typical oyster dredge harvest (M. Dumesnil, The Nature Conservancy, personal communication, 8/8/2018). Dumesnil reported that the mounds are intended to provide a diverse environment within the ecosystem. Further, he noted that it was important that the initial reef height was 4-5 feet below the low tide mark allowing small fishing boat access without concern for hull damage.
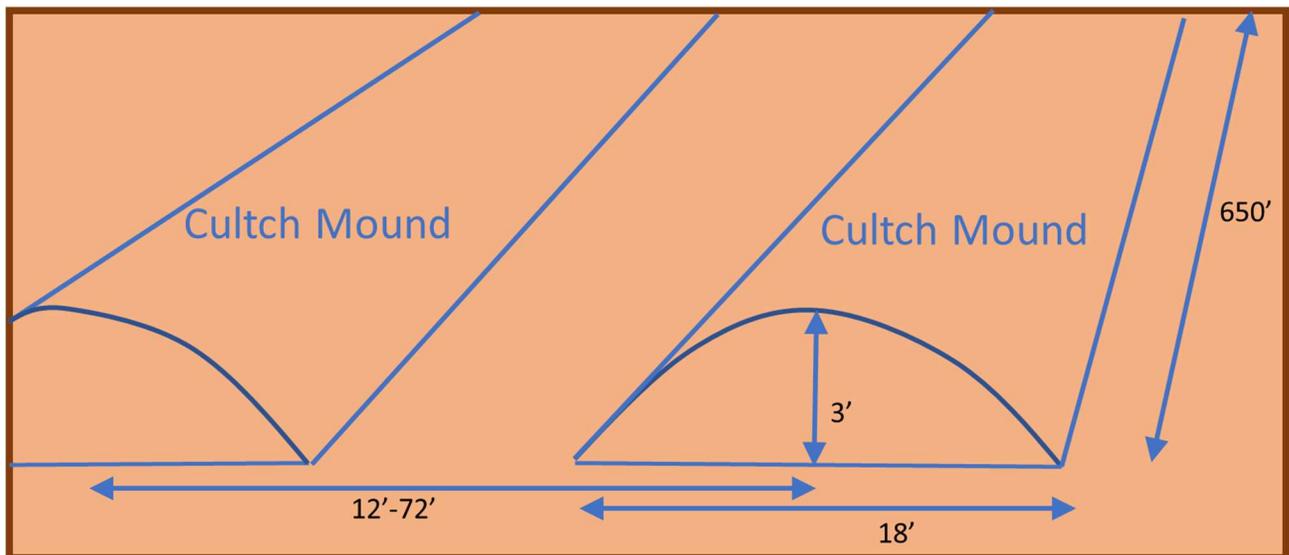

Figure 5 Construction diagram of oyster cultch for Half Moon Reef, Matagorda Bay

Methods

A geospatial modeling approach was chosen because project location is critical when estimating environmental, cost, and benefit impacts as well as when assessing the risk that the project succeeds. The available computing power for synthesizing large quantities of data is staggering, but the communication of that synthesis to humans requires a tool that can visually represent that synthesis. Open source examples of such tools are GRASS, QGIS, and FLOWMAP. For this project, ArcGIS™ Pro was the Geospatial Information System(GIS) tool chosen (ESRI 2018).

The tool links any type of data with a specific (x,y,z) location on the earth. In addition, the tool provides modeling capability known as ModelBuilder™ (ESRI 2018) with an interface that allows Python (van Rossum 2018) scripts for data manipulation, automated synthesis, and the passing of parameters. The methods cover the retrieval of relevant data, the model development, data synthesis, and reporting.

Top-level Model

Like the NESP flowchart in Figure 1, the top-level model in this study is developed with a benefit path, and a cost path (Figure 6). The benefit path could include all the services provided by oysters, however frequently one or two services dominates for each reference or proposed reef. This is the relevance filter that Olander articulates in the NESP documents. A municipality or agency evaluating the priority of a project chooses the most relevant services. For example, a remote inaccessible oyster reef might attract game fish but not anglers so there is no service value for recreational angling. The cost path may seem simple, but multiple entities public as well as private partners, may contribute to funding of projects, making some costs irrelevant especially the costs not borne by that entity. These costs are known and can be added or removed easily. The aggregate of these sub-models can be summed into a regional ROI that provides value information to stakeholders.
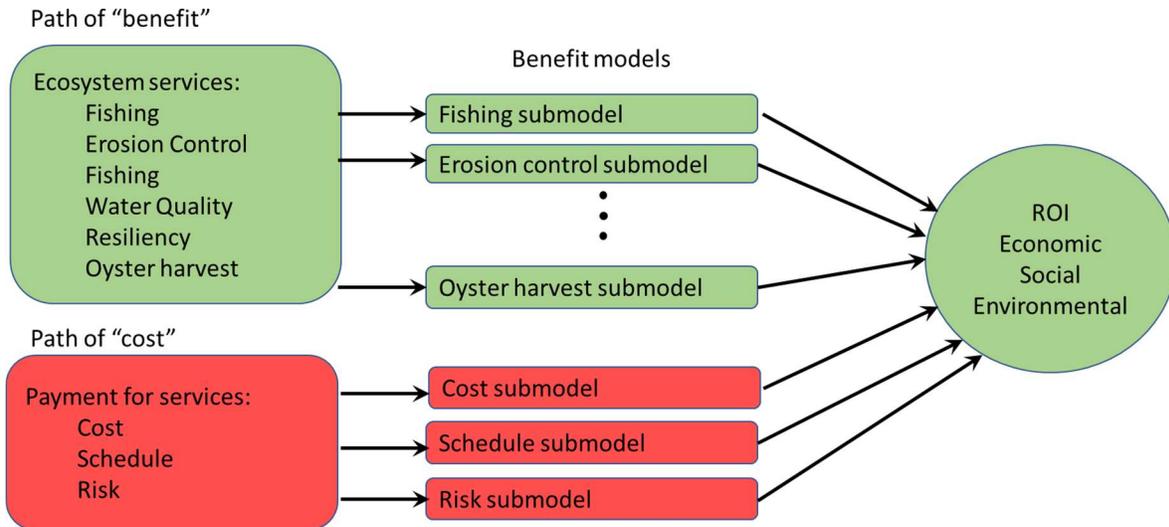
Figure 6 High-level flowchart

Choosing the reference reefs

The reference reefs chosen for this project had three distinct dominant services because of structure, location, and intent (Table 2). These reefs provide data relevant to the value of the proposed reefs and the risk of success.

Table 2 Reference oyster restoration reefs and characteristics

Reef Name/Bay	Cultch Structure	Location	Intent
Multiple reefs/Galveston	River rock flat	Submerged	Oyster harvesting
Mad Island Reef/Matagorda	Oyster shell	Inter-tidal	Shoreline erosion
Half Moon Reef/Matagorda	Mounded rock	Submerged	Recreational angling

As discussed in the study area section, in Galveston Bay river rock, 3-4" in diameter, is spread evenly across the muddy bottom allowing dredge harvest. Although not useful for low-cost oyster harvest using a dredge, the spacing between cultch mounds in Half Moon Reef was deliberately planned to create a more diverse habitat that attracts gamefish. Half Moon Reef and the Galveston reefs both remain submerged under normal tides. The structure and location of the intertidal shoreline erosion reef near Mad Island is dramatically different using caged oyster shell cultch for recruitment. These cages are interlocked, and the purpose is to accrete sediment on the land side and prevent shoreline erosion by the wave action of barges that pass by in the Gulf

Intracoastal Water Way (GIWW). The three reference reefs chosen show that each ecosystem service requires a unique benefit-cost model.

Data

The required data from each of the reference reefs include location, cost, and benefit inputs. The sources of the data were varied and included unpublished data from government agencies, public data provided by government agencies, university research databases, non-profit organizations dedicated to coastal preservation, private conversations with project engineers, and cost data from engineering firms that were involved in construction (Table 3).

Table 3 Data sources used in models for proposed restoration reefs

Bay and/or Reef Name	Data Description	Data Source
Galveston Bay	Harvestable oyster density samples (5 from each reef), quadrats of 0.25m x 0.25 m	Texas Parks and Wildlife Department, Emma Clarkson, email communication unpublished data, 12/18/2018
Galveston Bay	Geospatial shapefile showing natural and restored reef locations	Texas Parks and Wildlife Department, Emma Clarkson, communication unpublished data, 9/24/2018
Galveston Bay	Suitability index - Geospatial feature class with 7 level classification	(Reisinger and Pollack 2019)
Galveston Bay	Per acre construction costs of multiple reefs	Texas Parks and Wildlife, Bill Rodney, email communication o unpublished data, 11/26/2018
Matagorda Bay, Half Moon Reef	Economic benefit estimates for state of Texas	(Carlton et. al 2016) Published report
Matagorda Bay, Half Moon Reef	Construction and per acre costs using limestone/concrete material	The Nature Conservancy, Mark Dumesnil, telephone communication of unpublished data, 8/8/18
Matagorda Bay, Half Moon Reef	Bathymetry -Depth of bay at 30 meter resolution	(NOAA 2018) published data
Matagorday Bay, Intracoastal Waterway Reef	ReefBlock^{TM}, concrete revetment costs	(Townsend 2015) published data by US ACE
Matagorday Bay, Intracoastal Waterway Reef	Shoaling rates at multiple sites on Texas GIWW	(Townsend 2015) published data by US ACE
Matagorday Bay, Intracoastal Waterway Reef	Average dredge costs inland waterways US	(US Army Corps of Engineers, 2018) published data

As the prototype progressed, it became evident that the data accuracy was limited for these projects because cost records were not stored or were not accessible. Enough cost data existed for constructing a reasonable prototype benefit-cost model for the existing reference reefs. Public projects were subject to agency oversight, so the contractual costs are accurate and updated during the cost of the project but not all the costs were borne by agencies. Legal contracts with attached engineering drawings did provide accurate location data.

Data retrieval required iterative public requests for information from agencies, and the private organizations involved searched non-public records to provide information for this prototype. The cost of constructing an initial database that is useful for a tool like the one proposed in this study will be significant, unless standardized data formats and portals allowing automated searches are provided by government agencies.

