ABSTRACT

Title of Document:	USING DREDGED MATERIAL TO RESTORE THE CHESAPEAKE MARSHLANDS COMPLEX: PRELIMINARY APPLICATION OF A RISK-BASED OPTIMIZATION MODEL FOR COMPARING PLACEMENT OPTIONS
	Charlotte Shearin, Master of Science, 2010
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Using dredged material to restore wetlands in the Chesapeake Marshlands Complex (CMC) could offer solutions to two separate problems: 1) restoring and protecting the marshes in the CMC; and 2) finding an innovative reuse for dredged material from the Chesapeake Bay approach channels. The risk-based optimization model presented here assesses and compares restoration options for two alternative years (2023 and 2036) when the project may begin and represents a preliminary screening of material placement locations. Restoration of Zones 2a (Barbados Island) and 2b (Confluence Area) appear to provide significant environmental benefits, suggesting that restoration at these locations would provide the best return on investment. Low marsh restoration also provides a significant amount of benefits accrued. Based on sensitivity analysis, it appears that the choice of when to begin the project also represents tradeoffs between onsite habitat benefits and recreational benefits. Model results should be interpreted cautiously, considering the model limitations.

USING DREDGED MATERIAL TO RESTORE THE CHESAPEAKE MARSHLANDS COMPLEX: PRELIMINARY APPLICATION OF A RISK-BASED OPTIMIZATION MODEL FOR COMPARING PLACEMENT OPTIONS

By

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DEDICATION

For Darden and all his patience. Thanks for sticking it out with me!

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LIST OF ACRONYMS AND ABBREVIATIONS

BEWG: Bay Enhancement Working Group
BNWR: Blackwater National Wildlife Refuge
CMC: Chesapeake Marshlands Complex[1]
CMR: Chesapeake Marshlands Restoration
DMMP: Dredged Material Management Plan
GBA: Gahagan & Bryant Associates, Inc.
GIS: Geographic Information System
HAB: Harmful Algal Bloom
IPCC: International Panel on Climate Change
LiDAR: Light Detection and Ranging
MCY: million cubic yards
MD DNR: Maryland Department of Natural Resources
MES: Maryland Environmental Service
MPA: Maryland Port Administration
NED: National Economic Development
NER: National Ecosystem Restoration
POB: Port of Baltimore
SLR: Sea Level Rise
USACE: United States Army Corps of Engineers
USFWS: United States Fish and Wildlife Service
USGS: United States Geological Survey
WMA: Wildlife Management Area

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[1] The acronym "CMC" will henceforth be used to refer to the actual area of land known as the Chesapeake Marshlands Complex. The acronym "CMR" will be used to refer to the restoration of this land.

1. INTRODUCTION

1.1. Statement of the Problem

1.1.1. Loss of Wetlands

More than 130 U.S. National Wildlife Refuges are found in the coastal zone of the United States, encompassing 3 million and 1.5 million acres of estuarine and marine wetland habitat, respectively (USGS 2004). Sea level rise (SLR) threatens these ecosystems with inundation levels expected to exceed accretion rates and the ecosystems' ability to respond to increasing water depth and salinity. The Blackwater National Wildlife Refuge (BNWR) and surrounding area, heretofore referred to as the Chesapeake Marshlands Complex (CMC), is located approximately 70 miles south of Baltimore in Dorchester County on Maryland's eastern shore (Figure 1). It has been impacted by a combination of SLR and subsidence since the early 20th century with approximately 3,500 wetland acres already lost to sea level rise (Figure 2).

The marsh loss in the CMC is exacerbated for a number of reasons. High subsidence rates (estimated to be 3.5-4 mm/year) and low accretion rates (estimated to be 3.3-3.5 mm/year) cause more marsh loss here than elsewhere in the United States; and would do so even if sea level were not rising at all (D. Cahoon, personal communication, April 9, 2009). Much of the CMC is fresh or brackish marsh, and though this makes it a unique and rare ecosystem; it also means that when the higher-salinity Bay water enters the ecosystem due to SLR, it kills off even more marsh and further increases the wetlands loss. In addition, once marsh has been converted to open water via these various processes, the increased wave fetch over this open water increases erosion of the remaining marsh, thus exacerbating loss even more (Stevenson et al. 1985, Stevenson and Kearney 1996, Kearney et al. 2002). Invasive species such as nutria and tundra swans have also helped to destroy existing marsh.

Figure 1. Location of the Chesapeake Marshlands Complex.

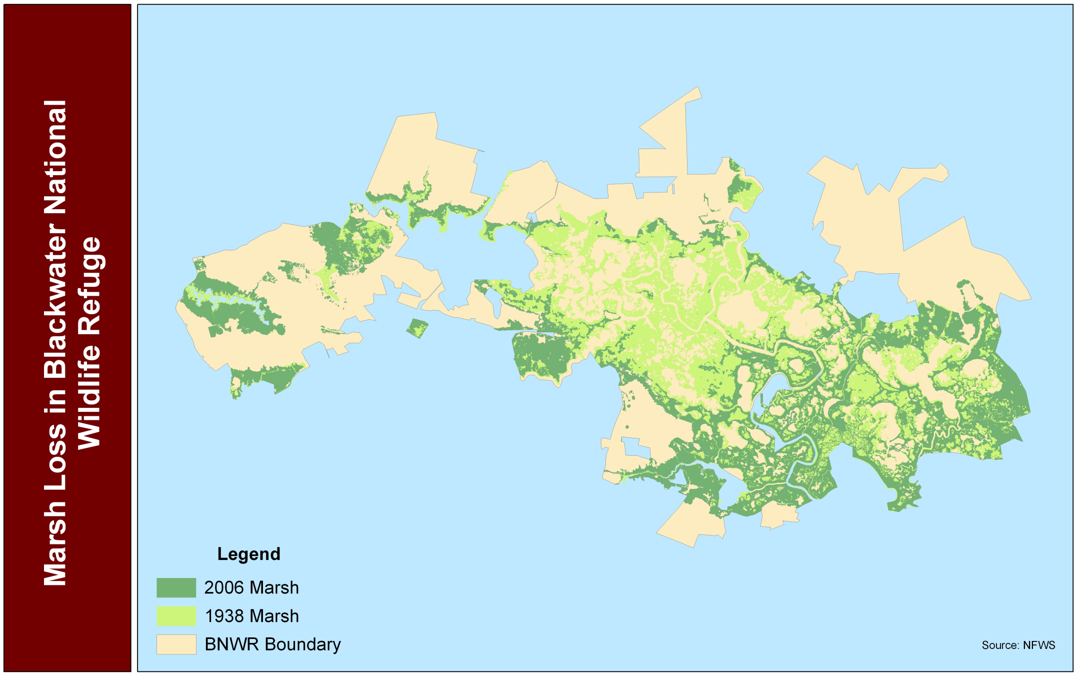

Figure 2. Preliminary results from a 2008 study conducted by Michael Scott of Salisbury University showing marsh loss in BNWR.

Larsen et al. (2004) used the Intergovernmental Panel on Climate Change’s (IPCC) low-level prediction of 3 mm/year of constant SLR to compare LiDAR images of current conditions in BNWR to expected future conditions under several time steps. Based on their calculations, there is actually a predicted increase in intertidal marsh (6.7% in 2050 and 19.8% in 2100) as high marsh converts to low marsh. With no mitigation of marsh loss, a predicted 7% of high marsh will be lost by 2100 under this scenario. Under the average-case scenario of 6.2 mm/year predicted by the IPCC, there is a much more drastic loss of both high and intertidal marsh by 2100 (Figure 3). These no-action scenarios illustrate the potentially devastating impact rising sea level could have on the Blackwater region.

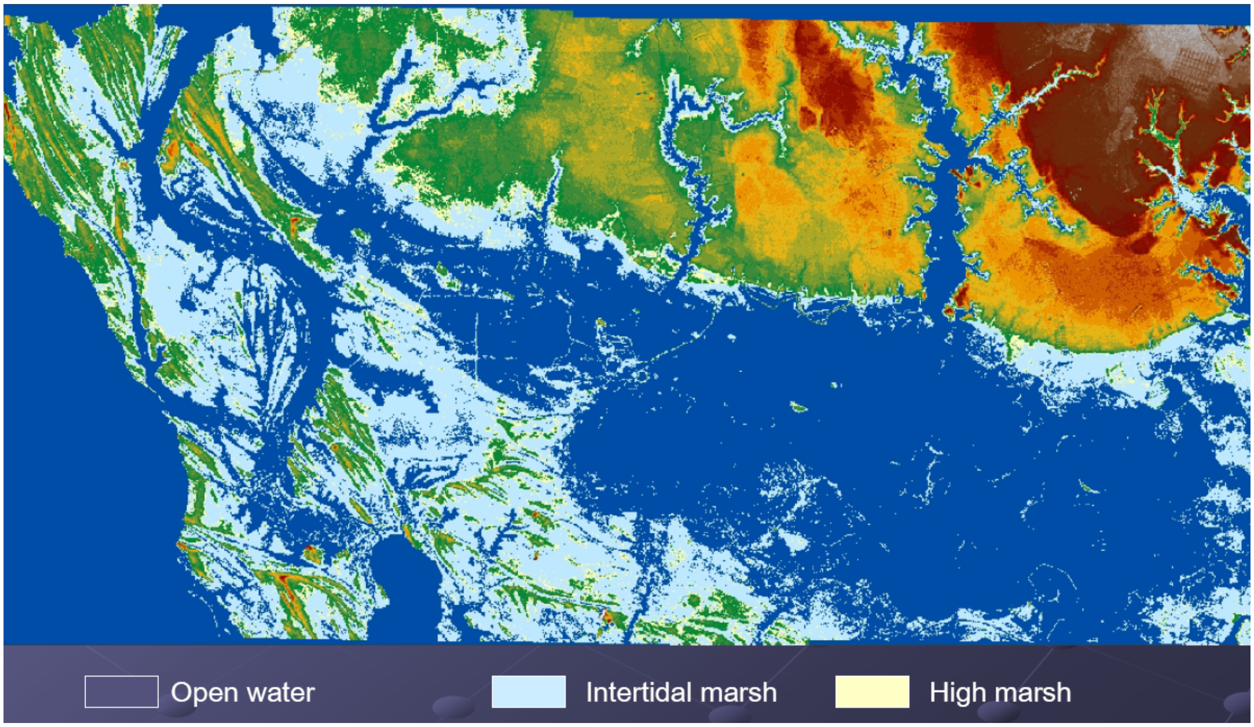

Figure 3. 2100 marsh condition in BNWR with 6.2 mm/year sea level rise. Source: Larsen, et al. 2004.

The analysis discussed here assumes an even greater rise in sea level of 11 mm/yr based on recent studies of the mid-Atlantic region and its increased risk of SLR (Titus et al. 2009). Because the Port of Baltimore (POB) has already identified adequate dredged material placement capacity up to year 2036, and because design and planning for CMC restoration may take at least ten years, it is further assumed here, for reasons described later, that the potential to use dredged material for restoration at the CMC will not exist until 2023 or 2036. Given the higher predicted SLR for the study area, it will experience even greater marsh loss by the earliest possible start dates of 2023 or 2036 than by 2100 under the average-case scenario used by Larsen et al. (Figures 4-6).

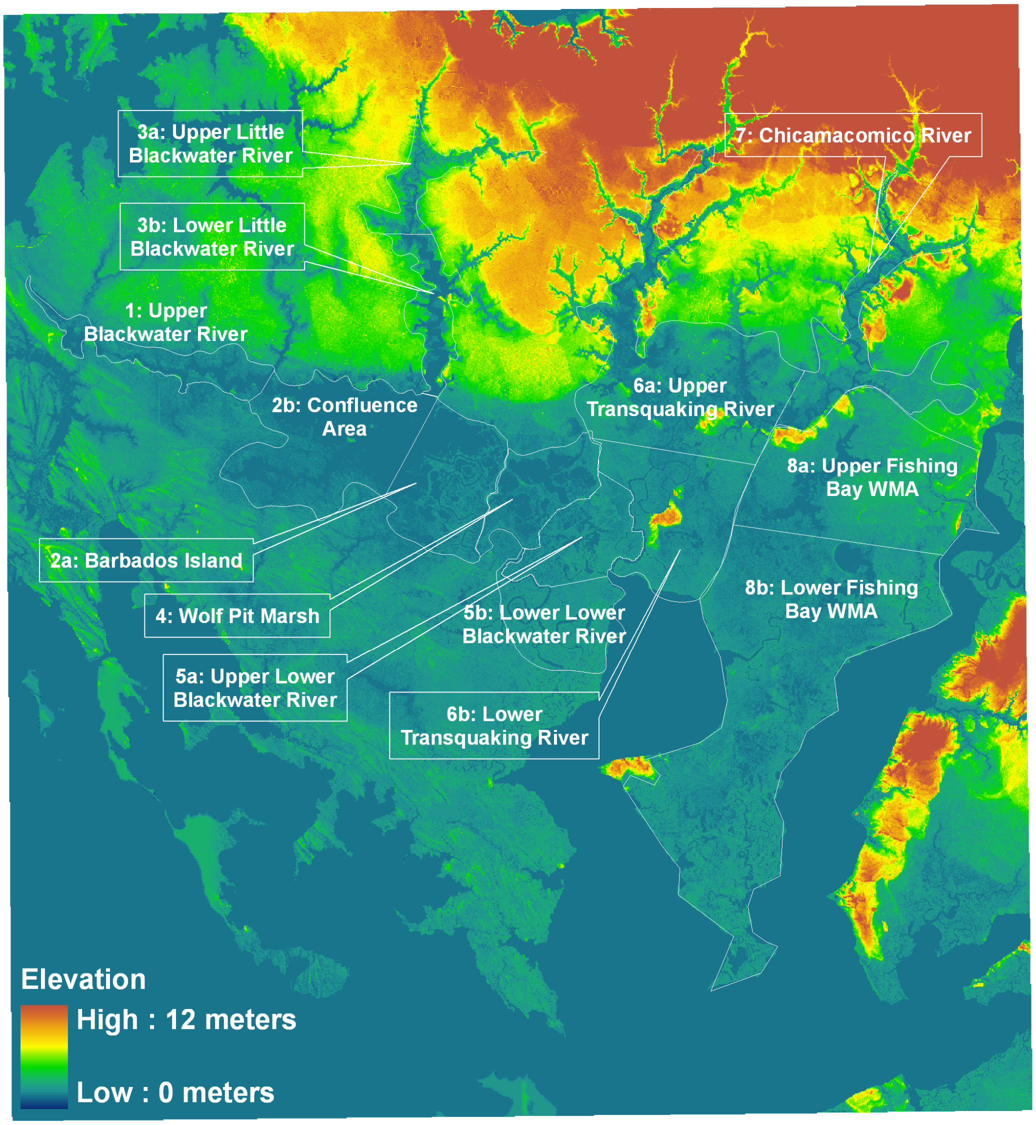

Figure 4. Current marsh condition in the CMC.

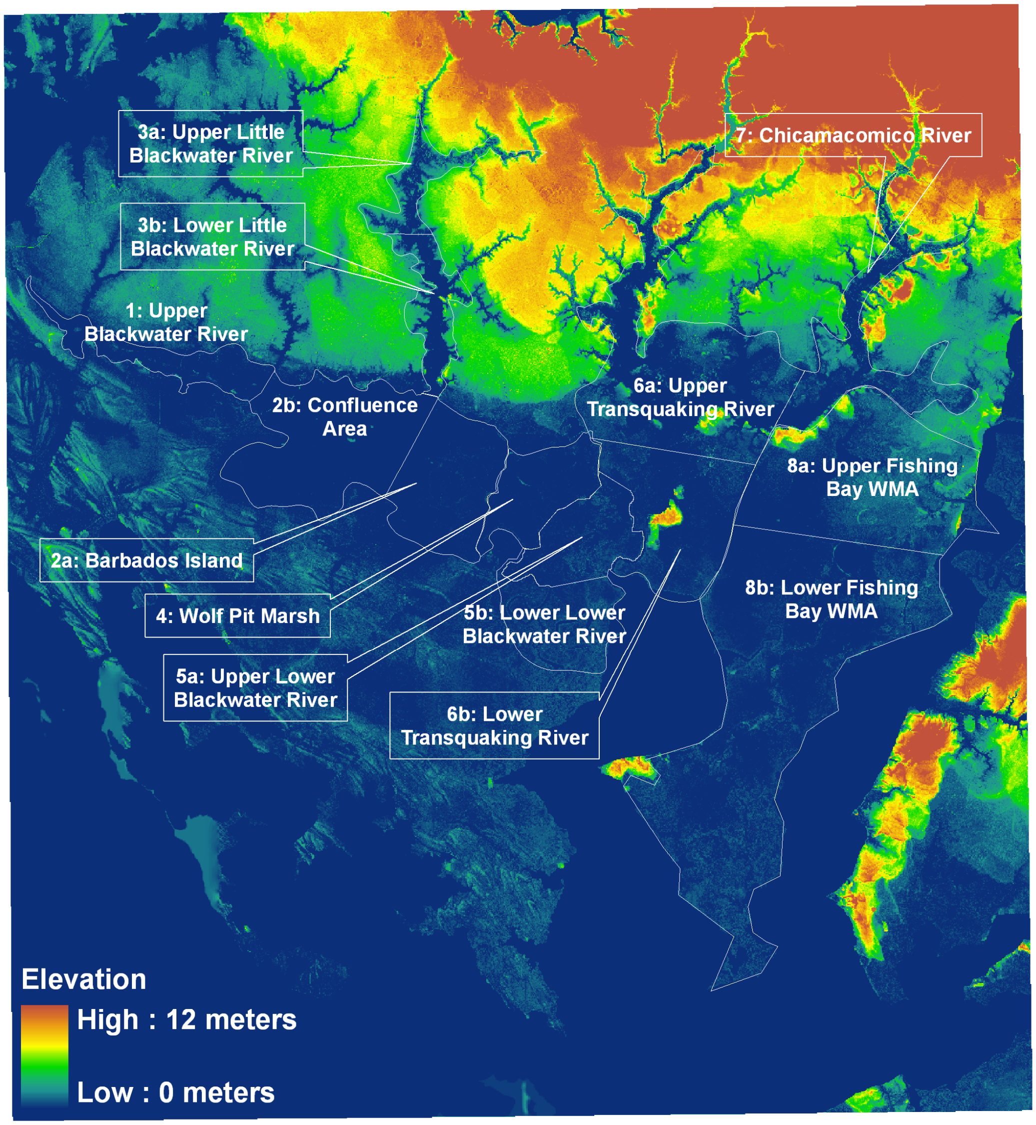

Figure 5. Expected marsh condition of the CMC in 2023 using a prediction of 11 mm/year sea level rise.