Sub-model development

The overall ROI model was broken into sub-models as shown in the flowchart in Figure 6. The focus for the prototype were the three distinctly different benefit models that focused on one of the dominant ecosystem services of each reef. The ModelBuilder™ tool within ArcGIS Pro™ program was used for all reef calculations with Python code augmenting where necessary.

For all three of the proposed reefs, the analysis started with a reference reef or reefs whose dominant relevant benefit matched the intent of the proposed reef. The reference reef data used to determine the proposed reef benefit was based on economic research and scientifically measured data. Costs were estimated in a similar manner.

Oyster harvest sub-model

The oyster harvest sub-model determines the estimated harvestable value of oysters in the proposed reef area based on density samples of oysters taken by divers in surrounding Galveston Bay reefs and a science-based suitability index model developed by Texas A&M Corpus Christi (Beseres Pollack et al. 2012; Reisinger and Beseres Pollack 2019). The density of the oysters predicted in the proposed reef uses a form of multivariate interpolation from scattered known samples in reference reefs. The available diver samples are an average of five quadrat samples across the restored reef (Appendix Table B.3). The quadrats were 0.25m x 0.25m. The samples were taken after the restored reefs had at least three seasons of growth allowing maturation to marketable size for the first larvae that attached to the river rock cultch.

The interpolation form chosen was the inverse distance weighting (IDW) method. The power of the inverse distance weighting was set between one and two. At a power of two, the algorithm heavily weights the closest points in the interpolation process and is known as inverse distance squared weighting. In addition to interpolating a predicted density based on samples, a

suitability index based on Pollack's data is applied as a risk factor after the potential marketable value of the oysters is calculated using the predicted density estimate. The suitability index was developed from environmental abiotic factors including salinity, dissolved oxygen, temperature, turbidity, and depth. The depth variable included constraints that favored certain depths for ease of reef restoration construction activities that allow low-cost use of barge transport of cultch material (Beseres Pollack et al. 2012). After including the suitability index as a risk factor, the final value of the marketable oysters present within the reef boundaries in one year is calculated. This example was developed to illustrate the both the usefulness of the tool and the limitations of the data.

The method for establishing the value of a marketable oysters on the bay bottom to the regional economy was to observe local pricing in February 2019 as this was being written and estimating the average oyster pricing through reasonable assumptions. The price that wholesalers pay dockside is proprietary competitive information for oyster sacks that are standardized to 110 pounds and contain 260 marketable oysters on average. In 2009 a study done by Texas A&M University calculated a dockside sack price of $21.00 (Haby et al. 2009). A report in the Victoria Advocate newspaper reports that oyster sacks in December 2014 were selling for $30 on dock (Sneath 2014 Dec 18). Texas Parks and Wildlife reports aggregate oyster landings and total dockside sack prices paid monthly in specific areas of the bays. For East Galveston Bay where the proposed reef is located, Table 4 shows some recent average prices.

Table 4 Average sack prices paid on dock by Texas wholesalers for 2014-2016

Year	Avg oyster sack price
2014	$34.07
2015	$32.30
2016	$37.72

The price of oysters does fluctuate particularly along the Texas coast where hurricanes like Ike and Harvey can devastate oyster beds. Not having access to the 2017 and 2018 sack prices, a reasonable assumption is a 2018 PPI adjustment (Appendix Table B.2) for these three

years and averaging which gives a sack price of $35.26 . With 260 oysters per sack, this translates to $0.154 per marketable oyster which is used in the model. The potential value of the reef is calculated using the harvestable oyster density, the reef area, the dockside price paid by wholesalers, all weighted by the oyster habitat suitability index which is used as a risk factor.

A simplified diagram of the model is shown in Figure 7 and the ModelBuilder™ version is shown in Appendix Figure A.1.
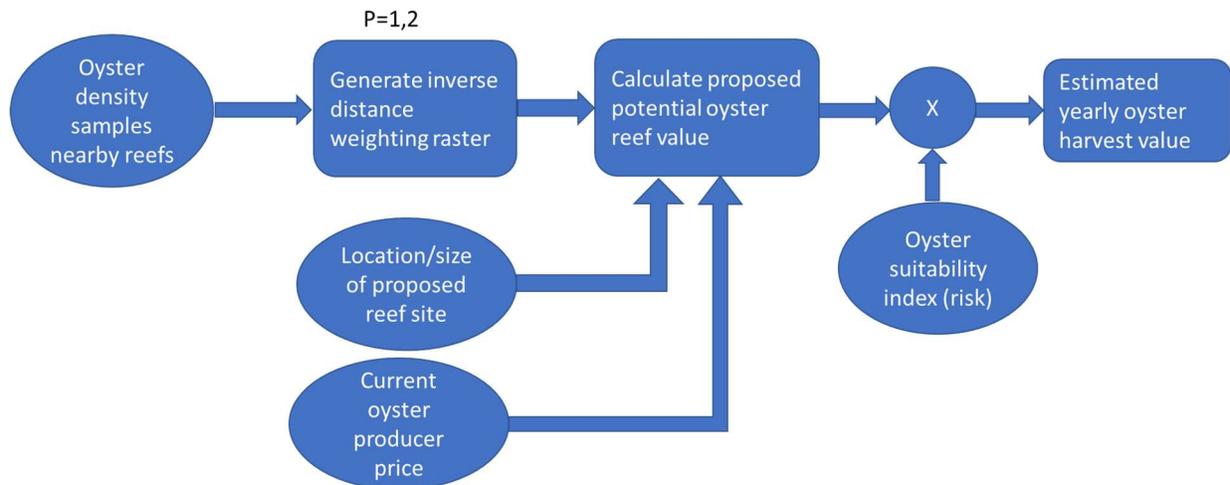
Figure 7 Oyster harvest benefit sub-model

Costs for reefs built in this manner can roughly be broken down into the cost of construction and the permitting fees. The construction costs are dominated by purchasing, transporting, and applying the cultch to the bay bottom. Low cost barge operation transport is used, and high-pressure water hoses are can be used for distributing the cultch across the reef area evenly. In East Bay, nearby reef costs varied between $19,956 and $23,152 per acre (PPI adjusted) after 2009, and permitting costs were about $30,000 (Bill Rodney, Texas Parks and Wildlife Dept, email communication dated 11/26/2018) as shown in Appendix Table B.1. An average cost of $22,086 per acre for the six reefs built after 2009 was used in the model. If costs vary considerably based on cultch-type and location (transport distance by truck and barge for example), then a more sophisticated cost model is justified. For the prototype, a high-low estimate is consistent with surrounding reefs built with river rock per Appendix Table B.1. The cost model is shown in Figure 8 and the ModelBuilder™ version is shown in Appendix Figure A.2.

Figure 8 Oyster harvest cost model for river rock cultch in East Bay
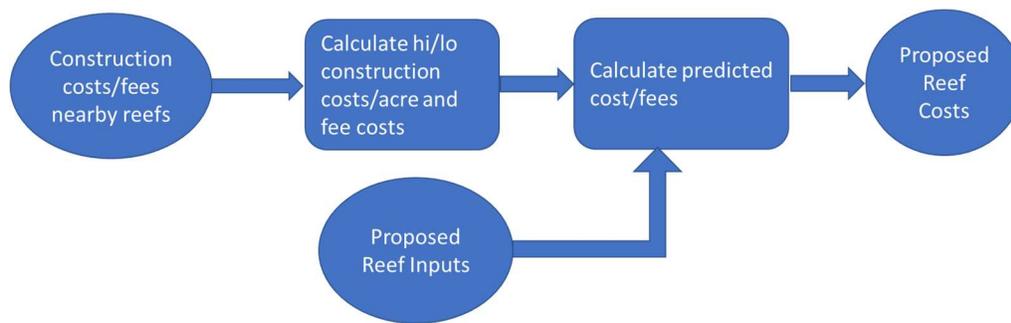
Soil erosion sub-model

Oyster reefs can be used to protect shorelines from eroding by attenuating wave action at some distance from shore or if the reef is situated on the shore itself, the reef can absorb the wave action and allow sediment accretion. One valuable service that oyster reefs might provide is erosion protection where frequent dredging is necessary. Dredging is an expensive operation and the lack of available locations for dredge spoil and environmental issues add to the costs. If the intervals between dredging can be increased by strategically placing oyster reefs, there may be a considerable direct savings benefit that offsets the cost of restoring reefs.

One area where oyster reefs may provide a quantifiable erosion prevention service is along the US intracoastal waterway (ICW), a protected navigable shipping channel through the coasts of the eastern seaboard and states that border the Gulf of Mexico. In many areas that serve as connections between larger navigable bodies of water, the Gulf Intracoastal Water Way (GIWW) is a narrow channel. Within Texas, the US Army Corps of Engineers (USACE) is tasked with maintaining the shipping channel dimensions at 12 feet deep and 125 feet wide (TX Dept. of Transportation 2018). The overall width of the body of water that includes a typical 3:1 slope may be 400 feet wide as shown in Figure 9. In the GIWW along the Texas coast, there are 150 one-way barge movements (TX Dept. of Transportation 2018: 4) each day. The wave action generated by the barge traffic erodes the shoreline of the channel. In Texas from 1998 until 2012, an average of 6.2 million cubic yards of silt was dredged from the GIWW channel each year (TX Dept. of Transportation 2018: 8).
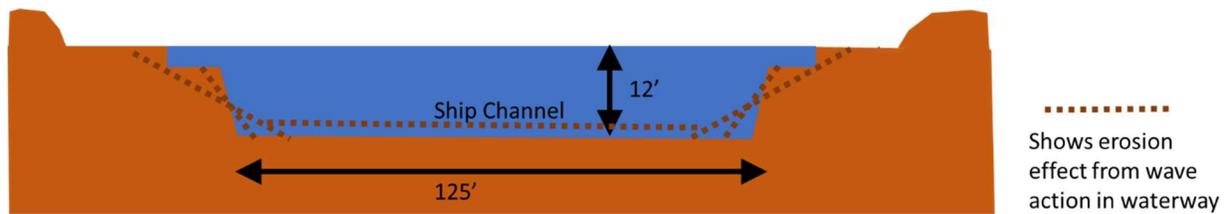
Figure 9 Gulf Intracoastal Water Way (GIWW) diagram showing required depth, width, and silting effects

The sediment that is eroded from the shoreline enters the water and eventually deposits in the channel. Over time, the continuous silting requires maintenance dredging to maintain the required depth. A study by the US Army Corps of Engineers (Townsend et al. 2014) using hydrologic modeling and measured data showed that most of the silt in the narrow channels of the GIWW was due to shoreline erosion. This study revealed that between 1995 and 2012, parts of the shoreline of the GIWW in the West Galveston Bay study area receded between 4-8 feet. Using numerical modeling, the researchers found that the 60-90% of the silt deposited in the channel was due to shoreline erosion in the narrow channel areas (Townsend et al. 2014). The rate of the silting or shoaling determines the time period between maintenance dredge intervals, and the average cost of dredging can be derived from dredge records kept by the USACE for the GIWW (USACE Navigation Data Center 2018). For US coastal and inland waterways, the US ACE accounts the expense for dredging as $5.89/cu. yd in 2017 averaged across 230 million cubic yards of silt removed. The silting rate can be indirectly measured by the dredging interval along the GIWW in structurally similar areas (narrow channels) with similar shoreline soils.