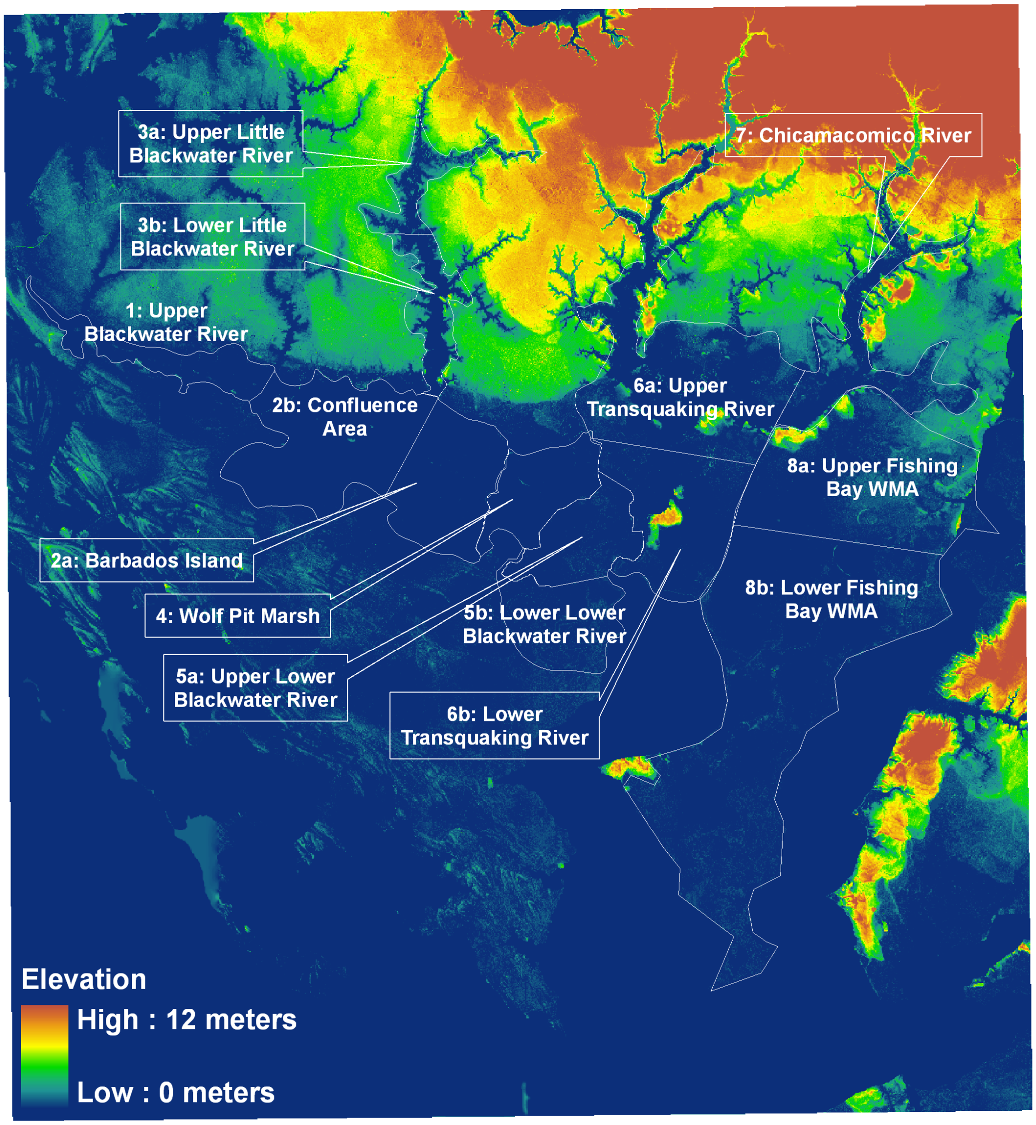

Figure 6. Expected marsh condition of the CMC in 2036 using a prediction of 11 mm/year sea level rise

1.1.2. Dredged Material Placement

Each year, the POB must find placement for 3.5 million cubic yards of dredged material removed from the Chesapeake Bay approach channels (this does not include material dredged from the Harbor as this material is considered unfit for environmental restoration purposes) (USACE 2005). The USACE considers the “base plan” for placing channel dredged material – that is, the least costly, environmentally safe plan under federal standards – to be open water placement. Despite a ban on open water placement of dredged material enacted by the state of Maryland in 2000, it is still considered the base plan under federal regulation; which means that any costs for using dredged material to achieve environmental goals that exceed the cost of open water placement must be justified on the basis of expected environmental benefits.

1.2. Potential Joint Solution

Using dredged material for wetland restoration provides a potential solution to two separate problems: 1) wetland loss at the CMC due to SLR; and 2) dredged material placement for channel material. It is important to note here that the goal of this study is to solve these two problems simultaneously. This may not provide the best solution to each individual problem and it is important to keep this mind. For example, using POB dredged material for the Chesapeake Marshlands Restoration (CMR) may not be the most cost-effective or timely option; rather, local material from nearby river channels may actually be a preferred source for dredged material.

In 2002 the Bay Enhancement Working Group (BEWG), which evaluates dredged material placement options in the Chesapeake Bay, conducted a study for the Maryland

Port Administration (MPA) to identify and rank environmentally beneficial alternatives for using dredged material. Initially, over 100 placement and use options were considered, including mine reclamation, agricultural placement and island and wetland restoration at various sites in the Chesapeake Bay. Using 42 environmental parameters to rank the final selection of 27 possible options, BEWG ranked the CMR project first in terms of potential environmental benefits. The BEWG did not make any adjustment to the ranking of options based on costs or risks, so the high ranking of the CMR by the BEWG is important only if the costs and risks associated with such a project are not prohibitive.

As part of a 20-year planning effort for placement of dredged material from the Chesapeake Bay approach channels, the United States Army Corps of Engineers (USACE) developed a dredged material management plan (DMMP) in 2005. As part of that plan, several hundred potential placement sites/options were considered and, after a programmatic analysis, three were recommended based on an assessment of their potential environmental benefits, costs, and risks. They were: 1) Poplar Island Expansion Project; 2) Mid-Chesapeake Bay Islands (James and Barren) restoration project; and 3) Chesapeake Marshlands Restoration project.

MPA, USACE Baltimore District, and other federal and state environmental agencies are already collaborating on the Poplar Island Expansion Project which is using dredged material to restore 735 acres of wetland habitat, 840 acres of upland habitat and 140 acres of open water embayment on Poplar Island in Talbot County, MD (USACE 2009). A

575-acre expansion of the existing project is expected to begin accepting dredged material in 2014 and to be filled, capped and environmentally restored by 2027. The availability of this site, and the unlikely availability of funding to develop an additional site such as the CMC until the Poplar expansion project is nearing capacity, is one reason it is assumed here that the CMR project will not take place until 2023 at the earliest.

The Poplar Island project provides the additional benefit of *in situ* experience and field study results for a larger-scale wetland restoration. Given that such information for wetland restoration is rare, much of the experience and data from the Poplar Island project was used to inform the CMR analysis presented here. For example, field observations have shown that some of the restored wetlands at Poplar Island are falling down or flattening after a year or two of growth. There is speculation that this may be due to the rapid growth of vegetation (which is due to the excessive availability of nutrients in the dredged material). Information on restoration effectiveness at Poplar was considered when determining the potential risk of restoration failure of the CMR. Differences between the Poplar Island project and the CMR project were also considered. For example, Poplar Island has the advantage of being a generally open system with steady flushing rates (given that it is an island in the middle of the Bay). However, the CMC is a closed system with low flushing and high residence time. Again, this was taken into account when determining the potential risk of the CMR project and the likelihood of harmful algal blooms occurring after restoration.

The other planned project, the Mid-Chesapeake Bay Islands project, includes restoration of Barren and James Islands in Dorchester County, MD. Alignment alternatives and habitat benefits are currently being evaluated for this project. Restoration is expected to begin sometime between 2014 and 2023 and not scheduled to be complete until 2060. A demonstration feasibility study is currently underway in the CMC as part of the third phase of the DMMP, though a large-scale restoration project might not begin until as late as 2036 when the POB would be in need of new placement options (Hamons 2006).

If it is determined to be feasible and justified, the CMR project would take place over 20 years, beginning perhaps in 2023 or 2036, and, based on some preliminary analysis, was estimated to cost approximately $1.9 billion (King et al. 2007). Based on the 2005 DMMP, it may be possible to justify approximately half of the costs of the CMR project on the basis of National Economic Development (NED) benefits which are related to the dredging itself and are associated with improvements in shipping and port activities. The remainder of costs would need to be justified on the basis of what are known as National Ecosystem Restoration (NER) benefits. These are associated with using dredged material to protect and restore wetlands, improve wildlife habitats, and generate other ecosystem services. The model developed here provides a preliminary basis for comparing alternatives for generating NER benefits as part of the CMR project based on an assessment of costs, risks, and environmental benefits. It provides useful background information for any future attempts to satisfy the USACE requirement that any potential CMR project be justified on the basis of incremental cost analysis and/or cost effectiveness analysis.

1.3. Project Relevance

The CMC represents the largest expanse of fresh and brackish marsh in Chesapeake Bay and recent evidence suggests that it is disappearing due to SLR more rapidly than previously predicted (Titus et al. 2009). Questions related to SLR and its potential timing and impacts are becoming increasingly important in scientific and policy circles. Equally important are questions about when, where, and how to adapt and respond to SLR; for example, by either attempting to resist SLR or by retreating from SLR. Many local governments are currently overwhelmed by the challenge of deciding how to adapt and respond and are in need of analytical tools and results that incorporate at least a basic consideration of the potential costs, risks, and benefits of various options. This project provides a prototype version of a decision-support tool that may be useful in making planning and investment decisions in the face of SLR. Although this optimization model is applied to wetland restoration at an environmentally important site, similar models are likely to be helpful to local planners as decision support tools for helping decide when, where, and how to protect infrastructure, important landmarks and historical sites, and residential or commercial real estate.

The CMC is recognized nationally and internationally as being highly valuable because of its unique habitat that supports diverse flora and fauna. The refuge is a designated “Wetland of International Importance” (The Ramsar Convention on Wetlands 1971) and has been called “one of the last great places” by the Nature Conservancy. As part of the Atlantic Flyway, the CMC is home to a variety of waterfowl throughout the year including snow geese, wood ducks, ruddy ducks, scaup, and Canada geese. Because of this, the refuge was named a priority wetland in the North American Waterfowl Management Plan (USFWS 2009). The CMC also provides a breeding and nesting ground for the endangered bald eagle, and is home to the endangered Delmarva Fox Squirrel.

In the mid-Atlantic region, public agencies and permit seekers spend, on average, $50,000 per acre to restore wetlands (King et al., 2007). Using this as a rough estimate of the public's "willingness to pay" for an acre of wetland, as reflected by decisions of public agencies, the dollar value of an acre of average wetlands in the Bay area can be assumed to be at least $50,000. Because of the unique and extraordinary value of the CMC as discussed above, one might arbitrarily but reasonably impute the dollar value of CMC wetlands to be $70,000 per acre. For the purposes of the analysis presented here, we will compare differences in restoration options at the CMC beginning at two different times: 2023 and 2036. Over 25,000 acres would be lost by 2023 which, at $70,000 per acre, would be valued at almost $1.8 billion; by 2036 over 40,000 acres would be lost, valued at over $2.8 billion. This does not account for the fact that restoring these wetlands also prevents erosion of other highly valued wetlands within the CMC; adding the indirect benefits associated with conserving these wetlands would make the losses associated with the "no action" option even higher.

The above exercise provides a rough aggregate willingness-to-pay valuation of wetlands that will be lost without some action at the CMC. However, there are other methods for quantifying individual wetland restoration benefits by assigning or imputing values to the individual ecosystem services they provide and then summing these values. For example, wetlands function as a natural filter for runoff entering streams and rivers. This in turn leads to improved drinking water quality, an ecosystem service which can be valued much easier than a wetland's function of filtration capability. However, service values only accrue in locations where a potential service is realized; for example, because users are present (Wainger et al 2001).

As mentioned previously, the POB must find alternative uses for the 3.5 million cubic yards (mcy) of dredged material dredged every year from the Chesapeake Bay approach channels. Projects such as the CMR provide a beneficial use for this dredged material, as well as offering significant environmental benefits. Additionally, the CMR project (if conducted in 2023 or 2036) offers potential placement for all of the POB's dredged material needs over a 20 year period. There also exists the possibility that the dredging needs for any given year may exceed the estimated 3.5 mcy. For example, a large storm can cause greater amounts of sediment to enter the Bay than during a normal year. The CMR project, because of its size, has the ability to receive this potential additional dredged material and thus provides an additional asset to the POB.

1.4. Focus, Objectives, and Approach

In order to justify the costs of transporting dredged material to Blackwater and using it to restore wetlands, it must be established that the environmental benefits gained are being maximized and costs constrained. This requires analysis to address the following questions:

- What sites/habitat types within the refuge should receive dredged material in order to maximize benefits under a given cost constraint?
- How much dredged material should be placed at each site in order to maximize benefits under a given cost constraint?
- How should multiple and sometimes competing environmental goals (e.g., habitat for birds vs. fish vs. mammals) rank in importance?
- How should the importance of competing benefits, such as onsite habitat benefits vs. dredged material capacity, be weighted?
- How should the inherent economic and environmental riskiness of the restoration be managed?

In 2007, King, et al. prepared a “Preliminary Economic Analysis of the Chesapeake Marshland Restoration (CMR) Project.” In it they outlined the methods for quantifying environmental benefits from restoring wetlands at the Blackwater Wildlife Refuge, which makes up most of the proposed CMR site, provided data on costs and monetary benefits of the restoration, and outlined the methods for conducting a risk-based optimization analysis to determine the best site placement of dredged material. In 2008, King, et al. updated this report with the “Interim Draft Economic Analysis of the Chesapeake Marshland Restoration Project: Cost, risk and benefit assessments and proposed optimization modeling.” These two reports described a general approach for assessing and comparing options and provide some preliminary data needed to conduct a risk-based optimization analysis. However, the approach was not carried through to any preliminary implementation or testing using cost data or best professional judgment about potential material placement capacity or environmental benefits at potential restoration sites.

This paper extends previous work by developing a mathematical optimization model that can be used to quantify and evaluate potential restoration options for several zones/subzones within the CMC. The optimization model developed here employs a standard Excel spreadsheet program that is imported into widely used optimization software (Oracle's Crystal Ball® software, 2008, Version 7.3.1, Oracle Corporation, www.oracle.com/crystalball/index.html) that is "risk-based" because it incorporates uncertainty associated with model inputs. Within the model, probability distributions are associated with the uncertain inputs, such that as the model runs through many iterations of a Monte Carlo simulation, it randomly selects different values within the distributions established for each uncertain input. These multiple iterations constitute one solution for the model. The model examines any specified number of solutions in its quest to find the optimal solution – that is, the distribution of dredged material that provides the highest benefit within the specified constraints. The benefits are associated with both dredged material placement capacity and various sets of environmental habitat or benefit indicators. Sensitivity tests are performed by adjusting the weights assigned to various benefit indicators and examining how the adjustments affect outcomes.

Because much of the necessary technical and engineering information about restoration alternatives has not been generated, the analysis presented here does not generate an "optimal" solution that can be viewed with a great deal of confidence. However, it does present what is currently known about restoration alternatives and carries to the next level research about how these alternatives should be compared in terms of costs, risks, and benefits. This optimization model is developed to provide an initial screening of dredged material allocation options for protecting/restoring wetlands in the CMC. This work has three major components: 1) a quantification of the onsite habitat, offsite habitat, recreational, and dredged material placement benefits of the restored wetlands; 2) a preliminary assessment of costs; and 3) the output from an application of a risk-based optimization model (using Crystal Ball®) which illustrates how such a tool can be used to rank site-specific dredged material placement options.

Given the current sequence of placement options under consideration, this project, if determined feasible and worthwhile in terms of combined NED and NER benefits, might not be undertaken until 2023 or 2036. However, large, risky, complex projects like the CMR have extremely long lead times so it is not too soon to begin screening out clearly impossible or inferior options and focusing attention on feasible options. The model developed here can be used to assess and compare options under a shifting baseline that accounts for SLR and compensates for resulting increases in depth of fill, marsh loss, and changes in relative marsh values due to increasing scarcity and vulnerability. The analysis will provide a set of preliminary base plan recommendations for material placement and restoration that are based on where the most benefits can be achieved under certain cost and available dredged material constraints.

For the purposes of analysis, we will compare differences in placement options for restoration beginning in two separate years: 2023 and 2036. This allows us to consider the differences associated with shifting baselines – how the CMC will have changed between these two different years – and what this means in terms of optimal dredged material placement and restoration. To the extent that the CMR project is still under consideration, state and federal agencies are considering linking it with the Mid-Bay Island Restoration, specifically as an extension of the James Island restoration. Therefore, the 2023 year is based on a 5-year lag time between when James Island will begin receiving material and when any potential CMR project using James Island as a staging area could begin. The 2036 baseline assumes that the CMR project would not begin until new dredged material placement options are needed by the POB which would be after the Mid-Bay Island restoration is approaching completion.

The general approach of the analysis taken here involved the following steps:

1) Build a general model that delineates the information needed, given unlimited resources for data collection, to fully assess and compare options for using dredged material to protect and restore wetlands as part of the CMR project.
2) Gather as much data as possible and compensate for data gaps using an expert panel.
3) Modify and scale down the general model to adapt to the use of an expert panel.
4) Develop and apply a risk-based optimization program based on the adapted model that works around significant data voids and engineering and cost uncertainties.

2. REVIEW OF LITERATURE

2.1. Optimization Models

Optimization models generally involve allocating scarce resources to meet competing objectives. They can be specified to maximize a desired set of parameters, such as benefits, while simultaneously meeting a set of constraints on another set of parameters, such as costs; or, conversely, they can be specified to minimize a set of parameters, such as costs, subject to achieving a given level of some other set of parameters, such as benefits. Quantitative optimization methods are used routinely in commercial, industrial, and military applications to minimize costs or maximize performance in situations where objectives, constraints, and options are too complex and/or too numerous to be assessed and compared in any other way (Optimization Online 2006). Such models are being used with increasing frequency to help prioritize and manage environmental conservation and restoration initiatives (Aravossis et al. 2006).

There are many different types of optimization techniques for solving problems with different types of potential solutions (Papalambros and Wilde 2000, Troutman 2006). In a broad sense, linear and closed-form models attempt to find solutions for simple functions with known variables. Simulation and nonlinear models, on the other hand, attempt to find solutions to more complicated functions that contain variables with uncertain values. There are also several specific optimization techniques that work in very different ways. "Hill-climbing optimization" models, for example, start with a random, potentially poor solution and iteratively make small changes to it, improving upon it until the model cannot determine any further improvement (FOLDOC 1993). This method, like most optimization techniques, does not guarantee an “optimal” solution but rather ensures the model has come close to an optimal solution. “Ant colony optimization” is often used to find the shortest round trip to link a series of cities (also known as the traveling salesman problem). It is used explicitly for finding the shortest path through a graph and is modeled based on the way ants create pathways from their colony to a food source (Dorigo 1992). The simplex method is an iterative procedure that solves a system of linear equations, stopping when the optimum is reached or the solution proves infeasible (FOLDOC 1993). “Particle swarm optimization” is based on “swarm behavior” and is typically used to model social behavior (Kennedy et al. 2001). Swarm behavior is the use of social influences to solve problems. As people interact, their beliefs, attitudes and behaviors change; these changes can be seen as individuals moving toward one another (or swarming) in socio-cognitive space and thus converging on a “solution.” Stochastic tunneling involves using Monte Carlo simulation to randomly hop from one solution to another that exhibits a designated difference in value (Hamacher 2006). A “genetic,” or “evolutionary,” algorithm is used for the optimization model in this study and is discussed below.

Risk-based optimization models like the one used for this analysis, incorporate uncertainty by allowing users to specify an expected range or distribution of values for any parameter or input. The model then uses a Monte Carlo simulation which searches the range specified for each uncertain parameter to produce a distribution of solutions in terms of resulting values of the model’s objective function. The model uses a genetic algorithm to examine the sets of control variables that are included in the model (such as the amount of dredged material available) until an “optimal” solution is found that either: a) maximizes a weighted sum of selected ecosystem benefits subject to a set of budget and material input constraints; or b) minimizes costs of achieving a selected level of weighted ecosystem benefits. These two objectives can nearly never be simultaneously met because the solution that achieves the greatest benefits is nearly never the least cost solution; the optimization must be based on one objective or the other. Genetic algorithms search for an optimal solution using a “survival of the fittest” mechanism. Options are pitted against one another to determine which is the most optimal with respect to the specified set of weighted objectives. Successful options are combined and experience random variations that allow them to evolve into better solutions if possible. Genetic algorithms can be used if the optimization problem has two characteristics: 1) it is possible to express the solution as a “string” of solution values; and 2) it is possible to calculate a value for each string in order to compare them with one another. A “string” is simply a code of solutions calculated by the genetic algorithm and can be binary in nature or use other encodings. For the CMR optimization model developed here, the “string” comprises the dredged material placement in each zone/subzone and the “value” is the benefits associated with that placement.

A variety of combined ecologic and economic optimization models have been used for natural resource planning. Polasky et al. (2005) developed a spatially explicit, combined biologic and economic model to search for efficient patterns between conflicting land uses (conservation reserves and commodity use). In that model, conservation outcomes could not be improved without lowering the value of commodity production. This heuristic model aimed to maximize the landscape biological score while guaranteeing an economic return at least as large as some designated value. Though it considered habitat preferences, habitat area requirements and dispersal ability for each species; the model did not consider the value of ecosystem services such as the provision of clean water, nutrient filtration, climate regulation and ecotourism (Polasky et al. 2005). In this way it differs from the current study which focuses on ecosystem services as benefit measures. Considering such ecosystem services would increase the value of conserving land in reserves and reduce the trade-offs between conservation objectives and economic returns.

Howard et al. (2005) used an optimization approach to determine a restoration strategy for contaminated agricultural ecosystems. The optimization used a cost-benefit analysis to determine the optimal level of cleanup when balanced against the costs of that cleanup. However, this optimization differed from the current study in that they used a decision support system composed of various models, of which the optimization analysis was just one part. Randhir and Shriver (2009) advocate a multi-attribute optimization approach for modeling restoration strategies in their examination of the relative gains in economic and environmental benefits (such as water quality and habitat). The current study does include such a multi-attribute analysis.

The Crystal Ball® software is recommended by the US Army Corps of Engineers (USACE) for use in evaluating water development projects and is required for many internal USACE applications of risk-based cost analysis (Moser 1996, USACE no date). The software has also been used in other types of environmental risk and management assessments (Carrasco and Chang 2005, Glorennec 2006, McKay et al. 2006, Bhat and Kumar 2008), though it has rarely been used for environmental restoration analysis. However, a similar program, RISKOptimizer® (Version 1.0.8, Palisade Corporation, http://www.palisade.com/riskoptimizer/default.asp), has been used for analyzing recent environmental restoration (North, et. al 2010, Wainger et al. 2007, Wainger et al. 2010). This program incorporates uncertainty in the same way as Crystal Ball® – by assigning a probability distribution to uncertain variables and running a Monte Carlo simulation – and also includes control variables, constraints and benefit weights. In North et al., an optimization model was used to examine tradeoffs among oyster restoration goals in Chesapeake Bay (i.e. reduction in seston, increase in light penetration, spawning stock enhancement, and commercial harvest). This model predicted benefits, quantified costs, and made location-specific recommendations based on the preferred goal. The uncertainty in this model stemmed from the salinity and mortality metrics incorporated into the model – these both had a probability distribution associated with them. RISKOptimizer® has also been used to determine the appropriate treatment level and location for invasive species removal. Wainger et al. (2007) developed an optimization model to maximize the change in specific and weighted sums of benefit indicators for ecosystem services (i.e. recreational antelope hunting, forage production for cattle, property protection from fire, and existence values associated with sage-grouse) associated with removing invasive cheatgrass in the intermountain west by adjusting the level of treatment intensity for each treated (burned) area. The benefit weights and cost constraints were both adjustable in order to account for different management goals. The results were consistent with multi-attribute theory (e.g. Randhir and Shriver 2009) by showing that greater benefits could be reached by choosing sites based on multiple attributes rather than focusing on individual services (Wainger et al. 2010).

These two studies (Wainger et al. 2010 and North et al. 2010) provided useful prototype models for the analysis conducted here, given that they both involved maximizing various environmental benefits of a restoration under the influence of a set of control variables and cost constraints. Also, RISKOptimizer® and Crystal Ball® are similar programs based around spreadsheet models, making it easy to understand and relate these studies to the one presented here.

2.2. Environmental Indicators

The CMR optimization model uses a weighted set of environmental benefit indicators associated with potential wetland restoration to determine the optimal allocation of dredged material among zones/subzones at the CMR site. For the purpose of this analysis, the benefits streaming from an ecosystem will be referred to as ecosystem services, such as improved/restored habitat, improved drinking water quality, and improved fishing. Quantifying these services as model inputs requires a conversion from ecosystem functions to ecosystem service (Table 1). Traditional benefits – those with a monetary value associated with them – fit well into a cost-benefit analysis but for many restoration benefits there is no common metric of dollar values so these services must be valued in other ways (Hansen et al. 1998). Additionally, because there are no markets associated with many ecosystem services, valuing such services can be difficult and oftentimes may not be comprehensive (Boyd and Wainger 2002, Johnston et al. 2002, Polasky 2002).

Table 1. Wetland functions and some associated services/values.

Wetland Functions	Wetland Values
Fishery Habitat	• Better commercial/recreational fishing, lower fish prices, improved international trade balance.
Waterfowl Habitat	• Better hunting and bird watching on-site, nearby, and elsewhere.
Fur-bearer Habitat	• Commercial and recreational opportunities
Storehouse of Biodiversity (onsite species diversity)	• Direct, indirect, serendipity value of scientific research, medical discoveries, genetic pools, seed banks, etc.
Food Chain/Biodiversity Support (offsite species support)	• Same as above, except off-site
Natural Products (e.g., timber, hay, cranberries, peat)	• Wholesale and retail market value and associated jobs, incomes
Groundwater Recharge/Discharge	• Drinking water quality, reduced human and environmental health risks
Floodwater Storage, Conveyance and/or Desynchronization	• Reduced soil erosion and property damage
Shoreline Anchoring/Erosion Control	• Protection of beaches, private property, infrastructure, ecosystem
Storm Surge/Wave Protection	• Reduced soil erosion and property damage
Sediment Trapping	• Protects aquatic ecosystems, reduced dredging, maintains hydropower
Pollution Assimilation	• Reduced treatment costs, improved public health and environment
Nutrient Retention/Filtering	• Maintain nitrogen balance; prevent algae blooms and anoxic conditions.
Natural Area/Open Space	• Active and passive recreation, research, teaching/learning)
Micro-climate Regulation	• General life support; ill-defined but important local/regional linkages
Macro-climate Regulation	• General life support; ill-defined but important national/global linkages
Carbon Cycling	• General life support; ill-defined but important national/global linkages

Cost effectiveness and incremental cost analysis are often used by the USACE for projects with non-monetary benefits. Cost effectiveness identifies the options that provide the greatest output for the lowest cost, and incremental cost analysis identifies the increase in costs that accompany increases in output. Neither provides an optimal solution, however, but simply presents the information to facilitate selection of a solution (Hansen et al. 1998). The CMR optimization model will take this a step further and attempt to identify the optimal combination(s) of dredged material placement across habitat types within zones/subzones. It is important to note that what is relevant when measuring the ecosystem service benefits of a restoration project is the *change* in services provided. In this way, the benefits resulting from existing wetlands at the time of restoration must be subtracted from the benefits of the total wetland area after restoration

The first step in the creation of the eventual optimization is to determine an appropriate set of indicators associated with an ecosystem function to be used as an indirect measure of some resulting ecosystem service. Environmental indicators are the physical, chemical or biological elements of an ecosystem that offer a measurement of the health of that ecosystem (Pastorok et al. 1997). To be relevant measures, they must be clearly connected to the ecosystem value or service being quantified and be responsive to potential stressors on the ecosystem (Pastorok et al. 1997, Dale and Beyeler 2001). Ideally, they should also require little sampling effort and be cost-effective. At the CMC, the environmental benefits being measured focus on onsite and offsite habitat creation and recreational use. Examples of indicators that might be used to measure these benefits include habitat suitability indices, hunting unit preferences and use rates of zones and subzones within CMC for bird-watching, hiking and biking.

Ecosystem services can be classified into a value hierarchy (Figure 7), beginning with a differentiation between use and non-use services (shown as active and passive use in Figure 7). Active use services can further be divided into direct and indirect services; and passive use values are divided into existence and life support services. Direct services offer value to humans that can be directly measured monetarily (e.g., mining, fishing, hunting). Indirect services are still used by humans but do not necessarily have a price tag associated with them (e.g., flood control, groundwater recharge, improved water quality). These values can be measured indirectly, however; for example, by calculating the loss of property value due to flood damage. Existence services offer value to humans but not through any use of the ecosystem. They are valuable simply because the ecosystem exists intact (e.g., endangered species, rare habitats, spiritual enrichment). Life support services may not be directly used by humans but are intrinsic to both the ecosystem and human existence (e.g., carbon cycle, keystone species, etc.).

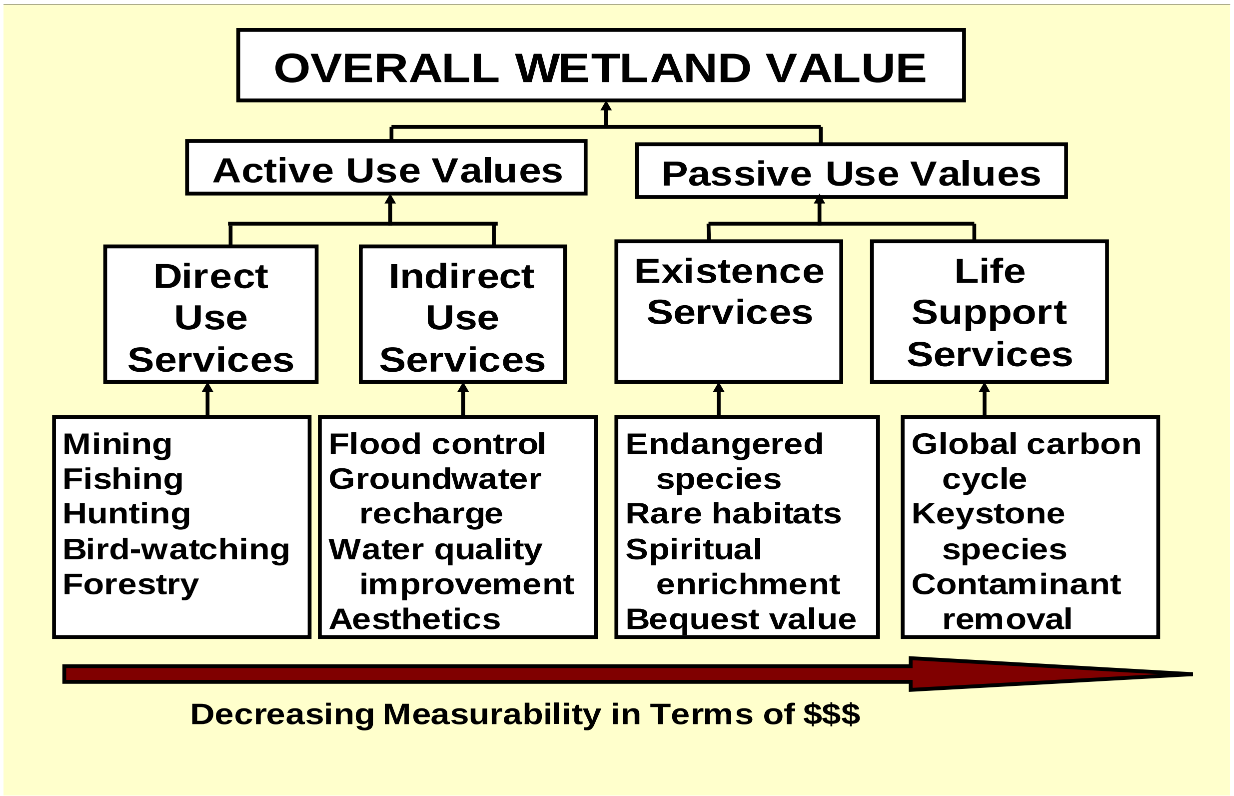

Figure 7. Wetland value hierarchy. Source: King et al., 2007b.

The benefits assessment for the CMR optimization model involves determining habitat use by several guilds of species. Habitat suitability indices (HSIs) are often used to quantify habitat benefits. However, they focus on one particular species and how the restoration affects that one species, rather than the habitat as a whole (Peterson et al. 2003). Recently, there has been a move to focus on communities or guilds of species (USACE 2006) or even simply habitat restoration and diversity (Peterson et al. 2003). There is high uncertainty associated with an HSI evaluation because substantial information on population regulation and population enhancement programs is required in order to accurately predict success (Peterson et al. 2003). However, habitat restoration with a focus on diversity carries far less uncertainty about success and performance.

Beechie et al. (2008) even found that declines in species at a restoration site were largely due to attempts to manage individual species rather than the ecosystem as a whole.

2.3. Risk and Uncertainty

For the purposes of this project, the USACE definitions of uncertainty and risk will be used: Uncertainty describes a situation with an unsure outcome; risk describes a situation with a probability of a negative outcome (Yoe 1996). In this way, risk denotes a subset of uncertain situations (Figure 8). Environmental restoration and management often have a high level of uncertainty and risk associated with them; and many studies encourage adaptive management policies so that as additional information that reduces risk and uncertainty becomes available, it can easily be incorporated and the plan adjusted (Anderson et al. 2003, Linkov et al. 2006, USACE 2007).

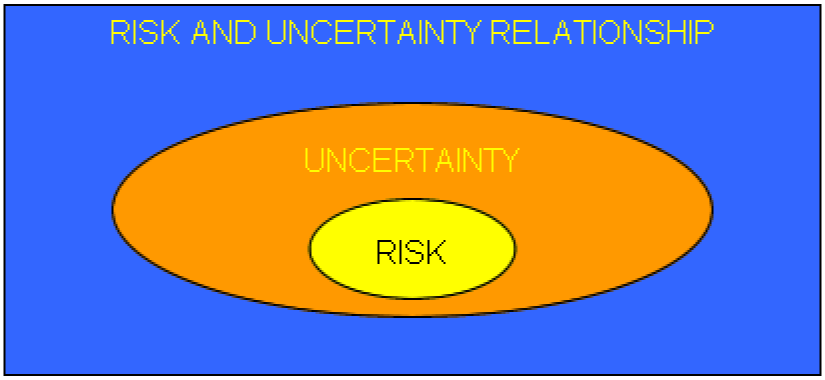

Figure 8. The relationship between risk and uncertainty. Source: Yoe 1996.

The CMR project has a number of different risks associated with it, each of which contributes to the uncertainty associated with the success of the project (discussed below). These risks can be divided into two categories. Restoration risk is the risk that the use of dredged material for restoration will not succeed at achieving potential benefits. This contributes to the uncertainty surrounding the overall effectiveness of the restoration. Ancillary risk is the risk that failed attempts at restoration may adversely affect existing habitat. Table 2 provides examples of the risks inherent to the CMR.

Table 2. Examples of risk.