In the benefit model where shoreline erosion might be the dominant ecosystem service, one method to establish value is in the cost savings of increased dredge intervals if both shorelines of a narrow channel are lined with oyster reefs. Models (Townsend et al. 2014) show that oyster reefs in the form of ReefBlock[TM] or OysterCastle[R] perform as well as concrete revetments if the shores are lined. Since the cost savings will be in the future, a net present value calculation can be used to determine if a stakeholder (in this case the federal government) is better off dredging at a shorter interval without the oyster reef or by investing in the creation of shoreline protection using oyster reefs and dredging less frequently. A Python script was developed that calculates the dredge interval as well as a net present value multiplier that results from multiple dredge occurrences in a given interval (Appendix Figure). Including a 7% discount rate in the analysis allows the federal government to determine if the money might be

put to better use elsewhere. In the ideal model, the suitability index as described in the oyster harvest model could be utilized as a risk factor in a similar manner. The index factor concept could be extended to the intracoastal waterway, but this data is not yet published. A top-level view of the erosion control model is shown in Figure 10.
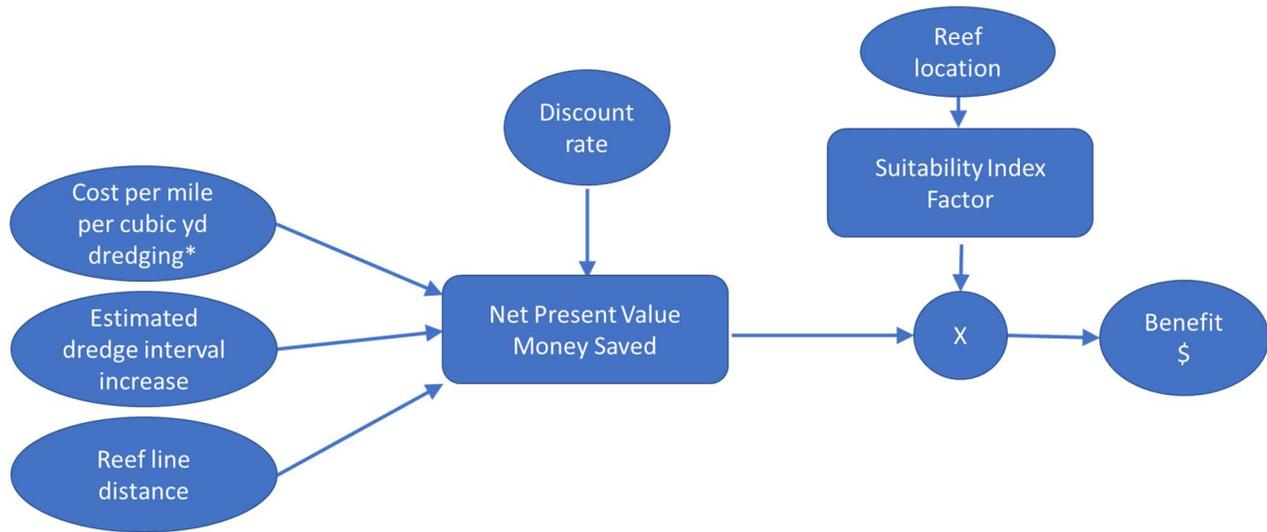
Figure 10 Erosion control benefit model for restored oyster reef

The cost model for a shoreline protection reef in an intertidal zone is like the submerged reef cost model shown in the oyster harvest benefit model. However, the shoreline construction costs are measured in linear feet. The constructs that are placed to anchor the reef are interlocking blocks of material sold on a per foot basis. ReefBlock™ or OysterCastle® are estimated (Townsend et al. 2014) in the $350 per foot range. Permitting costs were estimated at $30,000 per reef project.

Recreational angling sub-model

The area studied for the recreational angling model is between 5-10 miles southwest of the Mad Island reef in Matagorda Bay proper. In this area The Nature Conservancy spearheaded an oyster reef restoration in a 86-acre surface lease approved by the State of Texas (State of Texas General Land Office 2012). The final 54-acre restored oyster reef known as Half Moon Reef has extensive records for construction, costs, and benefits study and it serves as the reference reef for the angling model. The study was performed by a collaboration between Texas

Sea Grant and Texas A&M and quantified the benefit of the oyster reef for the local recreational angling business (Carlton et al. 2016). The study focused on the statewide economic impact using both revealed and stated preference techniques. The expense of such a study includes in-depth surveys and analyses that will not be possible for individual project. However, once a single study like this is complete, further analysis with a GIS-based tool enables predictive models for nearby projects that have a higher initial accuracy and by continual improvement processes will increase in accuracy over time. Half Moon Reef was located strategically in Matagorda Bay, a bay that had healthy historical habitat for oysters. Further, care was taken in placing this reef in an area where even at low tide, there was enough freeboard for fishing vessels to pass directly over the reef (M. Dumesnil, The Nature Conservancy, personal communication, 8/8/2018). A recreational fishing industry was well-developed in Matagorda Bay where speckled sea trout, redfish, and flounder are common sport species. There are three large marinas with boating channels are in the cities of Port O'Connor, Port Lavaca, and Palacios. Figure 11 shows Half Moon Reef, the location of the marinas, and the location of a proposed reef for illustrating the use of the decision tool.

Figure 11 Location of Half Moon Reef, three surrounding cities with large marinas, and a proposed reef

The basis for the recreational angling model is the Sea Grant/Texas A&M socioeconomic research where angler awareness, use of the reef, motivation and demographics, and economic

impact were studied and reported (Carlton et al. 2016). Some main points from the economic impact study can be condensed in Table 5.

Table 5 Results of economic impact study on Half Moon Reef (reference reef)

Economic impact category	Value in US$
Labor income, 12 new jobs created	$465,000
Value-added	$691,000
Output	$1,273,000

Given a restored reference reef like Half Moon Reef that has been subjected to extensive socio-economic analysis, a model based on the results of that analysis can be constructed for proposed reefs in Matagorda Bay. The most important variable for a proposed reef for recreational angling is location, and there are two variables that may be most critical for establishing a location's value – the suitability of the reef location for oyster reef health, and the distance of the reef from accessible boat docks. In Matagorda Bay, hiring guides and charters for sport fishing is an important component of the small coastal towns like Palacios, Port O'Connor, and Port Lavaca and recreational fishing on Matagorda Bay in 2016 provided an estimated at 432 jobs, $15.3 million in labor income, and a $23.7 million contribution to the Texas GDP (Carlton et al. 2016; Ropicki et al. 2016).

The recreational model uses the economic impact of the reference reef as a baseline and looks at a weighting for distance anglers must travel from major marinas and another weighting for the oyster suitability index that is a measure of predicted health for the reef (Beseres Pollack et al. 2012). The model establishes two parallel calculation paths given the location of a reference reef and the proposed reef. The parallel paths calculate a cost/distance weighting and the oyster suitability index for both reefs. These weightings are then ratioed and applied as a factor to the socio-economic valuation established for the reference reef. This determines the recreational angling benefit for the proposed reef. The top-level model is shown in Figure 12 and the ModelBuilder™ version is shown in Appendix Figure A.3.