Restoration Risk	Ancillary Risk
Sea level rise	Storm Damage
Erosion	Saltwater intrusion
Invasive Species	Biophysical changes in sediments
Compaction/Spreading of DM	Changes in water quality
Failure of plants to grow or take seed	Disruption of species life cycle activities
	Habitat removal or conversion
	Noise/Visual impacts

These project risks impact the expected realization of potential benefits at each restoration site and as such are incorporated into the optimization model as the probability that a benefit will be realized. For the purposes of this model, wave fetch is used as an indicator of overall restoration risk. Data on wave fetch in the CMC system is readily available and provides an acceptable metric for quantifying the potential for failure once the restoration is complete (Cooper and McLaughlin 1998, Shafer et al. 2003). One specific ancillary risk was also incorporated – the risk of harmful algal blooms occurring due to the excess nutrients in the dredged material used for restoration. This was deemed the most important and most easily estimated risk factor (J.C. Stevenson and J. Cornwell, personal communication, December 10, 2009). The model, of course, has the potential to incorporate numerous other risk factors.

For purposes of the analysis developed here, we address two major sources of uncertainty for the CMR project: impacts of sea level rise and uncertain expectations about overall restoration success. It is important to note that SLR, while posing an uncertainty as discussed below, is also responsible for generating restoration benefits, in the sense that restoration benefits are created only because there is a difference between the no-action baseline benefits and the post-restoration benefits assuming SLR. Without SLR, there would be no need for a restoration at the CMC, and thus no additional benefits from a restoration.

Because the CMC has an extremely small tidal range, it is highly susceptible to any changes in sea level. However, it is important to evaluate SLR at a local level and to consider human adaptation strategies when examining risks and impacts of future SLR (Knogge et al. 2004). In addition to being a threat to the wetlands of the CMC, SLR can also potentially have negative societal impacts including increased flood frequency, erosion, inundation, rising water tables, and saltwater intrusion of groundwater. Currently, the wetlands of the CMC buffer the coastal settlements in Dorchester County, but as they disappear, those residential and commercial areas are likely to become more vulnerable to SLR. A recent study of the effects of SLR on various marsh systems showed that fresh and brackish marshes (which compose the majority of the CMC) provide more benefits in terms of ecosystem services when compared to salt marshes; thus the loss of fresh and brackish marshes results in much larger losses in ecosystem services than loss of saltwater marsh (Craft et al. 2009). Not only does this finding validate the increased value of the CMC compared to other wetlands, it also clearly supports an argument for minimizing the uncertainty associated with SLR in the optimization model.

The GIS analysis conducted for this project (described in more detail in Section 4.2.4) visually depicts the effects of SLR at the CMC and incorporates predicted rates of SLR, subsidence, accretion, and elevation for the region. This aids in determining the future water depths of the restoration sites and thus the potential dredged material capacity; as well as eliminating a significant amount of uncertainty associated with SLR in the CMC.

The second source of uncertainty is the overall effectiveness or success of the restoration. As discussed earlier, the Crystal Ball® program deals with uncertainty by allowing value ranges and probability distributions as inputs related to expected benefits and costs. Probability distributions, for example, can be affected by the risks associated with the benefit variables as discussed above (e.g., high erosion risk affects expected habitat benefits). In this way, the model adjusts the outputs given the risks and uncertainty, incorporating the potential for restoration failure (i.e. benefits are not realized).

3. STUDY AREA DESCRIPTION

3.1. Blackwater and Vicinity

Blackwater National Wildlife Refuge is approximately 27,000 acres of mostly tidal marsh with fluctuating water levels and salinity (USFWS 2009). Originally established in 1933, BNWR was designated as a haven for migrating waterfowl including geese and several species of duck. The state-owned Fishing Bay Wildlife Management Area (WMA), adjacent to BNWR and included in this model analysis, also contains large expanses of tidal marsh in its 21,000 acres which provide similar habitat as those in BNWR (MD DNR 2002). Because several of the zones/subzones examined in this study include watersheds that are not technically part of either BWNR or Fishing Bay WMA (but are considered part of the CMC), the total area examined here is over 77,000 acres.

This project focuses on eight zones within the CMC, several of which were divided into separate subzones by USFWS and MD DNR based on differences in restoration goals, restoration risks and zonal characteristics. For example, Zone 2 was divided into Zone 2a, the Barbados Subzone, and Zone 2b, the Confluence Subzone (see Figure 4). For all habitat benefit decisions, USFWS were consulted for Zones 1 through 4 (federally-owned lands) and MD DNR for Zones 5 through 8 (state-owned lands).

3.2. Potential Restoration Zones

3.2.1. Zone 1: Upper Blackwater River

The Blackwater River is a source of freshwater for the marsh in and around Lake Blackwater. The confines of the upper Blackwater River are mostly freshwater marsh themselves and contain a number of ecological benefits. A natural heritage area has been identified adjacent to the river and contains rare plants such as the American frog's bit (*Limnobium spongia*). It is also home to numerous bald eagle nests and is a historical spawning ground for anadromous fish. However, as surrounding marshes have disappeared due to SLR and erosion, saltwater from the Choptank River has entered the fresher ecosystem and prohibited anadromous fish from migrating there. This saltwater intrusion has also exacerbated the marsh loss and efforts are currently underway to prevent it (i.e. installation of a weir). Should fish spawning start anew in the Blackwater River, time-of-year restrictions must be considered for a restoration project, as would potential salinity impacts.

The expanse of the upper Blackwater River is composed primarily of low marsh. The river channel itself is approximately four feet deep with the surrounding water depth varying between 1-18 inches. Many of the marshes located in and along the river are floating root mats of vegetation, though some places are firmer (i.e., above the footbridge near Moneystump Swamp). There are also many remnant stumps throughout the area which may cause logistical issues for a restoration there. However, the area has a high shoreline which will make it easier to establish new marsh without damaging existing marsh.

There is no wave fetch present in the Blackwater River zone. However, the potential for storm damage is high because the weir that has been installed will most likely not hold in a major storm.

3.2.2. Zone 2: Confluence Area (Zone 2a: Barbados and Zone 2b: Confluence Area)

Lake Blackwater is the confluence area for the Upper Blackwater and Little Blackwater Rivers. As such it possesses a unique location in the tidal range and is the largest remaining piece of freshwater marsh in Chesapeake Bay. There are many species that depend on this area including the seaside sparrow, migratory waterfowl and various fin and shellfish. It also offers protection to surrounding wetlands and provides storm mitigation. The Lake Blackwater marshes are composed of threesquare bulrush, vegetation rarely found in Maryland. Ecotourism is also a primary benefit of the area.

Saltwater intrusion from Fishing Bay poses a threat to this fresher ecosystem, as would any alteration to Shorters Wharf Road that would increase exchange. Restoration efforts would need to maintain as low salinity as possible. Though restoration efforts would inundate existing fish habitat, this is not a major concern in the long-term as gains will far outweigh any initial issues. The displacement of migratory waterfowl must be considered, so time-of-year restrictions would apply.

Most of the area is low marsh though the potential exists to restore it to a high marsh level, thereby potentially mitigating future SLR impacts. The focus, however, should be on achieving emergent wetland vegetation. There may be some potential for upland restoration on the islands in the lake. It would be important to stabilize the Blackwater River channel before beginning marsh restoration and work backward to the marsh areas once the channel is in place.

The water level in this zone varies considerably and is approximately three feet at its deepest point. However, in many places there is a considerable amount of sludge below this “bottom” – up to 13 feet in some places. This could greatly increase the dredged material capacity in those areas but also pose logistical problems for placement and maintenance (i.e. high compaction potential), as well as possibly harmful environmental issues (i.e. bottom sludge is displaced outward from the restoration site, increasing turbidity). The potentially high nutrient concentrations in dredged material may create eutrophication of the surrounding waters if the marshes are unable to absorb the nitrogen and phosphorus. Impact to the surrounding land may also become an issue during restoration, especially because much of it is privately owned.

The confluence area is currently highly vulnerable to wave fetch and wind erosion due to Lake Blackwater.

3.2.3. Zone 3: Little Blackwater River (Zone 3a: Upper Little Blackwater River and Zone 3b: Lower Little Blackwater River)

The Little Blackwater River is a freshwater source for the marshes located in BNWR. It provides habitat and spawning grounds for migratory fish such as large mouth bass and river herring, as well as habitat to some rare plant species, including frog’s bit (*Limnobium spongia*). There are also bald eagle nests present in the area and migratory waterfowl use it as habitat. Marshes here are composed of threesquare bulrush, rarely found in Maryland.

The restoration area is composed primarily of low marsh. In the upper reaches of the river (above the canal), there have been possible gains of scrub shrub and emergent marsh. In those areas, the river channel is clearly defined and is approximately 5-6 feet deep. However, below the canal, the river channel has basically disappeared and the water level is approximately 1-18 inches throughout. The Little Blackwater River also has a high compaction potential, though not quite as severe as Zone 2. It is currently vulnerable to water quality issues because of development of the surrounding land; therefore additional nutrient issues from dredged material may pose a problem. Impact to surrounding lands during restoration may also become an issue, as much of it is privately owned.

The Little Blackwater River is the least vulnerable zone to any impacts due to wave fetch, storm damage, or SLR.

3.2.4. Zone 4: Wolf Pit Marsh

Wolf Pit Marsh was a primarily freshwater marsh, though it has become increasingly saltier due to saltwater influx from the Transquaking River and Fishing Bay. Though there is concern about restoring this zone to a freshwater marsh, restoring it to any type of marsh would be an improvement over the current state and may result in creating freshwater marsh in the long run. Wolf Pit Marsh also provides habitat for migratory birds and bald eagle nests can be found on the islands in the marsh. It is composed of threesquare bulrush vegetation.

Wolf Pit Marsh is composed primarily of low marsh though, similar to Zone 2, the potential exists to restore it to high marsh thus compensating for future SLR impacts. The water level is between 1-18 inches throughout. It also has a high compaction potential which may cause problems during restoration but also increases the dredged material capacity.

Though Wolf Pit Marsh is currently vulnerable to some wave fetch, there is the possibility that this vulnerability will drastically increase should the marshes in and around Lake Blackwater continue to disappear. Wolf Pit Marsh is also closer to saltwater sources (i.e. Transquaking River and Fishing Bay) and thus more vulnerable to saltwater intrusion due to SLR.

3.2.5. Zone 5: Lower Blackwater River (Zone 5a: Upper Lower Blackwater River and Zone 5b: Lower Lower Blackwater River)

The Lower Blackwater River empties into Fishing Bay and is thus primarily brackish tidal marsh. This zone has immense importance in that, were it to break apart or degrade, there would be direct saltwater flow into Zone 2. Because Zone 2 has extremely high scarcity benefits (i.e. largest remaining piece of freshwater marsh in Chesapeake Bay), maintaining and/or restoring the marshes of the Lower Blackwater River is critical.

The Lower Blackwater River restoration area is primarily composed of high marsh, especially in the upper portions of the zone, near Zone 2. The river channel is between 10-20 feet deep with a water level of 1-18 inches outside of the channel. There is a significant amount of sandy bottom which means there is less compaction potential in those areas. However, not much sampling has been conducted in Zone 5 so there is a dearth of information available. The freshwater issues recognized in Zones 1-4 are not present here; though it will be important to maintain sheet flow throughout the marsh, meaning the elevation of restoration can not be high enough to block the flow of water feeding the marsh. Most of the surrounding land is state-owned so private land issues should not be a problem. Overall, Zone 5 currently maintains the most integrity of any zone.

Because the Lower Blackwater River is adjacent to Fishing Bay, it is highly susceptible to SLR and the edges are especially vulnerable to wave fetch.

3.2.6. Zone 6: Transquaking River (Zone 6a: Upper Transquaking River and Zone 6b: Lower Transquaking River)

The Transquaking River empties into Fishing Bay after traveling through both freshwater (upper reaches) and brackish (lower reaches) marsh. Because the ecosystem changes so drastically from near freshwater to saltwater, the Transquaking River can actually be viewed as two separate ecosystems: that above Best Pitch Road and that below it. The upper part of the river is composed primarily of threesquare bulrush. The upper Transquaking provides habitat and spawning ground for migratory fish while the lower portion of the river is important habitat to the black rail, a Maryland bird species in need of conservation.

The upper reaches of the river have experienced large amounts of marsh loss, while the lower portion of the river has experienced significantly less marsh loss. The upper Transquaking is also victim to nutria and geese grazing pressures, which has contributed to greater marsh loss there. The river channel in the lower Transquaking River is 10-20 feet deep while the channel in the upper river is only 1-3 feet deep. Elsewhere, it is approximately 1-18 inches, though this depth is primarily found in the upper reaches. The upper part of the river would also be susceptible to freshwater issues, though the lower river would not. There are also some compaction issues in the upper river that are not evidenced in the lower reaches. Though the upper river is surrounded by privately owned land, the owner, Tudor Farms, does have a partnership agreement with the USFWS. The lower river is surrounded by state-owned land.

The upper Transquaking River experiences little vulnerability due to wave fetch or storm damage. Because the lower Transquaking River is adjacent to Fishing Bay, it is more susceptible to wave fetch and SLR.

3.2.7. Zone 7: Chicamacomico River

The Chicamacomico River travels southwest through freshwater, threesquare bulrush marsh before eventually meeting up with the Transquaking River. The Chicamacomico provides habitat and spawning grounds to anadromous fish and migratory birds so there would be time-of-year restrictions for any restoration project in the area.

The Chicamacomico River restoration area is primarily composed of low marsh. Significant pressure from nutria and geese has contributed to the overall marsh loss. The river channel is 1-3 feet deep with depths of 1-18 inches elsewhere. There are some compaction issues in the area, though not as drastic as Zone 3. Like with Zone 6, Tudor Farms owns the private land surrounding the river.

The Chicamacomico River has comparatively little vulnerability to wave fetch, storm damage or SLR.

3.2.8. Zone 8: Fishing Bay Wildlife Management Area (WMA) (Zone 8a: Upper Fishing Bay WMA and Zone 8b: Lower Fishing Bay WMA)

Much of the Fishing Bay WMA is composed of threesquare bulrush vegetation with ponds interspersed among the marsh. However, it is currently being lost due to saltwater intrusion from Fishing Bay itself, the Nanticoke River and Chesapeake Bay. Fishing Bay provides spawning grounds for migratory fish and habitat for water birds – therefore, time-of-year restrictions would apply. It is also important to note that the Nanticoke River is navigable for barges so there is potential to transport dredged material directly to the site via barge.

Most of Fishing Bay WMA is composed of low marsh. It is very important that any restoration also maintain the ponds that naturally occur within the marsh. There are not many channels within the WMA but those that do occur can be up to 10 feet deep. Most places, however, are between 1-18 inches with a 2-3 foot tidal range from Fishing Bay. There are no compaction data available for the area but it is known that the upper part of the WMA is fresher water while the lower part, closer to Fishing Bay, is saltier. The surrounding area is mostly state-owned land so private land issues would not affect any restoration.

The Fishing Bay WMA, because of tidal flow, is very vulnerable to SLR and storm damage.

4. MATERIALS AND METHODS

4.1 General Model

Before the CMR project can begin, it will be necessary to conduct a more detailed study of alternatives than the preliminary one that is presented here. To facilitate that future study, a general model is presented below in order to help guide more accurately and fully determined placement options than the optimization model used in the current analysis. The general model described here was not used for optimization purposes but it does help clarify the data requirements that will be needed in the future to complete a comprehensive analysis of options.

In this general model, benefits are annualized over *t* years at a discount rate of *dr*. From an engineering perspective, an actual restoration would be conducted using individual 100-acre restoration cells. To this end, benefits are examined at a restoration cell level, allowing more specific estimates of costs and benefits to be used to evaluate a detailed set of options. Also, restoration intensity (the level of effort expended in order to conduct the restoration) is considered a factor affecting both costs (e.g., spending per acre of restoration) and benefits (e.g., speed and level of wetland restoration).

Expected Benefits

$$B_T = (1\text{-}dr)(P_{RR})[\sum\limits^{t}\sum\limits^{i}\sum\limits^{j}\sum\limits^{k} w_B[B_{DMkjit} + (P_{AR})[\sum\limits^{l} (w_l)\,(B_{lkjitr})\,(A_{kjit})]]]$$

B_T = Total benefits across all guilds, habitat types, restoration cells, zones/subzones, and years.

dr = discount rate.

P_{RR} = Probability of success, given restoration risk.

t = year; t = 1...30.

i = zone/subzone; i = 1...13.

j = restoration cell; $j = 1...n_i$, where n_i = number of cells in zone i.

k = habitat type; k = 1...4.

w_B = benefit weight.

B_{DMkjit} = Dredged Material Benefits for habitat type k at cell j of zone i in year t.

P_{AR} = Probability of success, given ancillary risk.

l = species guild; l = 1...6.

w_l = weight assigned to guild l.

B_{lkjitr} = Habitat Index score for guild l from restoring one acre of habitat k in cell j of zone i in year t at restoration intensity r.

$B_{lkjitr} = [B_{\mathrm{lkjitr}}]_a + [B_{\mathrm{lkjitr}}]_b + [B_{\mathrm{lkjitr}}]_c$

$[B_{\mathrm{lkjitr}}]_a$ = Onsite Benefits.

$[B_{\mathrm{tijkr}}]_b$ = Offsite Benefits.

$[B_{\mathrm{tijkr}}]_c$ = Recreational Benefits.

A_{kjit} = total acreage restored of habitat type k in cell j of zone i in year t.

Expected Costs

$$C_T = (1\text{-}dr)\sum^{t}\sum^{i}\sum^{j}(C_{jitr})$$

C_T = Total Costs across all restoration cells, zones/subzones, and years.

dr = discount rate.

t = year; t = 1...30.

i = zone/subzone; i = 1…13.

j = restoration cell; $j = 1 \ldots n_i$, where n_i = number of cells in zone i.

C_{jitr} = Cost of restoring cell j in zone i in year t at restoration intensity r.

$C_{jitr} = (DR_t * V_{jit}) + (D_t * LF_{jit}) + (TC_t * V_{jit} * M_{JI}) + (DC_{jit} * V_{jit} * M_{ji}) + (MC_t * V_{jit}) + (PS_{tr} * A_{jit}) + (PC_{tr} * A_{jit}) + (MM_{tr} * A_{jit})$.