As an example of how the model can help with decision-making, a proposed reef was deliberately located in the northwest portion of the bay in Figure 11. This is an area where the suitability index is potentially higher providing a more optimal habitat (Figure 13) but the distance to the reef from the three main marinas is longer. A stakeholder may ask if it is reasonable to assume that the economic impact will be less or greater than the reference reef. This model addresses only the distance and environmental effects. For this location, another variable is the angler decision to stop at Half Moon Reef without heading to the proposed reef location. A more sophisticated model would add factors that estimate added value vs. replacement value which could be based on angler surveys. Charter fishing captains may also communicate during the day with other charters on fishing activity that could add or subtract from the benefit. This social dynamic could be modeled with further surveys of charter captains.
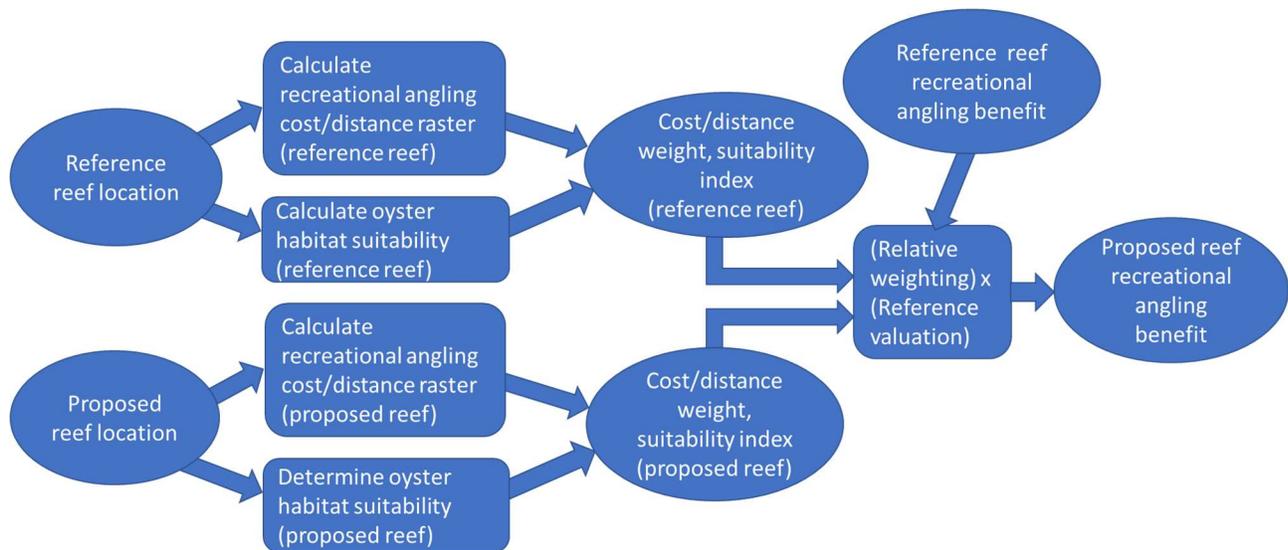
Figure 12 Recreational angling oyster reef restoration benefit model
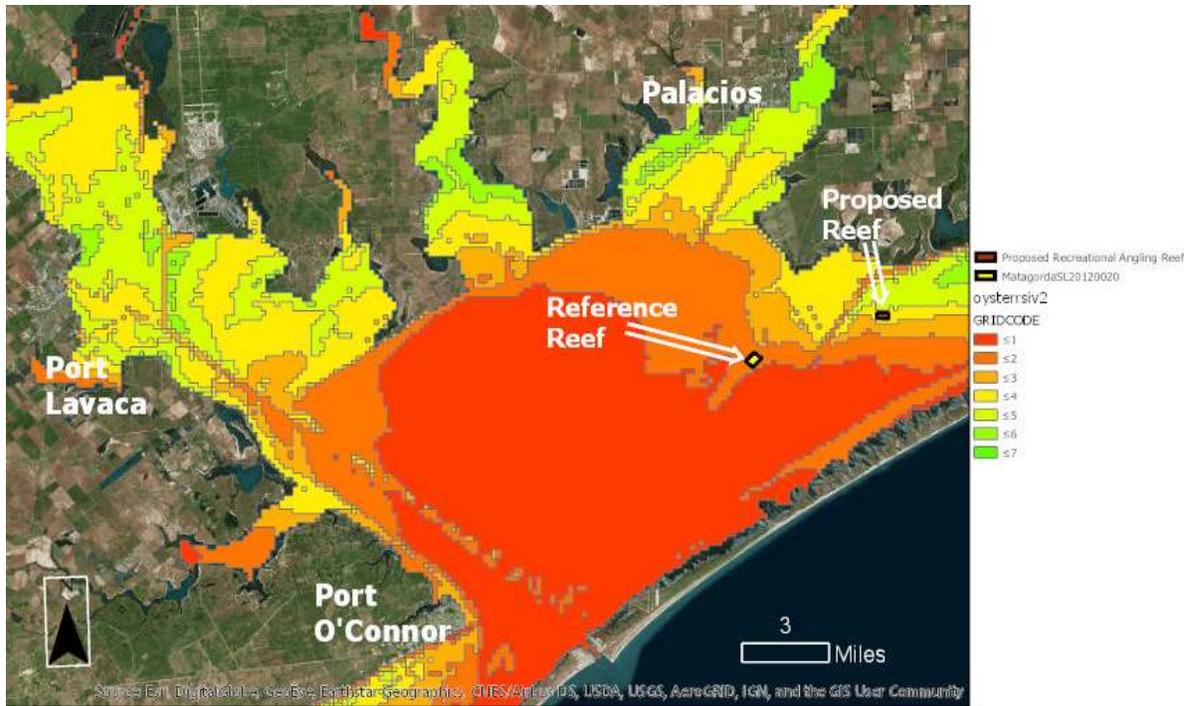
Figure 13 Suitability index for Matagorda Bay showing location of reference and proposed reefs

Separate from the suitability index raster, a cost/distance raster is developed from the bathymetry data in Matagorda Bay. This bay is shallow in some areas particularly near the main Port Lavaca and Palacios marinas where boat channels are dredged to allow greater freeboard. Over portions of the main bay, outboard motor vessels (the most common type on Matagorda Bay) can run full speed, but in more shallow areas, the vessel operators may decrease speeds for safety. A rate raster was developed from the bathymetry raster and the assumptions for speed vs. depth are shown in Table 6.

Table 6 Depth vs speed assumptions for an outboard on Matagorda Bay

Max depth (ft)	Min depth (ft)	Boat speed (mph)	Time (sec) to traverse pixels (center to center)
40	6	25	3
6	2.5	10	7
2.5	1.8	5	13
<1.8	X	X	100

The bathymetry raster is reclassified using this speed vs. depth table and shown in Figure 14. From this raster, the lowest cost/distance path can be chosen. Each pixel in the bathymetry

raster from the NOAA coastal information (NOAA 2018) is 30m x 30m. The time it takes to traverse one pixel measured in seconds is the "cost" for traversing the pixel. A least cost path can be generated in the GIS tool from each marina to the destination reef. The calculation of the benefit value for the proposed reef is based on the reference reef economic impact study, the weighting factor which is the ratio of the cost/distances of the proposed and reference reef, and the suitability index which is applied as a risk factor.
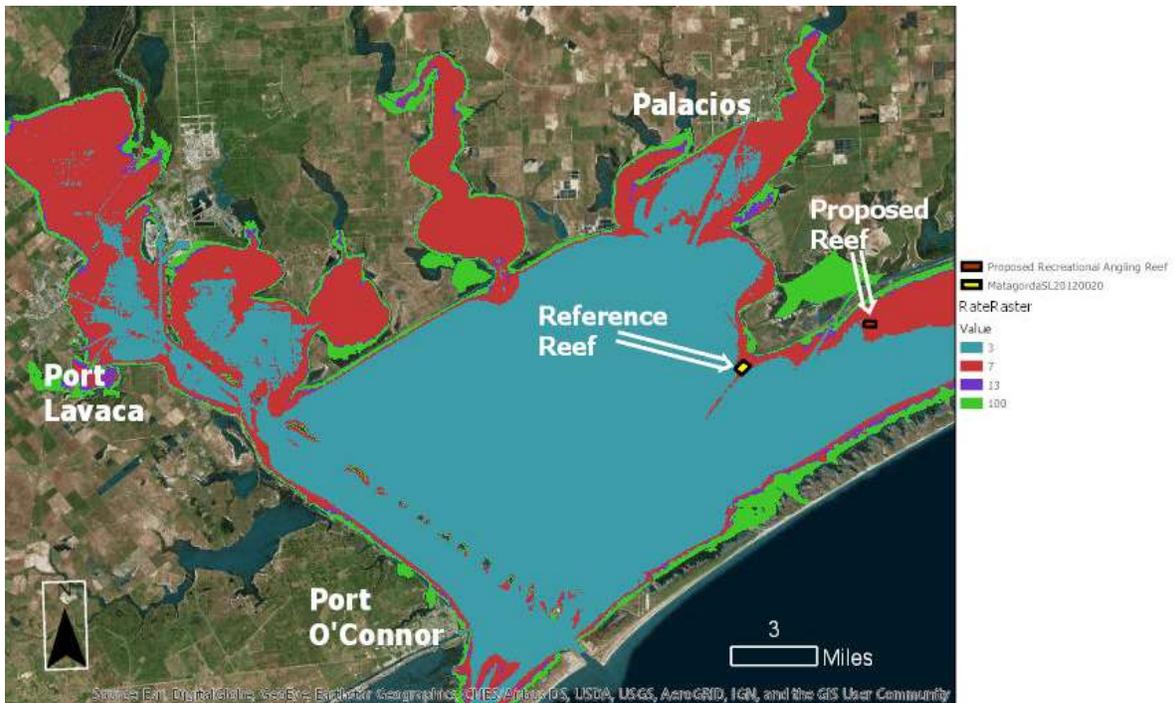
Figure 14 Rate raster used in cost/distance model

The cost model used is the same as described for the Galveston Bay for the oyster harvest model. The construction of a reef as described in the study area section of this report is rows of mounded cultch that form a diverse habitat attracting game fish. The construction method is more expensive and uses more material compared to distributed river rock in the Galveston reefs and varies between $90,500 to $133,000 per acre in 2014 dollars (Laine 2013). Permitting is the same, and engineering costs are estimated at 10% of the construction cost.

Results

Oyster Harvest Model

Using the oyster harvest model, choosing the location of a proposed reef might be viewed as an optimization of the predicted oyster density and the suitability index for the maximum harvest potential. The first step in the model is calculating the predicted oyster density. The location of a proposed 58-acre reef (brown rectangle) along with the surrounding restored reefs is shown in Figure 15.

In order to predict the oyster densities on the proposed reef, a predicted density raster is developed with an inverse distance weighting of the samples, a form of multivariate interpolation. The assigned weighting of the samples can be varied. Two weightings were assumed with respect to the distance from the sample, a ($1/d$) roll-off also known as a power=1 where "d" is the distance from the sample, and a ($1/d^2$) known as a power=2 roll-off. With higher power roll-off, the samples affect only close-by surrounding area. The difference in the density raster between roll-offs is illustrated in Figure 15 which shows the p=1 and p=2 roll-offs.
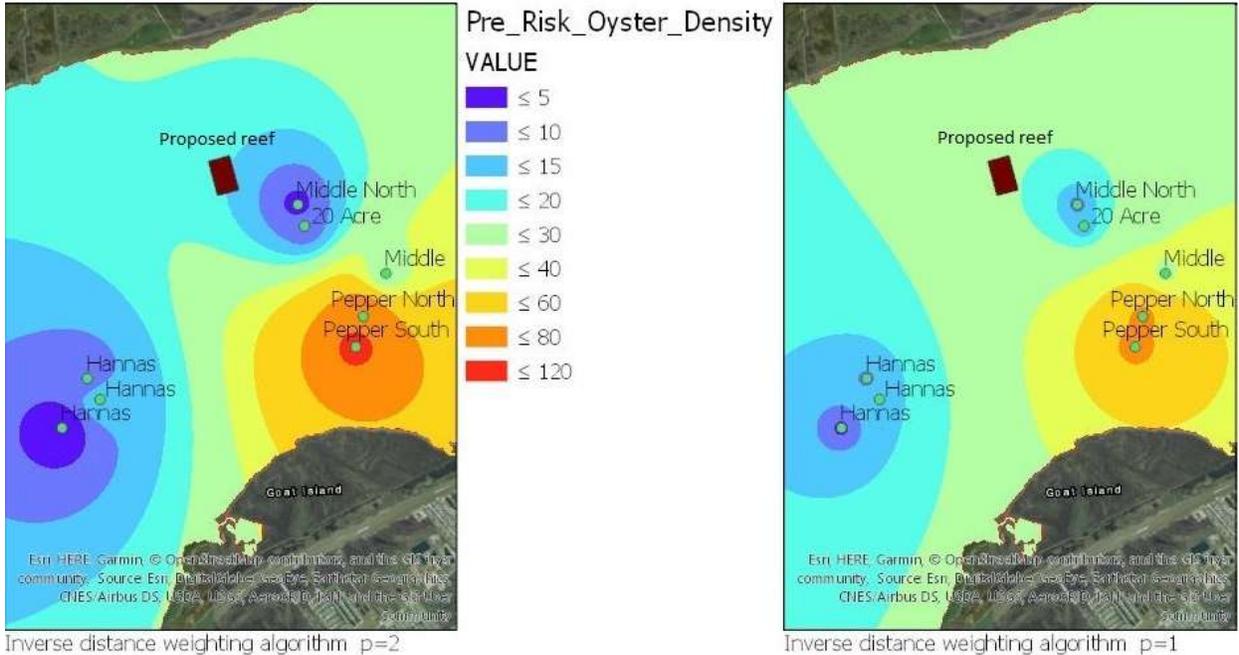
Figure 15 Predicted oyster density (# oysters/sq. m.) raster with p=2, and p=1 in the inverse distance weighting algorithm.

The predicted density within the proposed reef boundary is calculated using zonal statistics on the overlay of the marketable oyster density raster which provides a mean value. If it is determined that a more accurate interpolation method or roll-off is required, additional sampling and data analysis may be necessary.

A suitability index feature class (Figure 16) of the area around the proposed reef is divided into 7 classifications which are the weightings developed using salinity, dissolved oxygen, temperature, turbidity, and depth (Beseres Pollack et al. 2012; Reisinger and Beseres Pollack 2019). These classifications represent the probability that a reef will successfully grow in that location. In the Figure 16 color scheme, the green regions represent the best oyster habitat coupled with reasonable reef construction costs because of depth. Note that where the high marketable oyster densities were sampled in Figure 15, the oyster suitability region in Figure 16 is highest.

Figure 16 Oyster suitability index in East Galveston Bay

The suitability index factor for the proposed reef is derived by overlaying the proposed reef boundary with the Galveston Bay suitability raster, and determining the area mean using the Intersect tool in ArcGIS Pro™. This results in a number between 1 and 7, and then dividing by 7 provides the multiplying risk factor. Over time as the suitability index is proven as an accurate predictor, the sampling and risk weightings could be varied so that the dominant effect on value is the suitability index.

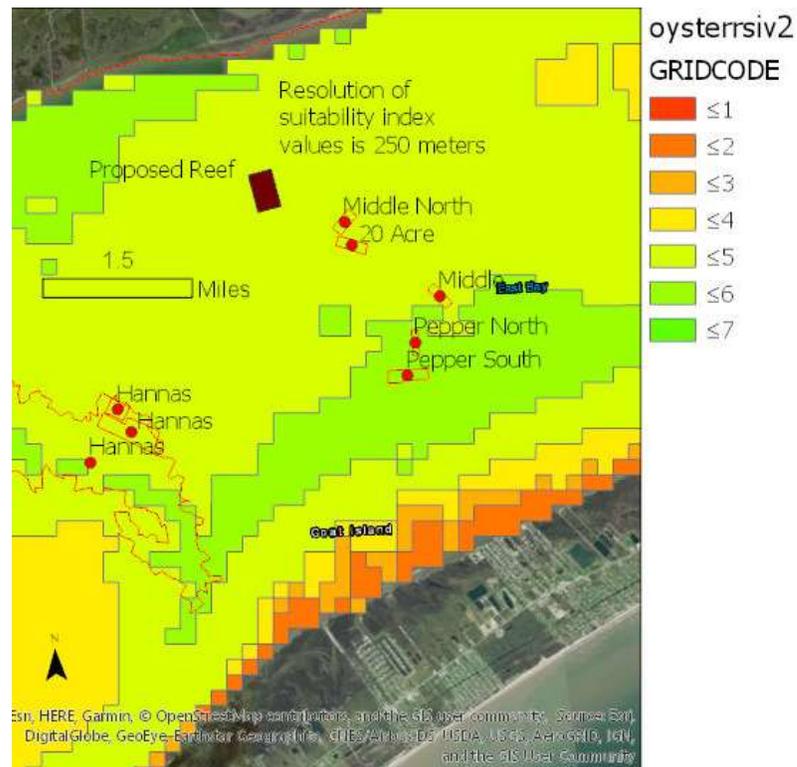The potential value for the reef is calculated using the predicted oyster density, the reef area, the dockside price paid for oysters by wholesalers and the suitability index risk factor. The result is the predicted yearly harvest value. Using this method, the calculated yearly harvestable oyster value for the proposed oyster reef location shown in Figure 15 and Figure 16 is listed in Table 7.

Investigation of the high density of oysters in the two Pepper reefs (Figure 15) revealed that the Texas Parks and Wildlife Department did not yet authorize dredging on the reefs after the restoration (Bill Rodney, Texas Parks and Wildlife Dept, personal communication 02/11/2019) . The other reefs in the study were all periodically dredged based on the algorithms that Texas Parks and Wildlife Department uses to open reefs for harvesting.

Table 7 Predicted NPV valuation of proposed East Bay oyster reef using p=1,2 in model

P value	Predicted mean density (oysters/sq. meter)	Harvest value /yr.	NPV benefit	NPV (benefit – cost)
1	20.9	$50,700	$311,000	-$982,000
2	15.4	$37,662	$196,000	-$1,097,000

The assumption in Table 7 is that the proposed reef area is 58 acres. The oyster harvest cost model includes the construction cost per acre and the permitting fees required. For this type of reef constructed of a flat layer of river rock, the estimated cost is $1,293,000. Assuming a 10-year investment focus, with a 7% discount rate, the oyster harvest benefit NPV shown in Table 7 with values of P in the cost-distance model set to 1 or 2. From an investment perspective, the total NPV (benefit – cost) is negative $1.1 million.

Soil erosion model

The location of the proposed soil erosion reef is around a pair of restored reefs used as reference near the Mad Island Preserve through which the GIWW passes. The proposed reefs are located on either side of the intracoastal waterway channel (Figure 17).
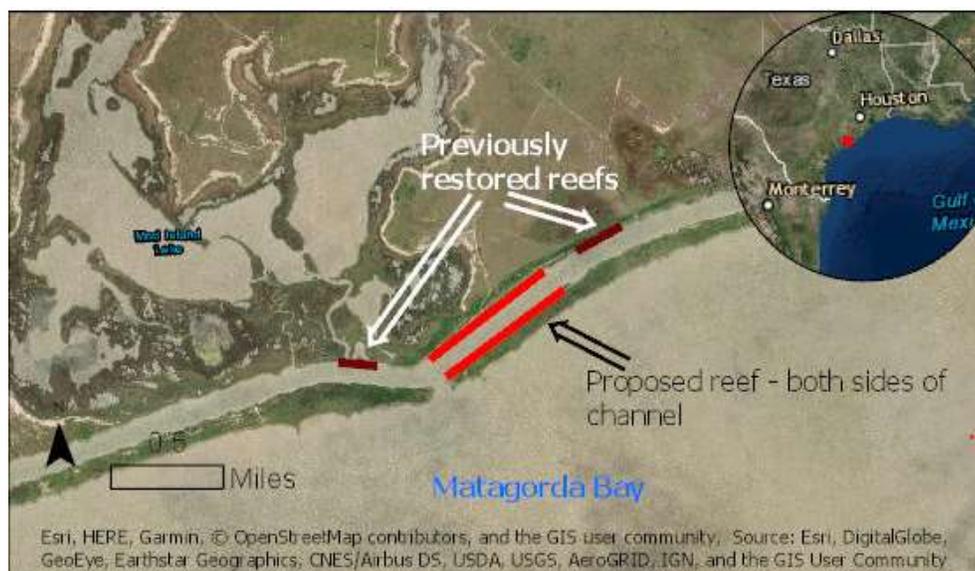
Figure 17 Location of proposed Intracoastal Waterway soil erosion prevention reef

For the model, shoaling rates were estimated based on the US ACE study in West Galveston Bay that measured rates of silt accumulation in cubic yards per year per within 5000 foot increments (cu.yds/yr./5000ft) (Townsend et al. 2014: 21–22). In this study the US ACE calculated an average value of 15,100 cu. yds/yr./5000ft. This is the shoaling rate that was used in the model for the proposed reef near Mad Island.

From the channel diagram in Figure 9 and assuming that the channel is a rectangle with bottom side equal to 125 feet and the side height equal to 12 feet, the average silt rate would be the equivalent of 0.22 ft of silt buildup per year per mile. The max silt rate measured in the US ACE study translates to 0.31 ft/yr./mi. If the US ACE will dredge when the average silt accumulation exceeds 1 foot, the model predicts the NPV of the dredge costs with and without the oyster reef. The benefit is the cost savings in the difference between the NPV calculations with and without the oyster reef protection and is shown for the average silt rate and the

maximum silt rates. A silt reduction factor is the reduced speed of silting/shoaling caused by the presence of the shoreline oyster reef which is holding the sediment. Per the (Townsend et al. 2014) study, a 60-80% reduction is the expected average silt rate reduction factor.