DR_t = Dredging costs in year t.

V_{jit} = Volume of dredged material placed in restoration cell j of zone i in year t.

D_t = Dike costs in year t.

LF_{jit} = Total Linear Feet of all restoration cells (j = 1,2,3…n) of zone i in year t.

TC_t = Transport Cost per mile per cubic yard of dredged material (to James Island) in year t.

M_{JI} = Mileage to James Island

DC_{jit} = Distribution Cost per mile per cubic yard of dredged material to cell j of zone i in year t (includes pipeline and booster pumps).

M_{ji} = Mileage to restoration cell j of zone i.

MC_t = Management costs of dredged material in year t.

PS_{tr} = Preparation Costs for wetland soils in year t at restoration intensity r.

A_{jit} = Area restored (acres) in cell j of zone i in year t.

PC_{tr} = Planting Cost per acre in year t at restoration intensity r.

MM_{tr} = Maintenance and Monitoring Cost per acre in year t at restoration intensity r.

Control Variables

V_{jit} = Volume of dredged material placed in cell j in zone i in year t.

w_B = weight assigned each benefit, B.

dr = discount rate

4.2. Adapted Model

The general model described above required far too much data to be applied within the time and budget limits of this project. For this reason, a simplified form of the general model was adapted so that it can be applied, at least for illustrative purposes, using data and expert opinion that could be collected. Adaptations made include: zonal-level calculations, as opposed to restoration cell-level calculations in the general model; lack of restoration intensity variation (assumed highest level of intensity); lack of a time component (costs and benefits calculated based on complete restoration at some future year without annualizing or discounting streams of costs and benefits over time).

Benefits

$$B_T = P_{RR} \sum^{i} \sum^{k} w_B \left[B_{DMki} + \left[(P_{AR}) \left[\sum^{l} (w_l)\,(B_{lki})\,(A_{ki})\right]\right]\right]$$

B_T = Total benefits across all guilds, habitat types and zones/subzones.

P_{RR} = Probability of success, given restoration risk.

i = zone/subzone; i = 1…13.

k = habitat type; k = 1...4.

w_B = benefit weight.

B_{DMki} = Dredged Material Benefit for habitat type k in zone i.

P_{AR} = Probability of success, given ancillary risk.

l = species guild; l = 1...6.

w_l = weight assigned to guild l.

B_{lki} = Habitat Index score for guild l from restoring one acre of habitat k in zone i.

$B_{lki} = [\mathrm{B}_{\mathrm{lki}}]_{\mathrm{a}} + [\mathrm{B}_{\mathrm{lki}}]_{\mathrm{b}} + [\mathrm{B}_{\mathrm{lki}}]_{\mathrm{c}}$

$[\mathrm{B}_{\mathrm{lki}}]_{\mathrm{a}}$ = Onsite Benefits.

$[\mathrm{B}_{\mathrm{lki}}]_{\mathrm{b}}$ = Offsite Benefits.

$[\mathrm{B}_{\mathrm{lki}}]_{\mathrm{c}}$ = Recreational Benefits.

A_{ki} = total acreage of habitat type k in zone i.

Costs

$$\mathrm{C}_{\mathrm{T}} = \overset{\mathrm{i}}{\Sigma}\, (\mathrm{C}_{\mathrm{i}})$$

C_T = Total Costs across all zones/subzones.

i = zone/subzone; i = 1…13.

C_i = Cost of restoring zone i.

$C_i = (\mathrm{DTU} * \mathrm{V}_{\mathrm{i}}) + (\mathrm{D} * \mathrm{LF}_{\mathrm{i}}) + (\mathrm{DC}_{\mathrm{i}} * \mathrm{V}_{\mathrm{i}} * \mathrm{M}_{\mathrm{i}}) + (\mathrm{MC} * \mathrm{V}_{\mathrm{i}}) + (\mathrm{PS} * \mathrm{A}_{\mathrm{i}}) + (\mathrm{PC} * \mathrm{A}_{\mathrm{i}}) + (\mathrm{MM} * \mathrm{Ai})$.

DTU = Dredging, Transporting, and Unloading costs at the James Island staging area.

V_i = Volume of dredged material placed in zone i.

D = Dike costs.

LF_i = Total Linear Feet of all restoration cells in zone i (assumed 100-acre square cells).

DC_i = Distribution Cost per mile per cubic yard of dredged material to zone i (includes pipeline and booster pumps).

M_i = Mileage to zone i.

MC = Management costs of dredged material.

PS = Preparation Costs for wetland soils.

A_i = Area restored (acres) in zone i.

PC = Planting Cost per acre.

MM = Maintenance and Monitoring Cost per acre.

Control Variables

V_i = Volume of dredged material placed in zone i.

w_B = weight assigned each benefit, B.

4.2.1. Onsite Habitat Benefits

A process similar to that used in the Mid-Bay Island Environmental Impact Statement (USACE 2006) was applied here with some adaptations for the sake of time and simplicity. When the habitat benefit analysis was conducted for the Mid-Bay islands, there was prior knowledge of when and where restoration would begin. The choices involved what type of restoration and restoration goals would be applied with no need to prioritize restoration sites. In the CMR study, on the other hand, the prioritization of restoration sites is the key focus. As a result much of the work that went into the Delphi exercise used to elicit expert opinion about restoration as part of the Mid-Bay Island project could not be factored into the CMR habitat value score. Also, a less time-consuming form of the Delphi method (Crance 1987) was used here where the expert panel was convened once and any discrepancies were settled over phone conference and email.

An expert panel, composed of five USFWS and six MD DNR representatives directly involved in this or similar restoration projects, was consulted. This panel determined the restoration goals for each zone/subzone using four habitat types: river channel and ponds, low marsh, high marsh, and hummock.[2] The panel based its goals primarily on historical land images for those zones with significant land loss, and current images for those zones with less loss (but with significant loss by 2023/2036 when restoration was assumed to begin). These restoration goals were used in calculations, along with water depth and marsh height, to determine the maximum amount of dredged material each habitat type within each zone/subzone can hold.

The expert panel was also used to determine the guilds, habitat use values of each guild for each habitat type, and the guild weights (Table 3). Similar guilds as those used for the Mid-Bay Island study were used here including birds, mammals, reptiles and amphibians. Additionally, the expert panel chose to include invertebrates and fish. As with the Mid-Bay island analysis, the guilds were assigned a value between 0 and 1 by the expert panel based on the use of each habitat type by each guild. In order to determine these values, the expert panel considered a multitude of potential uses each guild might have for each

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[2] For the purposes of this analysis, a hummock is defined as any vegetation higher than high marsh such that no standing water is present.

habitat type including food source, nesting, reproduction, and protection from predators. The expert panel then assigned a weight to each guild based on which guilds they thought were most important for restoration purposes (i.e. which guilds they wanted to attract to the restoration site, given a complete restoration). These usage values and guild weights were applied across all zones/subzones. For the optimization here, the habitat usage values were considered the uncertain variable; that is, they were allowed to vary across a specified probability distribution during the model iterations. This model-determined value was then multiplied by the total number of restored acres (determined by the model's allocation of dredged material) for each habitat type in each zone. This value was multiplied again by the assigned guild weight to determine the onsite habitat benefit value for each guild in each habitat type. These values were then totaled across guilds to find the total onsite habitat benefit value for each habitat type and then totaled across habitat types to find the total onsite habitat benefits for each zone/subzone.

This process was slightly modified for the habitat type Channel/Ponds. Because this habitat does not specifically require dredged material it would not be considered in the model's iterations (which center on allocating dredged material to various habitat types within various zones/subzones). Rather, it was assumed within the model that the amount of Low Marsh (the habitat type most likely to create channel or ponds) restored would provide the onsite habitat benefits of a proportional amount of Channels/Ponds habitat. This proportion was different for each zone/subzone and was equivalent to the proportion of desired Low Marsh to desired Channel/Ponds habitat as provided by the expert panel.

Table 3. Habitat Use Index and guild weights.

Guild	Channels/Ponds	Low Marsh	High Marsh	Hummocks	Guild Weight
Birds	0.75	1	1	1	0.35
Mammals	0.1	0.75	1	1	0.15
Reptiles	0.75	1	1	1	0.1
Amphibians	0.25	1	0.25	0.75	0.05
Fish	1	0.75	0.75	0.1	0.25
Invertebrates	0.5	1	0.25	0.5	0.1

4.2.2. Offsite Benefits

The expert panel was again consulted for offsite habitat benefit values. The panel scored each zone/subzone based on whether restoration of that zone/subzone would: 1) improve habitat benefits in a nearby zone or subzone; and 2) protect nearby zones or subzones from erosion. To simplify the analysis these values were used as inflators for each habitat type within each zone/subzone. An if-then statement was created for offsite benefits in the optimization model such that offsite benefits were only accounted for if the adjacent zone(s)/subzone(s) were restored. Because of model limitations, the full offsite benefit inflator was applied even if only partial habitat benefits were reached in the zone/subzone being restored, or even if only partial restoration occurred in adjacent zone(s)/subzone(s).

4.2.3 Recreational Benefits

Recreational benefits were calculated using a benefit transfer model available for download at http://dare.colostate.edu/tools/benefittransfer.aspx (Loomis and Richardson 2008). This model allowed for a calculation of the change in user days before and after restoration and provided a regional use value per day (in dollars) for each activity. User days were calculated by the Loomis and Richardson statistical model that accounted for: per capita income and population within a 60 mile radius; the presence of coastal water;

the presence of freshwater; the initial (2023/2036) acreage; and the acreage after restoration. The optimization model presented here includes three recreational activities: hunting, fishing and nonuse viewing. The total value was calculated for each zone by multiplying the change in user days by the value per user day and summing across recreational activities. These values were then normalized across zones and multiplied by the acreage restored (as determined by the model via placement of dredged material). This value was used as the recreational benefit value in the total benefits summation.

4.2.4. Dredged Material Capacity Benefits

A spatial analysis with GIS software was used to help determine the future effects of SLR at the CMC using recent LiDAR data, the predicted rate of SLR, and the measured rates of accretion and subsidence for the CMC. The LiDAR data was obtained for Dorchester County from Maryland Department of Natural Resources; SLR data was taken from a recent report detailing SLR in the Mid-Atlantic region (Titus et al. 2009); and recently measured accretion and subsidence rates for Dorchester County were obtained from USGS (D. Cahoon, personal communication, April 9, 2009). This information provided a no-action baseline of the land lost at the potential start of the project in 2023 and 2036. The maximum potential restored acreage of those habitat types requiring dredged material (i.e., low marsh, high marsh and hummock) was calculated using a GIS analysis of the 2023 and 2036-baselines and USFWS and MD DNR desired post-restoration habitat coverage.

The elevation after restoration of each of these habitat types was variable across zones/subzones. Actual field data was available for low and high marsh elevations in the

Barbados and Confluence subzones (2a and 2b) so average values for each subzone were used (D. Nemerson, personal communication, November 20, 2009). As agreed upon by the expert panel, it was assumed that those zones/subzones with tidal influence from Fishing Bay (i.e. Upper Lower Blackwater River, Lower Lower Blackwater River, Upper Transquaking River, Lower Transquaking River, Chicamacomico River, Upper Fishing Bay WMA and Lower Fishing Bay WMA) would have a wider difference in elevation between low and high marsh than those zones without tidal influence from Fishing Bay. For such zones/subzones, low marsh was considered between 0 and 1.5 feet, high marsh between 1.5 and 3 feet and hummock between 3 and 4 feet. For the remaining zones/subzones (Upper Blackwater River, Upper Little Blackwater River, Lower Little Blackwater River and Wolf Pit Marsh), it was assumed that low marsh existed between 0 and 6 inches and high marsh between 6 and 12 inches. For the purpose of calculating dredged material capacity, the upper bounds of these ranges were used.

Water depth was estimated for each zone/subzone by USFWS and these values were added to the predicted SLR increase. Additionally, it was assumed that restoration would fill in open water only, as opposed to amending existing marsh (at the time of restoration). Using these three factors (maximum potential acreage restored, restored elevation and SLR plus water depth) dredged material capacity was calculated for each habitat type within each zone/subzone. This capacity was used as the maximum amount of dredged material that could be allocated by the model for restoration of each habitat type within each zone/subzone. The actual dredged material used to restore each specific habitat type in each zone/subzone (as determined by the model) was used as the dredged material benefit in the total benefits summation.

All benefit values were scaled equally in order to remove any unit differences and to ensure the total benefits score was not unfairly influenced by any one benefit. Each benefit was then assigned a weight which was allowed to vary according to restoration goals. The weights were kept equal for the initial model runs under each baseline; however, these weights could be controlled by the user and were altered during the sensitivity analysis (see Section 5.1) to determine how much impact they had on choosing an optimal allocation of dredged material.

4.2.5. Costs

The best available cost data for the CMR project was obtained from a preliminary, planning level cost analysis performed by Gahagan and Bryant, Associates (GBA) and Maryland Environmental Service (MES) as part of an earlier assessment of this project. These two organizations provided their best estimates of costs for the following project components:

- Dike construction.
- Dredging, transporting, and unloading of dredged material at James Island.
- Distribution (via pipeline) of dredged material to the various restoration zones within the CMC (including booster pumps).
- Management of dredged material at the James Island staging area and the restoration site.
- Restoration (filling, grading, soil preparation).

- Planting/Seeding of restoration zones/subzones.
- Maintenance/Monitoring/Adaptation post-restoration.

Though most of these costs were similar for each of the restoration zones/subzones, some costs differed due to linear feet of dike needed, proximity to the James Island staging area, and the amount of dredged material required for restoration. Therefore, costs were a variable in the model that differed to some extent from one zone/subzone to another.

4.2.6. Modeling Uncertainty

The benefits and costs equations (see Section 4.2) were then entered into the optimization model. Variables with uncertainty associated with them (i.e. the Habitat Use Index) were assigned probability distributions. A uniform probability distribution was used with a maximum value of the USFWS and MD DNR-devised use value (see Table 3) and a minimum value of zero. Recreational and dredged material capacity benefits were not influenced by the Habitat Use Index and thus did not have a probability distribution assigned to them (see Sections 4.2.3 and 4.2.4 for details on how recreational and dredged material benefits were estimated).

Total cost was designated as a model constraint and assigned a maximum value, such that the total cost of the project was restricted to no more than $2 billion based on King et al.'s (2007) preliminary cost assessment. Total benefits and total costs were designated as forecast cells of the model and contained equations that related the model inputs to each other. (See Appendix A for more detail on the optimization model and Crystal Ball® software.) The model was run for 50,000 – 100,000 simulations (5,000 trials per simulation) with an 80% confidence contingency (solution values at the end of the model run fell within an interval that accounted for 80% of all solution values calculated thus far), as recommended by USACE for risk analysis. The sensitivity of the model was then tested by running the model with full weight placed on each benefit individually to determine which benefits contributed most significantly to the total benefit score and to determine how weights assigned to different benefits affected model outcomes.

4.2.7. Modeling Risk

Risk was also factored into the optimization model. Best professional judgment (J.C. Stevenson and J. Cornwell, personal communication, December 10, 2009) was used to estimate the risks associated with achieving habitat benefits based on previous experience at the Poplar Island restoration and what is known about the CMC ecosystem. The risk of potential harmful algal blooms (HAB) caused by the excess nutrients in the dredged material was incorporated into the model as an additional factor in the habitat benefits calculation. HABs can cause any number of subsequent problems in an ecosystem including low dissolved oxygen, high turbidity, and disruption of food web dynamics. It was estimated that there was a 70% probability of a HAB not occurring; the onsite habitat benefit score was thus multiplied by 0.7 to calculate the adjusted onsite habitat benefit score. The probability of a HAB (30%) was then multiplied by the likelihood of success if the contamination occurs (estimated to be 40%) and then applied to the adjusted onsite benefit score to arrive at the risk-adjusted onsite habitat benefit score. This also affected the offsite habitat benefits, as they were calculated as an inflator of the onsite habitat benefits.

The overall success of restoration was also considered here, where success is defined as prosperous vegetation that allows full habitat benefits to be reached. Wave fetch was used as an indicator of potential restoration failure and was estimated by best professional judgment to decrease the likelihood of a successful restoration by 40% (or, put another way, the risk posed by wave fetch results in a 60% chance of having a successful restoration). This estimate was based on what is known about the CMC ecosystem and its susceptibility to erosion caused by wave fetch. This was then applied as a deflator to the total benefits score to calculate the total, risk-adjusted benefits score.

4.2.8. Model Set-Up

A brief description of how the equations and variables presented above fit into the optimization model used here may be beneficial to those readers not familiar with such programs. The model itself is a simple excel spreadsheet that contains the Habitat Use Index (see Section 4.2.1) and a distribution of the zones/subzones, subdivided into the four habitat types. This zonal distribution is used for dredged material allocation (performed by the model during runs) and subsequent restored acreage calculations; calculation of each benefit (as described above); and calculation of costs. These calculations are summed for all habitat types within a zone/subzone and across all zones. This excel spreadsheet is then imported into the Crystal Ball® software where the variables are defined as either assumptions variables, which are the uncertain variables assigned a probability distribution (i.e. the Habitat Use Index values); decision variables, which are assigned a minimum and maximum value (i.e. the dredged material allocated to each habitat type in each zone/subzone); or forecast cells, which are the model outputs (i.e. total costs summed across all zones/subzones and total benefits summed across all zones/subzones). The OptQuest® add-on program to Crystal Ball® is then used to define the constraints on the model (i.e. the amount of dredged material placed over all zones/subzones cannot exceed 70 mcy) and the objective of the optimization (i.e. maximize total benefits with a requirement that total costs cannot exceed $2 billion). The model is then run for 50,000 – 100,000 simulations with 5,000 trials per simulation where one simulation is equal to one allocation of dredged material across zones/subzones (decision variable) and one trial is equal to the calculation of total benefits and total costs (forecast variables) given a specific value within the habitat use index (assumption variable). The model then averages the forecast cell values (total benefits and total costs) over the 5,000 trials and this becomes one simulation solution. Infeasible solutions (those that exceed the cost requirement) are discarded. The "best" solution (i.e. highest total benefit score within the cost constraint) is the "optimal" solution presented here. See Appendix A for more details on Crystal Ball® software and its optimization abilities.