Using the Python script in Appendix Figure A.4, a high and low silt rate was assumed based on the maximum and minimum rates measured by the US ACE on the nearby channel. When the silt rate reduction factor is varied, the difference in the dredge interval with and without the proposed reef can be calculated by the script. This translates to an NPV savings that is plotted in Figure 18.
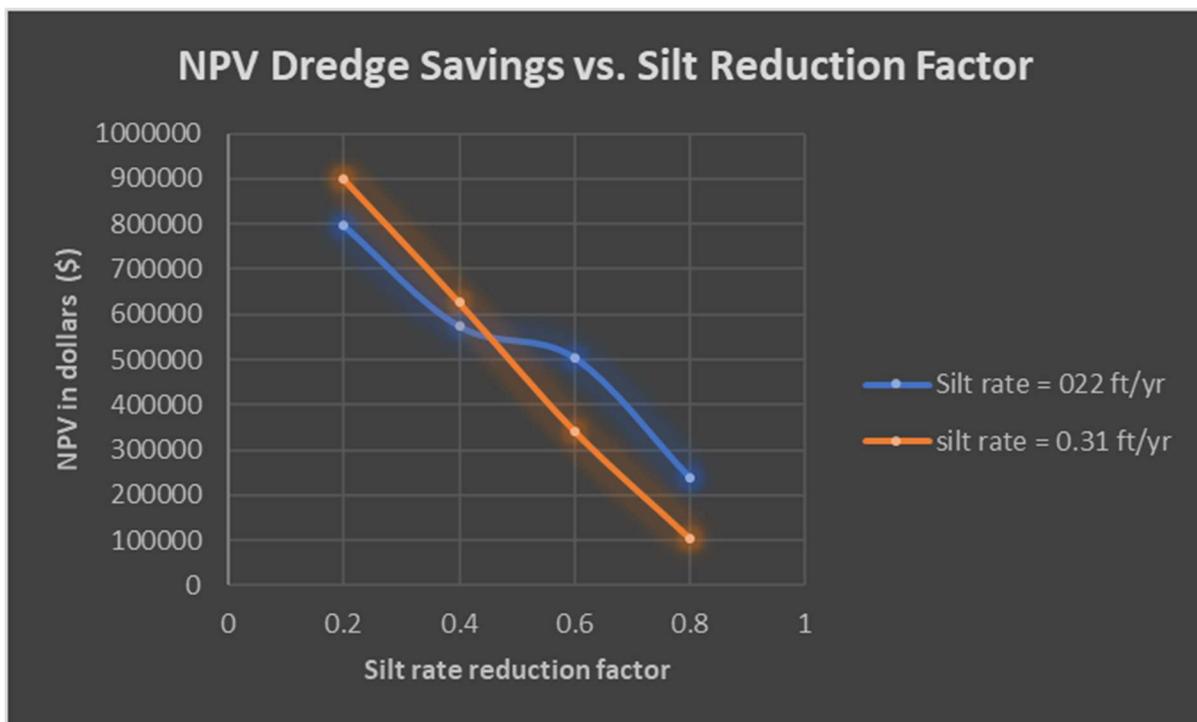
Figure 18 NPV dredge savings from shoreline oyster reef with two different silt rates assumed in the GIWW channel

The cost model for assumes $350/ (linear ft) construction costs. Included in the cost is a 10% adder on construction costs as an estimated engineering fee and $17,500 in permit fees. The construction costs including the permitting and engineering planning fees are based on discussion with The Nature Conservancy project manager (M. Dumesnil, The Nature Conservancy, personal communication, 8/8/2018). The engineering fees are negotiable, and the permit fees vary over the years. The reference reef in this case was constructed in 2007 and was a prototype. There were no engineering fees at that time.

Table 8 NPV calculations with varied silt rate and reduction factors (10 yrs.)

	60%	80%
Silting reduction factor	60%	80%
Silt rate = 0.31 ft/yr., benefit NPV ($)	626,101	899,646
(benefit-cost) NPV ($)	-1,853,899	-1,580,354
Silt rate = 0.22 ft/yr., benefit NPV ($)	573,190	796,483
(benefit-cost) NPV ($)	-1,906,810	-1,683,517

Using these assumptions from the reference reefs, the total cost of construction with fees for the proposed reef is $2,479,771 for a 6,400 linear foot (total includes both sides of channel). The result is a net negative NPV calculated over a ten year time frame that varies from -$1.7 million to -$1.9 million depending on silt rate and the silt reduction factor provided by the reef (Table 8).

Recreational angling model

The two critical components in the recreational angling model are a weighting calculation for the cost/distance and determination of the oyster suitability index. The cost distance algorithm using the reclassified boat speed rate raster in an input to the Cost Distance tool in ModelBuilder™ which provides an output raster for the entire bay where each pixel has a cost associated with it. This associated cost is the least cost distance from the pixel to a defined destination. The defined destinations are the reference reef and the proposed reef. For the proposed reef, the least cost distance from each marina is shown in Figure 19. This same process is repeated for the reference reef and the weighting is the ratio of cost/distances. The ratio of the (proposed reef)/ (reference reef) is 1.3 for the proposed location.
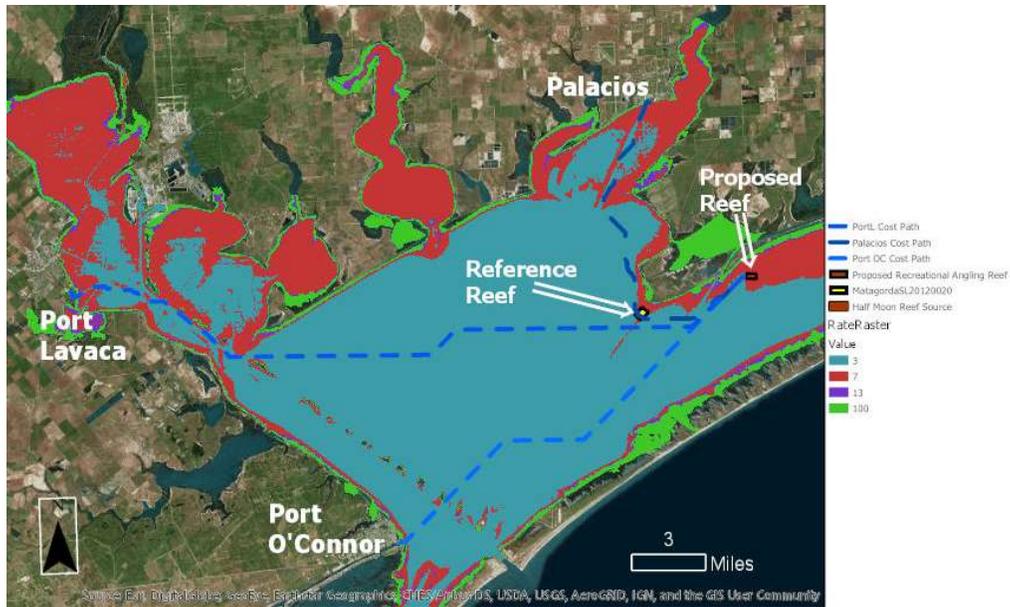
Figure 19 Least cost distance from Matagorda marinas to the proposed reef

Similarly, the oyster suitability index is a weighting in the value calculation and the feature class is shown in Figure 13. The proposed reef is overlaid on this feature class and the average suitability calculated. The overlay result shows that the suitability index for the reference reef is 2 and for the proposed reef is 4. Note that Half Moon Reef, the reference reef, was located where there is freeboard margin for vessels and that depth may result in a slightly lower suitability index. The proposed reef is slightly shallower at mean low tide. The total economic impact may be calculated as the reference reef economic impact multiplied by the sustainability index and cost distance factor. For the model the economic impact is ($1,273,000) * (1/1.3) *4/7 = $560,000 per year where the cost distance increase results in a 30% reduction in the potential value of the reef. The suitability factor is a probability multiplier that the reef becomes established.

The cost of the proposed 57-acre reef is between $5.65 million and $8.2 million depending on cultch material. The highest cost was based on the construction of a 12-acre addition to Half Moon Reef by the US Army Corps of Engineers using stockpiled concrete instead of the limestone cultch used in the original 42-acre reef. The aggregate of the 42-acre and 12-acre construction costs for the "reference reefs" was $5.4 million (Carlton et al. 2016). The net NPV for the reference reef is positive $2,100,000 based on the Carlton et al. economic impact study.

The benefit-cost NPV for the proposed reef using the model with the lower cost estimate is -$2.73 Million which is much less than the economic impact of the reference reef because of the increased distance to the reef and the risk that the reef will grow at the proposed site (Table 9).

Table 9 NPV calculation result for proposed recreational angling reef

Construction cost/acre	Reef total cost	NPV benefit	Benefit-cost
$90,500	$5,650,000	$2,920,000	-$2,730,000

Discussion

Obtaining the data for the models required contact with many organizations including research institutes, government agencies, engineering companies, and conservancies. Many stakeholders became joint funding sources, each with different methods for storing project data, and different motivations for participation that result in certain information being stored while discarding the rest. For example, an environmental non-profit organization may have exact 5-year old cost data showing the funds that the organization provided on a project, but does not store the local, state, or federal funding amounts. The project manager in a non-profit may remember what the matching ratio of public vs. private funding but it is not included in the data stored. Fortunately for this pilot study, the oyster reef restorations are large enough projects so that at least one individual in each organization had access to data, and it generally took a few phone calls to retrieve most of it. One large cost that is not tracked in the model is the hours that the private and public entity workers spent on the project as part of their general working day. This is a significant cost because it may be 10 years between the start of planning and the start of a reef construction. The permitting process can require input from many stakeholders. This project concentrated on the costs that could be retrieved with either a written or verbal record.

One of the cost drivers that could be added for a more accurate model going forward is project schedule. The accuracy of the estimates for the chosen projects was limited since most organizations did not keep written records of the permitting schedule, the delays prior to the start of construction, or the delays during construction. The time value of money was included in the

models, but the assumption was that there were no delays once the construction process started. For accurate ROI calculations, discounting is critical, and delays need to be recorded.

Each of the three models contains limitations and can be modified to provide more accurate results with additional research. Coastal restoration decision makers and local municipalities may be interested if an analysis with this tool if it offers some insight into the return that taxpayers, impact investors, or conservationists might receive on an investment. If the model accuracy is proven, a quantitative response could be given for example, when a local government official asks, "Does the return from oyster harvest alone as an ecosystem service justify the investment?"

Oyster reef harvest model

For the datasets that exist, there is not yet a high confidence in accuracy in the modeled ROI because of uncertain oyster densities. The oyster harvest model uses a constant oyster harvest for 10 years. The reference reefs (Pepper Reefs) in Galveston Bay south-east of the proposed reef location had high densities of marketable oysters Figure 15 because they were not yet opened to harvest by Texas Parks and Wildlife. The evidence from the Pepper reefs shows that these early densities prior to harvest may be more than 4x higher than the long-term density predicted by the inverse distance weighting algorithm. The long-term density for the proposed reef predicted by the model is affected by the Pepper reef densities. Regularly harvested reefs had lower densities, so a more accurate and complex model would yield large initial harvests which helps net-present-value. The rate of harvest will have a large effect on the ROI.

The density data in this study came from research divers who physically counted and measured oysters using a quadrat method in Galveston Bay. The state of Texas uses a separate process of sample dredging to determine which reefs to open for harvest. The sample dredges do not provide an accurate measure of absolute density and to date, correlating the dredge samples to diver samples was not successful (E. Clarkson, TPWD, personal communications, 12/18/2018). The manual count by divers is a more accurate record of density, but the cost of accurate monitoring is high. Perhaps new monitoring technologies using lower cost underwater autonomous vehicles (UAVs) may soon offer automated methods of observing densities.

A second potential area of inaccuracy in this model is the depth information contained in the Pollack suitability index model (Beseres Pollack et al. 2012). The prototype cost-benefit model assumes that the suitability index was a pure habitat suitability index. The depth

weighting in the Pollack suitability index favors depths between 1-2 meters because of the ease of using barges to construct oyster reefs at that depth. This is not a pure habitat suitability index. This did not affect the results of the example in this study because the depths of the reference and proposed reef were in the same depth classification. Because of this relationship, the suitability index includes an element of construction risk that needs to be considered if a benefit-cost model that includes construction risk is developed for general usage and will affect results in deeper regions of the bay. It may be advisable to remove the ease of construction from the suitability index and add a weighting to the cost model that depends on depth.

If low-cost accurate sample density measurements can be made, the state might use the model as a way of deciding when and where to restore a reef, and how long to leave reefs unharvested to rejuvenate and maximize the return. For example, allowing some reefs to accumulate oysters well beyond a 2-3-year maturity increases fecundity. Strategically placing "restored nursery reefs" might result in larger overall oyster population and harvests (M. Dumesnil, The Nature Conservancy, personal communication, 8/8/2018). The quantitative measure of reef value could be used to drive management methods and research into areas that result in more sustainable oyster harvests, or in even lower cost methods of restoring reefs.

Once the accuracy of the model is improved, the effect of the restored reef on recreational angling (still likely a secondary value compared to harvest for this construction) can be investigated as well as any of the other services that might be desired by the community in determination of the relevant ROI. Analyses like these will help drive creative efforts at lowering cultch construction costs even further until a positive ROI is achieved.

Soil erosion model

Similarly, although the results of the erosion model show that investing in oyster reefs may not have a positive NPV, the model is incomplete. The federal government might view the reefs as cost effective if the models include the costs associated with preparation of dredge material placement areas. Available locations for deposition are sparse, and environmental impact concerns add cost and may result in a positive NPV. Instead of concluding that it is lower cost to continue periodic drilling, the federal government might decide that using oyster reefs to reduce silting in the GIWW is a good investment.

If reducing silting is a good investment, one alternative to a living shoreline (oysters) for the US ACE is concrete revetments but these are higher cost at $400/ft (Townsend et al. 2014:

28). Oyster reefs, where they can thrive, are not only a lower-cost alternative to concrete revetments; they have two advantages over hardened structures. Oyster reefs are self-healing so if there is storm damage or ship damage, the reef will repair itself in most cases. Since the reefs are living and constantly replenishing, these natural shorelines will accommodate sea level rise due to climate change. Adding this benefit to a long-term model, particularly the ease of maintenance, will also make the NPV more positive.

In the area where the proposed reef is located, near the Mad Island Preserve, the shoreline recession was the main reason for constructing the existing reefs (M. Dumesnil, The Nature Conservancy, personal communication 8/8/2018) 2009. These reefs are shown to have accreted considerable sediment on the main shore which stabilized the banks and added nearly 20 feet of shoreline to the Preserve land. For the proposed project, a value could be calculated for a 20 ft x 3200 ft strip of land which is 1.5 acres. The current land prices in the area range from $1,000 for "unimproved marsh with no public roads" to $27,000 per acre for larger tracts >50 acres still in the floodplain and accessible by road (Lands of Texas 2019) so this does not meaningfully change the NPV dredge calculation.

This example shows how the tool can set priorities using NPV as a measure of impact. The result informs decision-makers given multiple scenarios and does not obviate the decision by private funders to contribute toward restoration of an area when the NPV from the major ecosystem services is negative. It's possible that in a negotiation, the stakeholders may use the NPV results to set priorities or determine aggregate and funding levels committed by each entity. For example, the US ACE might be willing to raise the priority of oyster reef installation if a conservancy raised a fraction of the funding. The conservancy also perhaps raises the priority because the impact of the erosion protection reef is now commensurate with the reduced level of investment that they are willing to provide. The tool provides both parties with a way to negotiate the funding amounts.

Recreational angling model

The proposed recreational angling reef has a negative NPV because the location significantly increased the cost-distance compared to the reference reef. The planners may decide that a better placement might be in the favorable sustainability index regions between Port Lavaca and Port O'Connor where the overall cost-distance is reduced.

As noted, this model needs to account for the decision process of charter fishing captains who now face the decision of where to start a half day or full day of fishing. It might be an incorrect conclusion to assume that placing another reef in this area will reduce the economic impact of the original Half Moon Reef. For example, communication between charters on any given day may show that game fish are more prevalent on one reef than the other depending on wind, temperature, current, or tide. Given the two choices and combined success rate, the aggregate number of fish being taken from both reefs may be increased by the charter communications. This might then stimulate overall increased economic impact from recreational angling. These types of social dynamics could be added to the model. As data becomes available on fishing behavior, the model can be refined to account for additional reefs in any bay with multiple boat ramps.

Conclusion

The comprehensive modeling tools that synthesize a return on investment give decision-makers a quantitative view of costs and impacts. When the decision-makers who necessarily view projects from a funding/impact perspective have quantitative rather than qualitative data, specific goals can be articulated, and actions such as driving research into more cost-effective restoration solutions will have specific targets.

The socio-economic modeling of complex environmental systems will result in better accuracy in the long-term, however this study illustrates the holes that exist in the data, the difficulty in accessing relevant data, the behavioral uncertainty when humans interact with the environment, and the ongoing scientific research. Using this type of model may result in large error bars initially, and the models may be most useful as indicators of trends. However as consistent results from environmental projects are collected, the geospatial and temporal predictions will increase in accuracy. Other disciplines such as finance have done much work on socio-economic models based on statistical mechanics where random processes are acted on by forces (Richmond and Sabatelli 2004). The usefulness of these more sophisticated behavioral models with accuracy improved over many years may have overlap that requires less investment when applied to human behavior in the environmental space. Searching for these cost-effective overlaps and parallelism can be the subject of socio-economic research. One such boundary-spanning realization occurred when the financial world recognized how of statistical mechanics could be applied to markets. Because the the economic return on investment was large,

investment in these models by financial houses was judged wise. The environmental community can benefit from the trajectory on the learning curve for boundary-spanning models and perhaps apply them with much less financial and time investment.

Environmental data storage and accessibility issues will likely improve with time. Stakeholders in environmental decision-making can mandate higher quality data curation where economic data is tightly coupled to scientific data contextually. This will enable more accurate and automated search algorithms. The process of manual requests for information from state and federal sources in this study required correspondence with "public requests for information" iterations measured in weeks. This process could also be automated. Significant efforts are being made at the federal level to automate Freedom of Information Act (FOIA) records and is being replicated at the state and local levels (Dillow 2016). Automated access to contextualized data is critical for these predictive tools to become ubiquitous. Data portals at the federal, state, and local levels, along with user-friendly application interfaces will drive usage by non-tool experts. While data curation efforts and access are improved, expertise in tool usage will be required and the costs of tool and database construction will likely limit their usage. Larger scale projects might justify the cost to use predictive tools.

As this tool was being proposed, with support from the National Academies' Gulf Research Program, a collaboration between Duke University's Nicholas Institute for Environmental Policy Solutions, The Harte Research Institute, and The Nature Conservancy is attempting to standardize metrics in the Gulf of Mexico Ecosystem Service Logic Models & Socio-Economic Indicators (GEMS) using oyster reef restoration as a prototype. The goal is to establish Gulf-wide standard metrics for determining outcomes (Olander et al. 2018). This effort is aligned with future search technologies.

Model accuracy for local projects requires accurate environmental data that is easier to assemble and acquire at small scale. Benefit transfer models such as the broad assumptions based on simple assessments for estimating global ecosystems services will result in large valuation error as discussed (Costanza et al. 1997). However, if local project data is stored in publicly available databases with contextual labeling, and sophisticated search engines with automated algorithms are employed, aggregating the values of historical and potential PERC projects, assessing impact, costs, and risks may provide synthesized data for large scale planning at the state and regional levels. This "bottom-up" approach is conceptual currently and, in the future,

will rely on automated algorithms and standard keywords. Tools like this prototype, may already be useful in smaller scale areas where it is feasible to assemble the data currently stored in multiple organizations with manual request for information processes.