4.3. Model Assumptions

Several assumptions not yet discussed were made regarding the model and its inputs. As mentioned previously, it was assumed that 2023 and 2036 were the years in which a potential restoration would begin and these were considered the baseline years for all calculations. However, it was further assumed that the benefits were being measured at some future year when restoration is complete. Cost data were in 2009 dollars. The accretion and subsidence rates (D. Cahoon, personal communication, April 9, 2009) were assumed to remain constant between now and 2023/2036. In fact, they were so close in value (3- 3.5 mm/yr and 3.5-4 mm/yr, respectively), it was further assumed that they would balance each other out and not contribute to additional SLR. The annual rate of SLR itself was also assumed to remain constant between now and 2023/2036 at 11 mm/yr.

For purposes of the GIS analysis, there were several assumptions made. In order to determine the amount of Channel/Ponds habitat that remained in 2023 and 2036, a judgment call was made by the expert panel based on GIS analysis: it was assumed that all of the river channel and ponds would be gone by both 2023 and 2036 in all zones except 3a and 3b. It was further assumed that all of the mainstem channel in subzones 3a and 3b would be gone by 2023 and 2036 with the smaller channels branching off of the mainstem remaining mostly intact in both years. The actual area of the Channel/Ponds habitat category was somewhat difficult to calculate and thus several assumptions were made in order to do so. The channel areas were calculated in GIS by buffering each channel or offshoot to a width specific to that individual channel and multiplying the buffer width by the length of each segment (calculated by GIS statistics). All segment areas were totaled for each zone/subzone.

The Ponds portion of the Channel/Ponds habitat category was determined differently for federally-owned lands and state-owned lands. The USFWS decided that in their zones (1-4), they did not need to differentiate between a “pond” and “open water” – meaning that any area in the zone that was not Low Marsh or High Marsh was by default Channel/Ponds habitat. Therefore, separate calculations for “channel” vs. “ponds” were not necessary. For the state-owned lands (5a-8b), MD DNR chose to quantify “ponds” habitat area as 2% of Low Marsh habitat area. This amount was then added to their desired “channel” area to calculate the total Channel/Ponds habitat area.

See Table 4 for a step-by-step summary of the optimization model process.

Table 4. Step-by-step process for preparing and running the optimization model.

	Model Component	Description	Source
Step 1		Divide zones into subzones where appropriate.	Expert Panel (USFWS and MD DNR)
Step 2	On-Site Habitat Benefits	Determine habitat types, guilds, usage values and guild weights. Calculate onsite habitat score.	Expert Panel (USFWS and MD DNR)
Step 3	Off-Site Habitat Benefits	Determine offsite inflator based on habitat use and erosion protection. Calculate offsite habitat score.	Expert Panel (USFWS and MD DNR)
Step 4	Recreational Benefits	Determine recreational score using benefits transfer model. Calculate recreational benefits.	Loomis and Richardson, 2008
Step 5	DM Benefits	Calculate DM capacity using restored acreage, sea level rise predictions, marsh elevation, and water depth.	GIS Analysis, Expert Panel, NAB
Step 6	Costs	Obtain cost estimates for each stage in the restoration process.	GBA and MES
Step 7	Equations	Define the relationships between all inputs in an excel spreadsheet model such that the outputs (total benefits and total costs) are determined by dredged material placement.	
Step 8	Probability Distributions	Assign probability distributions to habitat suitability index values.	
Steo 10	Benefit weights	Assign a weight to each benefit type.	
Step 11	Model Constraint	Assign constraints to model (i.e. maximum cost and dredged material availability).	
Step 12	Model Target	Assign model's target (maximize benefits while restricting costs to $2 billion).	
Step 13	Run	Run model and assess results.	
Step 14	Sensitivity Analysis	Perform sensitivity analysis on weights assigned to benefits and guilds.	
Step 15	Results	Interpret results and develop recommendations.	

5. RESULTS AND DISCUSSION

By offering a combination of restoration alternatives (i.e. various habitat types within various zones/subzones), the model helps identify restoration options with the highest sum of weighted benefits or options that can meet a specific benefit target at the lowest possible cost. Based on the available information, therefore, the model allows the user to weed out those options that are clearly inferior because other options provide the same benefits at lower costs or provide higher benefits at the same costs. Although based on incomplete information, these model runs will be useful for guiding subsequent assessments and comparisons of the most promising options; and for targeting data collection to test and invalidate or accept some of the results presented here that reflect various combinations of best professional judgment and preliminary optimization modeling.

5.1. Adapted Model

5.1.1. General Results

The results of a model run, with a particular set of weights and constraints, provide one potential distribution of dredged material to restore wetlands (Table 5) where maximum benefits are achieved under a given set of cost and dredged material constraints (Table 6).

Table 5. 2023 and 2036 acreage restored across zones of the CMC.

2023														
Habitat Type	**1**	**2a**	**2b**	**3a**	**3b**	**4**	**5a**	**5b**	**6a**	**6b**	**7**	**8a**	**8b**	**Total**
Channel/Ponds	0	828	2,615	0	551	702	0	0	0	0	0	0	0	4,697
Low Marsh	0	1,324	2,615	0	1,287	702	0	0	0	0	0	0	0	5,928
High Marsh	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hummock	0	0	0	0	0	0	0	0	0	14	270	0	0	284
Total	0	2,152	5,230	0	1,838	1,404	0	0	0	14	270	0	0	10,909
2036														
Channel/Ponds	300	1,092	2,714	0	0	1,080	0	0	0	0	0	0	0	5,186
Low Marsh	600	1,747	2,714	0	0	1,080	0	0	0	0	0	0	0	6,142
High Marsh	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hummock	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	900	2,838	5,429	0	0	2,161	0	0	0	0	0	0	0	11,328

Table 6. Model output for dredged material allocation in 2023 and 2036.

	2023	**2036**
Total DM (cy)	28,268,090	31,508,213
Total Acres	10,909	11,328
Total Benefits Score	2.93	2.60
Total Cost	$1,988,474,868	$1,999,994,931

There were several obvious differences in the equally-weighted model results generated using the same model specifications for the two project commencement years, 2023 and 2036. The 2023 model spread the dredged material out over six zones (no dredged material was placed in Zone 1, Zone 3a, Zone 5a, Zone 5b, Zone 6a, Zone 8a, or Zone 8b), while the 2036 model paced dredged material in only four zones, leaving 60% of the zones empty, including Zone 1, Zone 3a, Zone 4, Zone 5a, Zone 6a, Zone 7, Zone 8a, and Zone 8b. This resulted in greater benefits from the 2023 model (13% greater than the 2036 model) at a slightly lower cost. Despite the lower benefits, the 2036 model used a larger amount of dredged material (11% more) and restored a slightly greater amount of acreage with that dredged material (4% more).

The costs associated with using dredged material turned out to have a significant effect on zone selection. In 2036, restoring the same acreage of the same habitat type requires more dredged material than restoring it in 2023 (due to SLR). This also increases the costs associated with restoration; thus, restoring the same acreage in 2036 will cost more than restoring that acreage in 2023. In fact, because of the high cost associated with transporting and placing the dredged material, it is actually impossible to use the entire 70 mcy available under the $2 billion cost constraint in either year. As we see from the model runs, even those options that use the most dredged material only allocate approximately 45% of the 70 mcy available. This may explain why the 2023 model was able to spread the dredged material out over a greater number of zones. Because cost increases with distance from the James Island staging area, it costs less to place dredged material in nearby zones and avoid traveling to the zones that are farther away. As would be expected, the 2036 model placed little or no dredged material in the zones farthest away from James Island but instead selected sites in the four zones nearest the staging area.

There were a number of similarities between the results of the two models that are also noteworthy. Both models placed a significant amount of the dredged material in Zone 2a (Barbados Island) and Zone 2b (Confluence Area), specifically in the low marsh habitat category. As a result, low marsh in these zones made up a significant amount of total acreage restored (36% for the 2023 model and 39% for the 2036 model). This indicates that, based on model inputs, restoring low marsh in the Confluence Area and Barbados Island provides significant benefits and should be considered for restoration, regardless of the baseline year examined here. Also, low marsh across all zones/subzones was allocated a significant majority of dredged material in both models (approximately 54% for both model start years). Again, this indicates that low marsh provides significant benefits and may potentially be the most important habitat type for restoration purposes regardless of how far into the future the restoration is expected to begin.

It is also important to note that both models placed no dredged material in Zone 3a (Upper Little Blackwater River), Zone 5a (Upper Lower Blackwater River), Zone 5b (Lower Lower Blackwater River), Zone 6a (Upper Transquaking River), Zone 8a (Upper Fishing Bay WMA) and Zone 8b (Lower Fishing Bay WMA). This indicates that a restoration undertaken in these zones may not provide benefits significant enough to justify the costs, no matter the baseline year. Thus it would appear that the model runs indicate that using dredged material for restoration in these zones is clearly an inferior alternative that should not be considered until other alternatives have already been undertaken. Zones 2a and 2b, for example, are determined to be a superior restoration option to Zones 3a, 5a, 5b, 6a, 8a, and 8b in both model runs, based on an equal weighting of all benefits.

Theoretically the model should eventually find the solution that restores the most acreage and uses all, or nearly all, of the available money. This appears to be true of the 2036 model run which was run for 50,000 simulations (approximately 24 hours) and used $1,999,994, or 99.9997% of available funds. The 2023 model run, however, was run for 100,000 simulations (approximately 48 hours) and used only $1,988,474,868 of available funds, or 99.4237%. Because this represents the vast majority of funds available, it was determined that the model had run for an acceptable amount of time and reached an acceptable "best solution." While a great deal of time could be spent re-running the model until all funds have been used, this would most likely not significantly increase the total benefits score or alter the model-generated optimal solution and was determined not be worthwhile.

5.1.2. Uncertainty Results

The ability of Crystal Ball® optimization software to incorporate uncertainty into the model was a key factor in choosing it for this analysis. By examining the range of total benefit score values associated with each model solution discussed here, we can interpret the role uncertainty played in the optimization.

Uncertainty is incorporated into this model via the Habitat Use Index values. Because the actual use of each habitat type by each guild can not be definitively determined, a probability distribution was associated with each guild use value. For each simulation of the model, 5,000 different values were randomly chosen from the associated probability distribution for each guild-habitat use in the Habitat Use Index. The model then calculated the total benefits score for each of these 5,000 value combinations. Based on the model results for the 2023 model run, the minimum total benefits score is 2.00, while the maximum total benefits score is 3.83, with an average total benefits score of 2.93. For the 2036 model run, the minimum total benefits score is 2.00, the maximum is 3.00, and the average is 2.60.

These results show that the 2023 model run has a wider distribution of scores than the 2036 model run, and thus a higher average total benefits score. This is most likely due to the fact that the 2023 model run has more placement options for dredged material than the 2036 model run under the same cost constraint, given the high cost of distributing the dredged material. Because less dredged material is required to restore the same acreage in 2023 than in 2036, the 2023 model can place more dredged material and travel to farther away zones to do so than the 2036 model. This increases the potential total benefits score for the 2023 model run.

5.1.3. Sensitivity Analysis

5.1.3.1. Benefits

Sensitivity analysis (Figure 9) shows that the results were most influenced by onsite habitat benefits during runs commencing in 2023 and by recreational benefits during runs commencing in 2036. It is also interesting to note that most of the 2023 model runs achieved greater benefits using less dredged material (and restoring more acreage) than the 2036 model runs, indicating that the 2023 model had a lower cost/acre restored (Table 7).

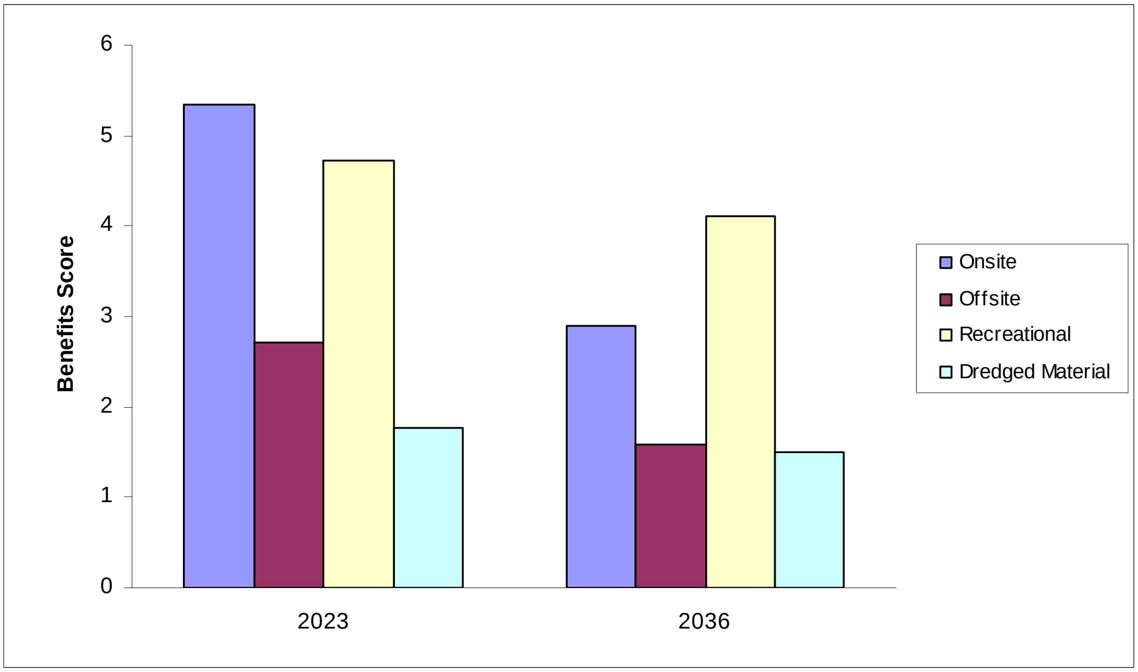


Figure 9. Sensitivity results for each baseline model year showing which benefits most influenced the total benefits score.

Table 7. Sensitivity results.

Model Run	Benefits Score		DM Used (cy)		Acreage		Cost	
	2023	2036	2023	2036	2023	2036	2023	2036
Onsite	5.35	2.89	28,605,317	30,370,751	9,148	8,626	$1,992,192,833	$1,889,385,901
Offsite	2.71	1.59	28,992,690	31,895,398	6,154	7,819	$1,966,189,850	$1,948,283,866
Recreational	4.73	4.11	28,509,972	29,365,664	9,045	8,181	$1,845,050,527	$1,897,899,316
Dredged Material	1.76	1.51	30,681,836	30,364,982	6,066	6,361	$1,991,308,296	$1,951,362,517

Though the 2023 onsite habitat benefits model costs were approximately 5% higher than the 2036 model, the onsite benefits achieved were almost double. In fact, the sensitivity analysis shows that cost-wise, there were only marginal differences between the model years for all sensitivity analysis runs. The acreage restored shows relatively small differences between the runs (10% or less) as well, except in the case of the offsite habitat benefits run. Here, the 2036 model restored 27% more acreage (using 10% more dredged material) but achieved only 59% of the benefits achieved by the 2023 model. This difference can probably be explained by examining the distribution of dredged material. The 2036 offsite habitat benefits model run placed dredged material across just six zones, while the 2023 offsite habitat benefits model run spread it out over eleven zones. While this resulted in lower costs for the 2036 model, it also meant lower benefits. Because offsite habitat benefits are only generated by restoring habitat in adjacent zones/subzones, allocating dredged material over more zones/subzones increases the likelihood of restoration occurring in an adjacent zone/subzone, thus achieving greater offsite habitat benefits.

Comparing the spatial distribution of dredged material placed by the model during the various runs provides some insight into how the benefit weights affect restoration priorities. The 2023 model runs all show that Zones 2a and 2b provide significant benefits, no matter which benefit is maximized (Figure 10). However, maximization of offsite habitat benefits shows more emphasis on restoring Zones 8a and 8b, as does maximizing dredged material benefits. The greatest acreage was restored under the equally-weighted scenario but maximizing onsite habitat benefits and maximizing recreational benefits achieved 84% and 83% of this restored acreage, respectively. The 2036 model runs also show the greatest emphasis on restoring Zones 2a and 2b, no matter which benefit is maximized with the exception of onsite habitat benefits which focuses mainly on Zone 2b (Figure 11). Maximizing dredged material benefits offers the greatest distribution between zones/subzones and the greatest acreage was restored under the equally-weighted model run. These results will be useful for future decisions regarding restoration priorities. For example, a project beginning in 2023 that hopes to maximize the acreage restored should focus on the equally-weighted scenario. However, should decision-makers wish to maximize the amount of dredged material used, the dredged material model run would provide the greatest benefit.

Though the total benefits score for each sensitivity analysis run ultimately represents the maximized benefit, scores for all other benefits were also calculated (but not included in the final total benefits score). A comparison of each calculated benefit under the various model runs offers potential indirect benefits that may result from focusing on individual benefits. For example, by maximizing onsite habitat benefits during the 2023 model runs, very high recreational benefits were also achieved (Table 8). Similarly, by maximizing recreational benefits, the greatest offsite habitat benefits and very high onsite habitat benefits were achieved. For the 2036 model runs, maximizing onsite habitat benefits provides the highest recreational benefit and close to the highest dredged material benefit. This information will be particularly important for future research when deciding what benefits are most important and should be included in future analyses.

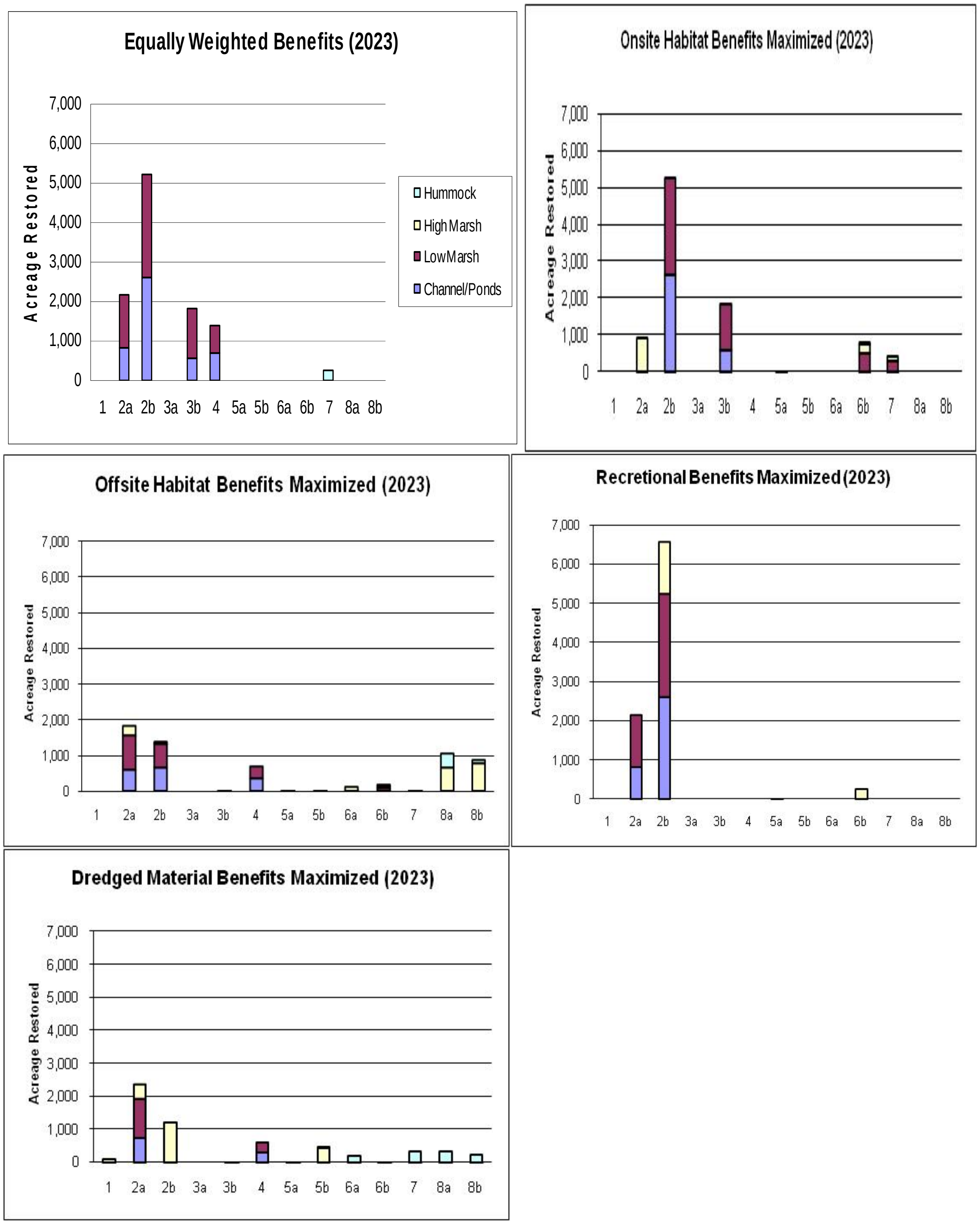


Figure 10. Acreage restored under various benefit weightings for 2023 model runs.

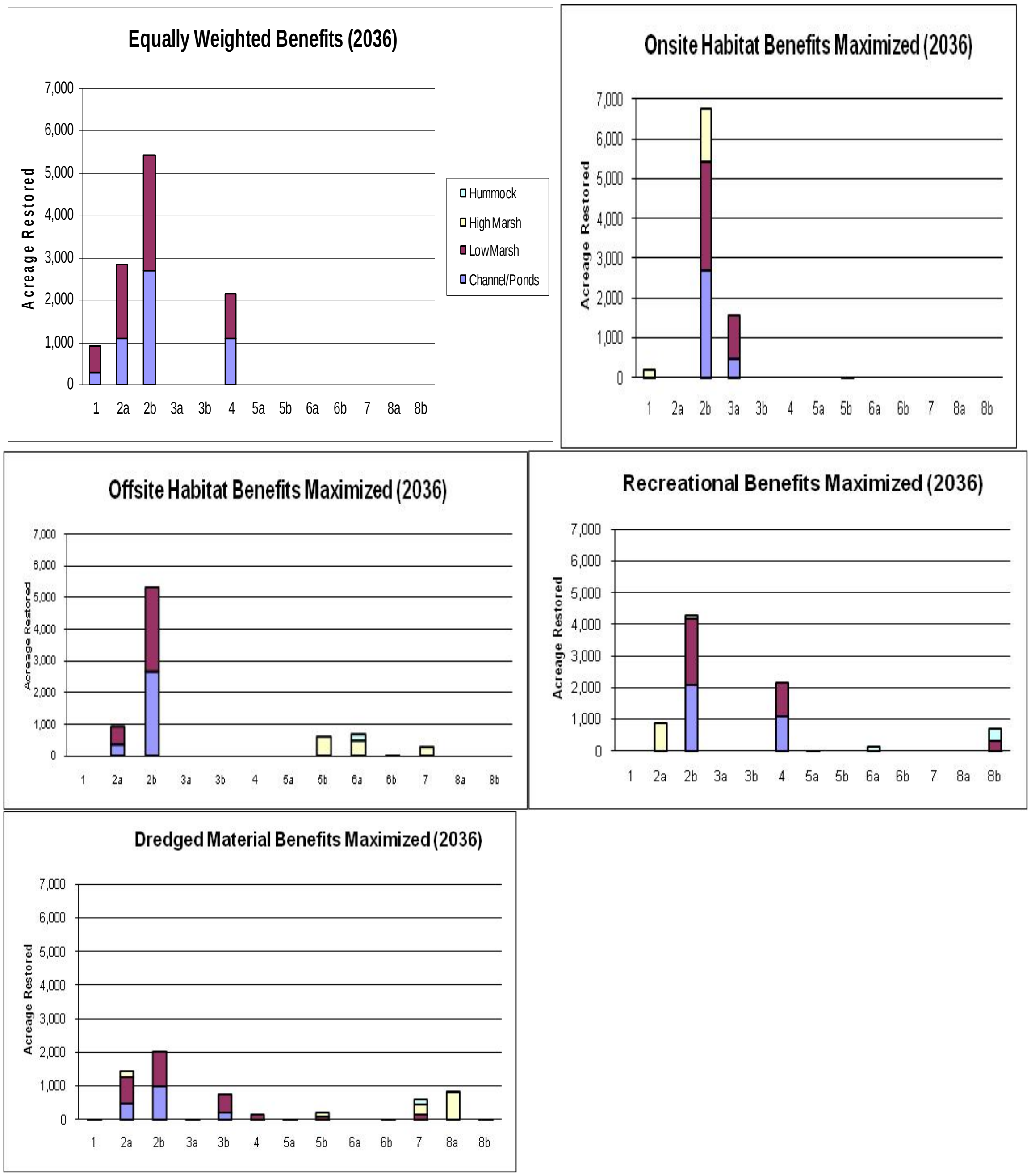


Figure 11. Acreage restored under various benefit weightings for 2036 model runs.

Table 8. Breakdown of benefits scores under various benefit weightings.

Maximized Benefit	Onsite	Offsite	Recreational	Dredged Material
			2023	
Onsite	5.35	0.01	4.07	1.64
Offsite	3.48	2.71	2.06	1.66
Recreational	5.28	3.16	4.73	1.63
Dredged Material	3.32	2.16	1.99	1.76
			2036	
Onsite	2.89	0.00	4.42	1.51
Offsite	2.61	1.59	3.97	1.59
Recreational	2.72	0.24	4.11	1.46
Dredged Material	2.10	1.32	2.52	1.51

It should also be mentioned that, while the actual values for each benefit measured under various benefit weightings differed, the proportions of each benefit to the total benefit score did not vary significantly (Figure 12). During the 2023 model runs, onsite habitat benefits consistently represented the greatest proportion and during the 2036 model runs, recreational benefits represented the greatest proportion. The smallest proportion was usually contributed by dredged material benefits in the 2023 runs and by offsite habitat benefits during the 2036 runs.

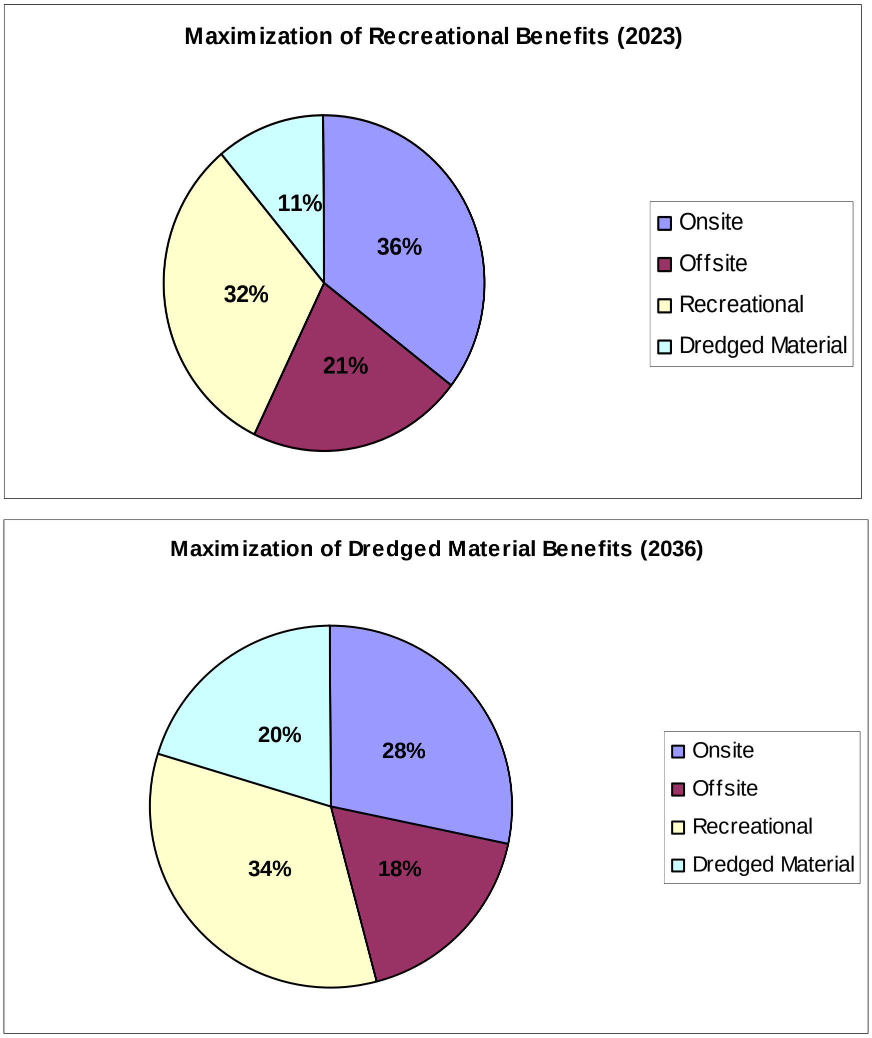


Figure 12. Representative distribution of benefits for each model year.

5.1.3.2. Costs

An abbreviated sensitivity analysis was also conducted using just the 2023 model in order to determine whether significant differences arose under varying financial situations. Given that the CMR project is considered expensive and risky, it is likely that less money will be available, as opposed to more. For this reason, the model was run under monetary constraints of $500 million, $1 billion, and $1.5 billion. As would be expected, the total benefits score decreased with decreased funding, as did the amount of dredged material used and subsequent acreage restored (Table 9). The distribution of dredged material placed by the model shows that Zones 2a and 2b are still an important focus (Figure 13). When compared to the model run under $2 billion, the dredged material is distributed over fewer zones/subzones, most likely due to the added expense of transporting the dredged material as discussed previously. These results also show that some zones may be somewhat more important under lower cost constraints. For example, both the $500 million and $1 billion model runs restored acreage in the Upper Little Blackwater River Zone (3a); however the $1.5 billion run did not. This indicates that there may be a threshold cost constraint between $1 and $1.5 billion where restoring Zone 3a no longer becomes economically feasible or environmentally important. A similar threshold may be present for other zones/subzones, indicating again that the results presented here are subject to the constraints placed on the model and may change if those constraints are changed.

Table 9. Sensitivity results for cost constraint variations.

Model Run	**Benefits Score**	**DM Used (cy)**	**Acreage Restored**	**Total Cost**
$500 Million	0.92	7,414,621	2,375	$492,368,177
$1 Billion	2.01	14,877,963	4,940	$991,795,747
$1.5 Billion	3.13	18,882,390	7,397	$1,242,944,320
$2 Billion	3.57	28,658,992	9,227	$1,995,452,347

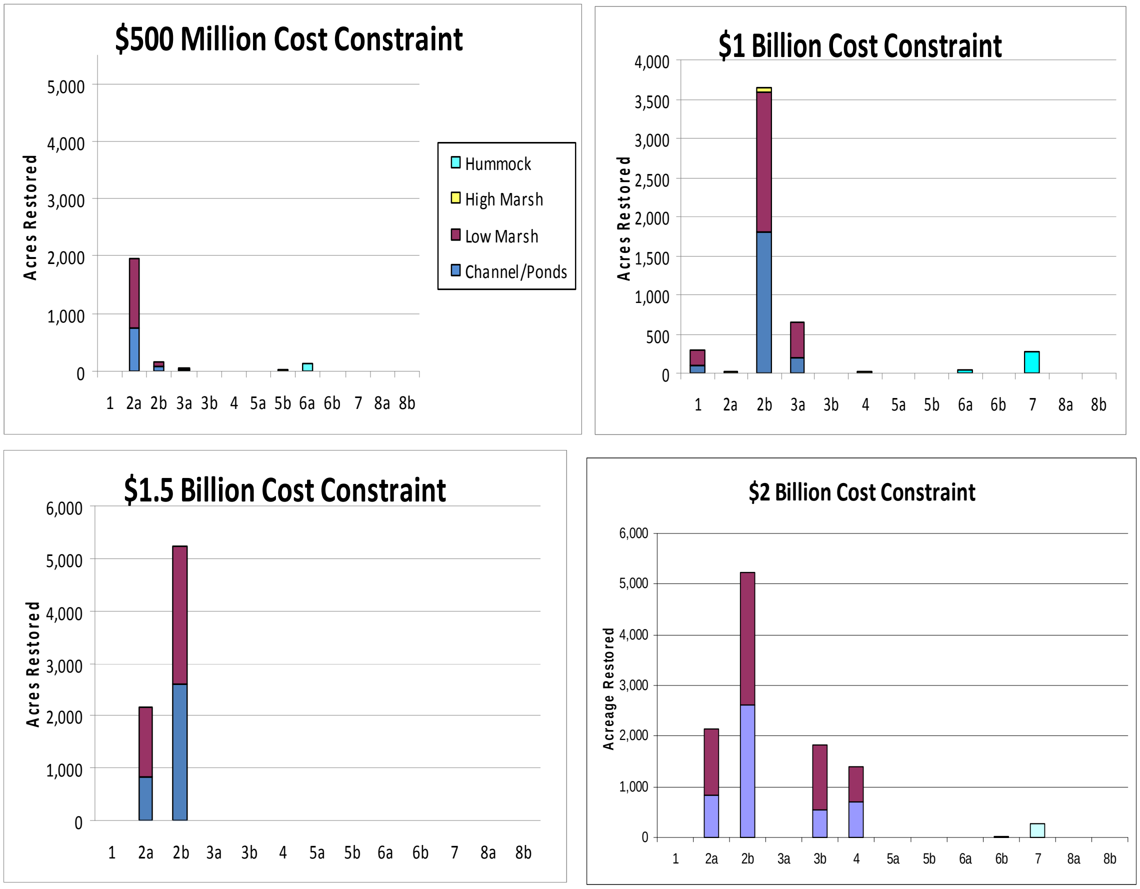


Figure 13. Acreage restored under various cost constraints run on the 2023 model.

5.1.4. Discussion

It is important to note that the results presented here represent a first attempt at quantifying the various benefits, costs and risks associated with using dredged material for a CMC restoration, and that they offer one potential solution for allocating dredged material throughout the restoration zones/subzones. There is much that can be improved upon with this model, and many opportunities for more accurate and site-specific data (see Section 5.2). Also, as with most optimization models, the results greatly depend on the assumptions and constraints placed on the model which will most certainly be improved as more information is collected about the CMC and more observations are made to validate SLR impacts on the composition of various habitat types at the CMC.

For example, one assumption used in the model is that subsidence and accretion rates will remain steady between now and the start of the restoration. This assumption was necessary because of data gaps that may be filled in the near future which could significantly affect the model results. It is highly unlikely that subsidence and accretion will maintain a constant rate and the importance of both in determining SLR could dramatically change the predictions that have been made by others (Titus et al. 2009) and used to set up the model applied here. If sea level rise in the CMC region is much greater than the prediction of a constant rate that was used here, it could dramatically alter the dredged material capacity of each habitat type in each zone/subzone. Predicting future accretion and subsidence rates based on recent measurements has not been done for the CMC region, and the rates used here were not spatially specific but applied more or less uniformly across all zones. Should models for predicting future rates not be feasible, it would increase the accuracy of the optimization model used here to at least incorporate a spatial aspect to the measurements.

For the purposes of this model, only four benefit types were considered: onsite habitat, offsite habitat, recreational, and amount of dredged material used. This in no way exhausts the potential benefits of a CMC restoration. As discussed earlier, wetland restoration can provide benefits such as erosion control and subsequent property protection; groundwater recharge and subsequent water quality improvements; shoreline anchoring and subsequent infrastructure and property protection; etc. These benefits could be fit into the optimization model by determining their various leading indicators – those metrics that are considered suitable measurements of such benefits. For example, the filtration capacity of wetlands can be accounted for by measuring the nutrient concentration of water entering a wetland versus the nutrient concentration of water leaving a wetland. This difference in nutrient concentration could then be considered the improved water quality benefit of a wetland. The optimization model used here has the capacity to include any number of additional wetland restoration benefits which would greatly improve the model results. The number of environmental benefits addressed in the models developed here and the types of indicators used to reflect them were dictated, to a large extent, by a combination of data limitations and limitations on the amount of time and money that could be spent to complete this initial exercise to examine and compare options for the CMC project.