Finally, the application of the tool is not limited to oyster reef restoration or general marine projects. When applied to relevant benefits, a quantitative ROI perspective is the same as any ROI model for products and services. This tool therefore can be applied to any environmental project, marine or terrestrial, if it addresses a societal need. Environmentalists need to be encouraged to utilize economics and ROI for planning, and for economists to view the "natural world" as a system that can predictably return on an investment.

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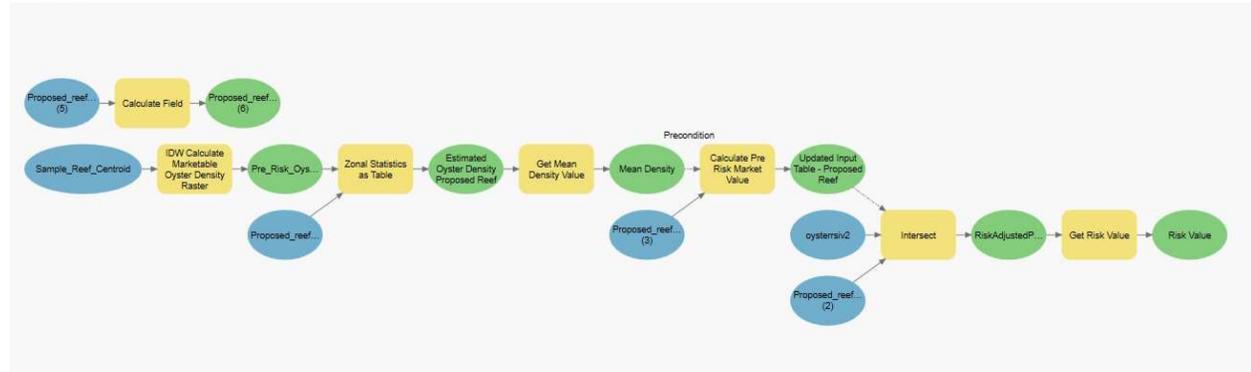
Appendix A   GIS Model Flowcharts

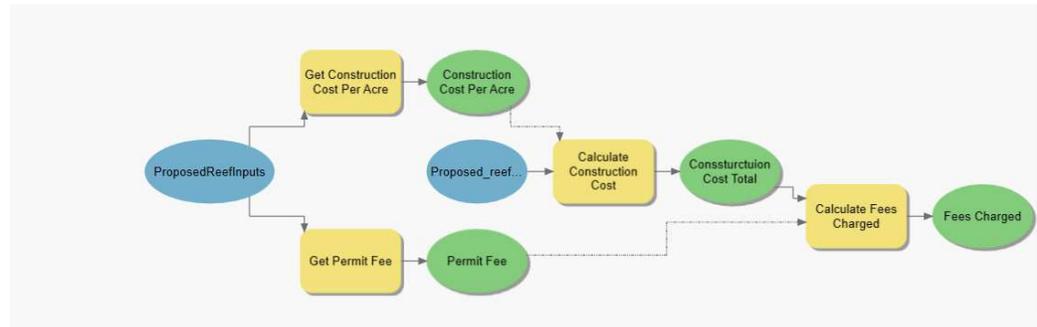*Figure A.1 GIS model for oyster reef restoration harvest*

Figure A.2 GIS model for oyster reef restoration cost
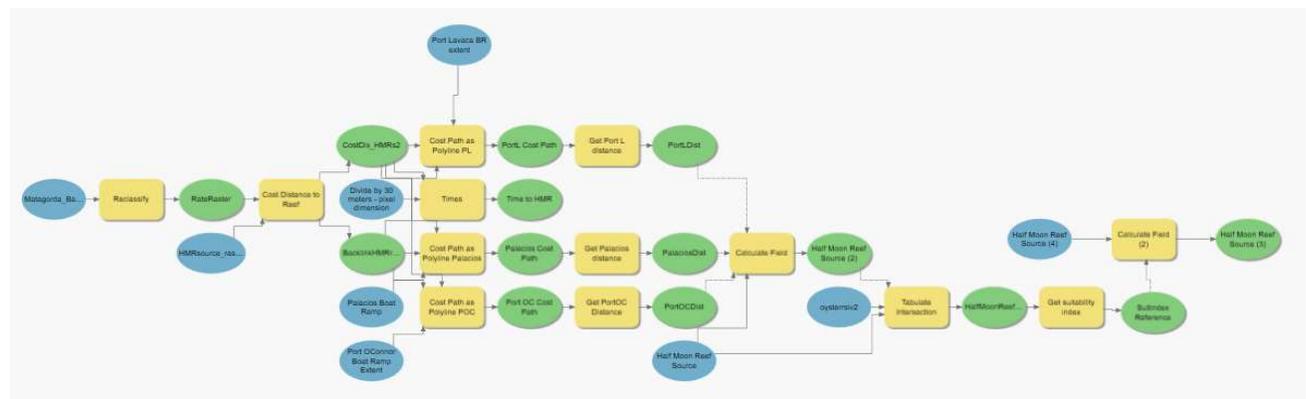
Figure A.3 GIS Model for recreational angling oyster reef benefit

```python
#calculating the NPVfactor given siltrates

#These variables must be passed in
intervalYrs = 16
siltrate = 0.5
maxtrigger = 1.5
discrate = 0.07
print(intervalYrs, siltrate, maxtrigger, discrate)

#initialize loop variables
NPVfact = 0.0
siltAccum = 0.0
numberDredges = 0

#loop that calculates the discounted factor and number of dredgings during intervalYrs
for i in range (1,intervalYrs + 1):
    siltAccum = siltAccum + siltrate
    print (siltAccum)
    if siltAccum >= maxtrigger:
        NPVfact = 1/((1+ discrate)**i) + NPVfact
        siltAccum = 0
        numberDredges = numberDredges + 1
print ("The NPV factor is ",NPVfact, "and the number of dredges is ",numberDredges )
```

Figure A.4 Python code for determining dredge intervals in shoreline erosion model

Appendix B   Data Used in Models

Table B.1 Construction costs for Galveston Bay oyster harvest model - Producer Price Adjusted (PPI) (Bureau of Labor Statistics 2018)

Year	Reef Name	Cultch Price ($/yard^3)	Cost/Acre	Total Acres	2018 PPI Adjust	Thickness (inches)	Rock Dia (inches)
2009	20-acre	56	$36,000	20	$37,839	3	1-2
2011	Middle	38	$19,101	18	$19,956	4	1-2
2011	Hanna's Reef	38	$19,101	20	$19,956	4	1-2
2014	Middle North	57.31	$22,503	15	$23,152	3	2-4
2014	Pepper Grove North	57.31	$22,503	10	$23,152	4	2-4
2014	Pepper Grove South	57.31	$22,503	29	$23,152	3	2-4
2014	Hanna's Reef	57.31	$22,503	74	$23,152	4	2-4

Table B.2 Bureau of Labor statistics (PPI) mining NAICS 532412 (Bureau of Labor Statistics 2018)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008	118.9	119.1	119.1	119.1	119.0	117.4	117.4	117.4	117.1	117.5	117.5	117.4
2009	117.3	117.3	116.9	116.8	117.8	115.5	116.5	116.1	116.3	117.4	117.2	114.1
2010	116.9	116.3	112.0	113.9	111.7	112.6	112.8	114.1	115.3	115.4	116.5	117.2
2011	116.1	114.4	117.3	115.0	112.3	116.2	117.8	117.5	120.1	118.2	119.8	121.7
2012	120.4	119.7	121.1	117.2	117.7	114.3	116.6	119.1	120.2	121.2	123.7	123.2
2013	122.9	122.9	121.9	123.2	122.5	123.1	124.8	124.4	126.0	125.5	124.0	125.6
2014	117.6	119.3	119.9	118.3	119.2	117.9	117.6	119.1	120.0	121.2	120.7	122.0
2015	121.5	121.0	119.4	119.2	121.3	120.6	118.9	119.9	118.4	117.8	118.8	118.7
2016	117.7	118.2	118.5	117.5	119.9	119.9	119.1	118.4	118.1	117.5	117.3	118.4
2017	117.8	117.6	117.6	117.6	118.5	117.7	117.6	118.3	121.4	122.0	121.7	121.9
2018	123.0	123.9	122.7	121.4	120.9	121.4	122.0	120.9	120.6	120.8	121.5	122.6

Table B.3 Galveston Bay diver samples on reefs

Date	Year	Project	Reef Names	Site Type	Method	Abundance Live	Abundance Mkt	Area Correct	Density Live	Density Market
10/12/2016	2016	CIAP	Pepper South	Restored	Diver Quadrat	10	2	0.0625	160	85.33333
10/12/2016	2016	CIAP	Pepper North	Restored	Diver Quadrat	12	3	0.0625	192	80
10/12/2016	2016	CIAP	Middle	Restored	Diver Quadrat	16	2	0.0625	256	21.33333
7/5/2018	2018		April Fools	Natural	Diver Quadrat	2	2	0.0625	32	6.4
7/6/2018	2018		Hannas	Natural	Diver Quadrat	0	0	0.0625	0	0
7/20/2018	2018		Hannas 2014	Restored 2013	Diver Quadrat	0	0	0.0625	0	14
7/19/2018	2018		Hannas 2011	Restored 2011	Diver Quadrat	7	1	0.0625	112	6.4
7/19/2018	2018		Middle North	Restored 2011	Diver Quadrat	2	1	0.0625	32	3.2
7/19/2018	2018		20-acre	Restored 2013	Diver Quadrat	6	0	0.0625	96	6.4
7/6/2018	2018		Pepper Grove	Natural	Diver Quadrat	0	0	0.0625	0	0
7/6/2018	2018		Redfish	Natural	Diver Quadrat	0	0	0.0625	0	6.4
7/5/2018	2018		San Leon	Natural	Diver Quadrat	0	0	0.0625	0	0