Additionally, the habitat benefits were based on the usage value of six animal guilds and four habitat types. Breaking these animal guilds down into more specific groups would certainly alter the model results. For example, the “birds” guild used here could be divided into several different kinds of birds such as wading birds, shore birds, nesting birds, waterfowl, etc. Determining a use value for these sub-guilds would again add more specificity to the model and allow for inclusion of competing factors that occur within the guilds used here.

There are also many other forms of risk that could be incorporated into the model. The model described here includes only two measurements of risk: the risk of algal blooms and subsequent decrease in water quality due to excess nutrients in the dredged material; and the risk of restoration failure which was determined to be correlated with wave fetch.

Other possible risks include risk of storm damage during and after restoration; saltwater intrusion due to restoration efforts; noise/visual impacts from restoration; etc. The probability of these risks can be quantified in ways that were not possible within the scope of this project.

The probability of the risk to water quality and overall success of the restoration incorporated in this model were quantified by best professional judgment. This is likely to impart a subjective bias, though one loosely based on scientific data. Rather than using expert opinion based on results at Poplar Island, as done here, the risk to water quality could be quantified using probabilistic modeling of historical data (i.e. likelihood of a severe storm event occurring). For overall risk (based on wave fetch), incorporating a spatial aspect would be very beneficial. By normalizing the spatial data, an individual deflator could be applied to each zone that represents this probability of overall risk. Risk is often higher at some restoration sites than others; this may certainly be true of sites at the CMC because it represents such a large area of land with a wide variety of characteristics. Spatially quantifying risk would further aid the model in choosing more optimal restoration sites as it would provide further delineation of the differences that exist between sites. A model is currently available that aids in spatially determining wave fetch and could be applied to this analysis (http://www.umesc.usgs.gov/management/dss/wind_fetch_wave_models.html). When incorporating risk into the model, it is important to include not only the probability of the risk occurring, but also the likelihood of achieving benefits even if the risk does occur.

This ensures that we account for the difference in benefits between the lack of the risk and the occurrence of the risk.

The onsite and offsite habitat benefits were determined via expert panel using a modified Delphi method. Using an expert panel to quantify the Habitat Use Index and offsite habitat use values inherently implies subjectivity since opinion is used to create model inputs. In order to avoid this subjectivity, and if more time and money were to become available to examine CMC options, it would be ideal to conduct field research to determine a species list for each zone/subzone and then determine how each species uses each habitat type in each zone (e.g. food source, nesting/reproduction, etc.). Data could then be used to create more accurate habitat indices with which to compare areas and potential restoration outcomes.

Even without using this somewhat time-intensive method, the benefit quantification could be improved upon. Due to time restrictions and scheduling conflicts, for example, members of the expert panel from USFWS met to discuss the federally owned zones/subzones and members from the MD DNR met separately to discuss the state-owned zones/subzones. Different meeting arrangements may have yielded different results in terms of “best professional judgment.” To overcome potential conflicts after these initial meetings, any subsequent issues that arose were handled over email or phone conference. For example, after the first meeting there were discrepancies between USFWS- and MD DNR-designated use values for each guild (which comprised the Habitat Use Index). In a traditional Delphi method, these discrepancies would have been presented to the group via mail/email and another meeting convened to discuss and resolve them; and this process would continue until consensus was reached. Here, however, time was imperative and the quickest method for resolving these discrepancies was via a phone conference. Because the phone call was set shortly after an email notifying the expert panel of these discrepancies was sent; attendance at the phone conference was much lower than it would have been if there was more time available to set a date that worked for all or most of the panel. Time-dictated modifications such as this most certainly affected the accuracy of the method for determining the habitat use values and subsequent onsite and offsite habitat benefits and reduced the level of confidence below what may be possible in the future if researchers have more time and/or a budget to convene (and perhaps pay a stipend) to a group of experts.

The method of normalization used for each benefit could also have potentially influenced the results presented here. The maximum potential score across all zones was used to standardize each benefit score by dividing the model-determined benefit score by this maximum potential score. Because acreage was incorporated into all benefit scores, the largest zone (Zone 8b) had the maximum potential score (assuming a full restoration of that zone). Therefore, using it for the normalization of benefits likely underestimated the other benefit scores. Additionally, the normalizing benefit value calculated for Zone 8b was based on a full restoration of the zone. Full restorations of any zone was rarely chosen by the model, thus potentially further underestimating the benefits of partial restorations in all zones/subzones, including Zone 8b. Using a restoration-cell level of analysis would improve this complicating factor – if all cells are approximately 100 acres, there should be no unfair advantage due to size.

As this model represents a first attempt at measuring benefits, costs and risks, it is important to mention how the process evolved and what aspects were altered from the original plan so that subsequent research can take this into account. First, the zones that were originally designated by the USACE were modified at the request of USFWS and MD DNR. Not only did the expert panel divide some of these zones into subzones but they also changed the boundaries of a number of zones so that they included or excluded some lands. Also, when deciding upon what habitat types to include in the habitat index, the expert panel originally designated an "open water" habitat type. However, due to the amount of open water that will be available in 2023 and 2036, this habitat type becomes so abundant that additional units lose nearly all of their "scarcity" and resulting habitat value. Therefore, this category was eliminated and, at the request of the expert panel, the "Channel" category was changed to "Channels/Ponds" to include smaller areas of open water that have some special value and would require some extent of marsh restoration.

5.2. Future Research Necessary to Apply General Model

A general model was built to reflect how a risk-based optimization model might be developed in an ideal situation with abundant resources and a reasonable amount of time available for data collection and analysis. This model should be useful in the future if and when researchers begin to examine whether a multibillion dollar CMC restoration project makes sense in terms of costs, material placement capacity, and environmental and other benefits. Because of time and monetary restrictions for this project, an actual optimization was not run using this general model. Instead, the potential usefulness of the general model was examined by applying an adapted version where inputs were constrained by time and data restrictions.

For the preliminary optimization analysis using the adapted model, the CMC region was broken down into thirteen zones/subzones. Dredged material was allocated to three habitat types within these zones/subzones. This entails a relatively low amount of spatial detail given that the largest zone was over 20,000 acres, and even the smallest was more than 1,800 acres. Based on expert opinion it was determined that whatever the size of the restoration area, restoration activities are usually conducted separately for 100-acre cells (C. Roche, personal communication, January 8, 2010). Using this designation, the habitat types within each zone could be divided into geographically specific 100-acre restoration cells. This would significantly improve the cost estimation as some costs depend on distance from the James Island management area which would be somewhat different for each 100-acre cell; and offer more specific optimal site recommendations for maximizing benefits by allocating dredged material. For this reason, both the general model (that was not tested) and the adapted model (that was tested) were specified with control variables addressing the amount of dredged material and the number of habitat acres restored at the 100-acre restoration cell level.

There are many data requirements that would need to be met in order to run the idealized general model. For example, the elevation of low and high marsh has been measured (by a National Aquarium, Baltimore study) in two of the study zones (Zone 2a and Zone 2b); however, elsewhere in the marsh, this value had to be estimated based on what is known about the tidal range, structural restrictions to the tides, etc. Similarly, water depth has not been spatially and completely measured across all zones and, for the purposes of the adapted model, had to be estimated by the expert panel. In order to accurately run the general model, this data would need to be collected for each individual 100-acre restoration cell in each zone.

A time factor is also considered in the general model, taking into consideration the discount rate and the fact that, due to the nature of habitat restoration and the lag time between when restoration is complete and when the habitat reaches its full potential, benefits do not immediately accrue at their assumed maximum value (Figure 14). In a complete analysis, benefits accrued in the future must be discounted back to the net present value because they do not have the same value as benefits accrued immediately. Normally, the discount rate used is specific to the year in which restoration begins (and is determined by the Office of Management and Budget and based on the current interest rate); however, this particular restoration is complicated further because restoration is not assumed to begin until 2023 or 2036 and we cannot be certain what discount rate should be used at those times. For the idealized model it would therefore be appropriate to assume a very low, long-term discount rate in order to account for differences in annualized benefits and costs.

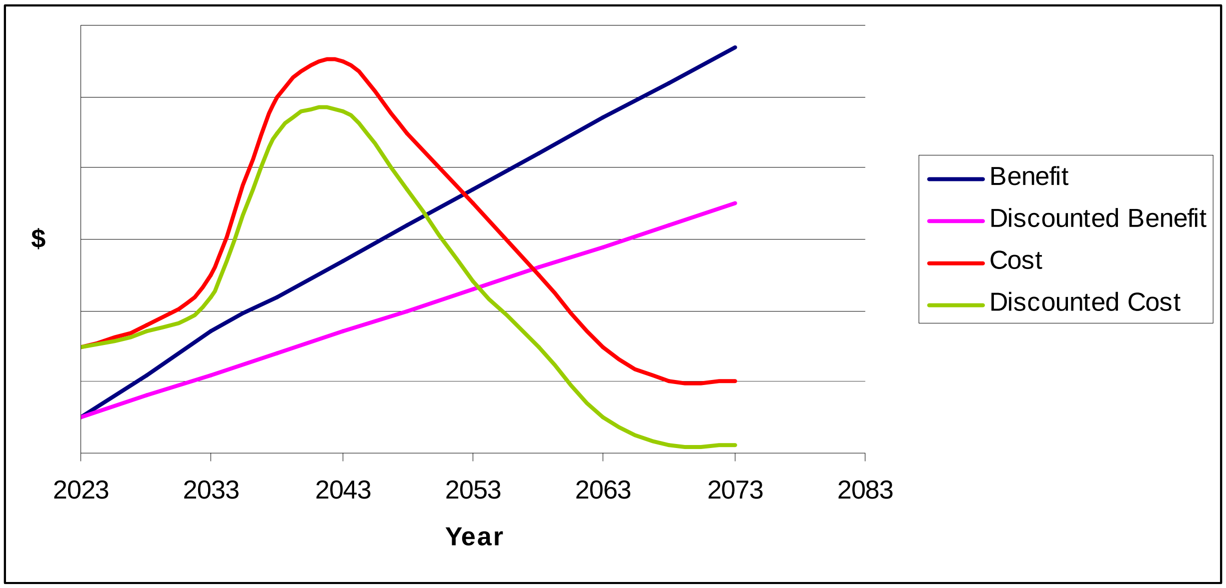


Figure 14. Discounted costs and benefits.

Differences in restoration intensity, perhaps measured in terms of up front and/or average annual dollar spending on restoration per acre, would also greatly alter both the costs and benefits of any restoration option and should be considered in subsequent analysis before the CMR project is undertaken. This is especially true in order to be sure that any future CMR project is evaluated based on "full cost accounting" or when it is clear that the amount of money that will be forthcoming for such a project is dependent on the expected environmental restoration benefits. For example, if applying the highest restoration intensity only ensures a 1% increase in benefits when compared to the mid-restoration intensity but requires a 25% increase in spending; a high restoration intensity option may be considered wasteful (added benefits that do not exceed added costs) and, perhaps more importantly, may reduce the economic justification for the project. Initial investigations suggest that there is a potential $50,000 increase in costs per acre between the no-action and high restoration intensities so with thousands of potential restoration acres it is very important to examine the costs and benefits associated with restoration intensity as a component to the analysis.

Future research should focus on the data improvements laid out here. Using 100-acre restoration cells, as opposed to the much larger zones/subzones used in this analysis, will provide more precise estimations of costs and benefits. To this end, more specific measurements of marsh height, water depth, and even accretion and subsidence rates, would also improve the specificity of the model. It is important to note, however, that often more precision can actually decrease the accuracy of results. The potential trade-off between precision and accuracy could be examined by using a model similar to the one presented here to determine what data is most important for improving the accuracy of the model (as discussed in Section 7). Incorporating the variable of time by using a discount rate would also provide a more accurate representation of the costs and benefits. A closer consideration of restoration intensity is also extremely important, especially given that the CMR project has limited funding and could potentially be a multimillion dollar restoration. The analysis conducted here using the adapted model provides a baseline assessment for future models and associated research surrounding the optimization of dredged material placement options at the CMC.

5.3. Expert Panel

During the interview process, the expert panel was asked to provide their own priority rankings of the restoration sites under their jurisdiction (Zones 1-4 for USFWS and Zones

5a-8b for MD DNR) (Table 10). This ranking was based on their knowledge of restoration needs and the importance of each site for reaching habitat goals.

Table 10. Expert panel ranking of restoration sites.

Ranking	USFWS	MD DNR
1	2a: Barbados	5a: Upper Lower Blackwater River
2	2b: Confluence Area	8b: Lower Fishing Bay WMA
3	4: Wolf Pit Marsh	5b: Lower Lower Blackwater River
4	1: Upper Blackwater River	6b; Lower Transquaking River
5	3b; Lower Little Blackwater River	6a: Upper Transquaking River
6	3a: Upper Little Blackwater River	8a: Upper Fishing Bay WMA
7	N/A	7: Chicamacomico River

It is interesting to note that both USFWS and MD DNR made several of their rankings based on how much of the zone/subzone was owned by private landowners. For example, the majority of the Little Blackwater River is privately owned and outside the jurisdiction of USFWS. For this reason, they ranked these two subzones low on their list of priorities. Similarly, MD DNR ranked the Upper Transquaking River and Upper Fishing Bay WMA low on their list because a large portion of both zones is privately owned. Dealing with private land owners would add a number of complications to any restoration undertaken by state and federal agencies which is why they tended to give those areas with significant private land relatively low priority. At this time, the optimization model does not take land ownership into account, although there may be reasons why it should do so (e.g., necessary payments to private land owners). This may explain some of the discrepancy between the expert panel’s prioritization and the prioritization of options that resulted from model runs.

The expert panel members also based much of their decision on the current state of the marsh. For example, in the federally-owned zones, there has been considerable deterioration in Zones 2a and 2b, which is why USFWS ranked them at the top of their list. However, the model was run based on 2023 and 2036 baselines, by which time there is significant marsh loss throughout all zones and it is not obvious which zones will have lost more marsh per unit area. Similarly, MD DNR ranked the Upper Lower Blackwater River subzone first because it is currently the most susceptible to marsh loss. However, based on SLR predictions, by the time restoration may be undertaken much of the state-owned zones, including the Chicamacomico River which MD DNR thought had the least risk of deterioration, will already have been lost to SLR.

Despite these cognitively-influenced decisions on the part of the expert panel, the model results and expert opinions show some surprising similarities. For example, USFWS ranked Zone 2a first in importance and Zone 2b second in importance (out of the federally-owned zones); as discussed earlier (see Section 5.1), both the 2023 model and the 2036 model restored significant acreage in Zones 2a and 2b. Similarly, the expert panel ranked Zone 3a as the least important (among federally-owned zones) while both model runs placed no dredged material in that zone. Both model runs placed little or no dredged material in Zones 7 (Chicamacomico River) and 8a (Upper Fishing Bay WMA) which MD DNR ranked last on their list of priorities. In general, both models tended to focus on the federally-owned zones, indicating they may generate more restoration benefits than the state-owned lands.

6. CONCLUSIONS

The analysis presented here illustrates a preliminary application of a risk-based optimization model that could be used to assess and compare options for the CMR project. Given the high costs and risks associated with undertaking such a project and the severe limits on time, data, and budget available to develop this preliminary application; a more thoroughly developed model would most certainly be needed before any results can be trusted. Nonetheless, this preliminary exercise has proven itself useful as a way of using expert opinion to screen out CMR project options that seem inferior and identify those that seem to hold the most promise based on current expert opinion; while at the same time testing the use of risk-based optimization models. Most model results make environmental and economic sense and are consistent with, or have obvious reasons for not being consistent with, the priorities established previously by local subject area experts. These results offer one logical potential solution for maximizing a given set of environmental benefits under a selected set of cost, dredged material availability, and placement capacity constraints.

The model results also illustrate clearly that because of expected SLR impacts, the optimal allocation of dredged material and the benefits achievable by the optimal allocation depend a great deal on the year in which restoration commences. Despite these differences, there are three very clear conclusions that can be reached based on a comparison of model results under both potential start years: 1) given the constraints and assumptions used on the model, Zones 2a (Barbados Island) and 2b (Confluence Area) provide significant restoration benefits; 2) restoration of low marsh habitat provides significant benefits; and 3) given these constraints and assumptions Zone 3a (Upper Little Blackwater River), Zone 5a (Upper Lower Blackwater River), Zone 5b (Lower Lower Blackwater River), Zone 6a (Upper Transquaking River), Zone 8a (Upper Fishing Bay WMA) and Zone 8b (Lower Fishing Bay WMA) provide little restoration benefits. These conclusions, which suggest future researchers should focus more attention on one option and less on another option, result regardless of whether the model is run with a 2023 or 2036 start year. This illustrates one important benefit of using this type of optimization framework for organizing information about environmental restoration options under circumstances where shifting baselines associated with SLR impacts and other changes generate uncertainty about expected costs, benefits, and risks.

The previous section listed a number of improvements that can be made to the adapted model in order to generate more accurate, comprehensive, and reliable results. Despite this, the model and research presented here offer useful insights into ways to quantify and compare tradeoffs related to environmental and economic benefits, dollar costs, and controllable and uncontrollable risks in order to determine an “optimal” dredged material allocation for a CMR project. The application also illustrates that this type of model is useful to test the sensitivity of results to assumptions made and weights assigned to competing benefit types. Although the model developed here was static, versions were run using two separate start years, 2023 and 2036, which generated two sets of potential outcomes that can be compared to provide some insights into the effects of time on the “optimal” restoration configuration.

7. RECOMMENDATIONS

Based on the experience of developing the model presented here, several recommendations can be offered regarding future research if MPA or USACE decide to further consider the CMR project as a beneficial use of dredged material from POB access channels. First, an expanded version of the cost equations developed in this paper should be used to guide a preliminary assessment of the range of possible costs of transporting, stockpiling, managing, and applying dredged material to achieve various environmental goals at the CMC. Second, an adjustable risk-based optimization model like the one developed here, with more details, should be constructed prior to making significant investments in data collection at the CMC site in order to determine what data collected at what locations will be most valuable for clarifying tradeoffs, setting priorities, and justifying the feasibility of the project in terms of expected costs, risks, and benefits. Third, future research should address a wide variety of potential and often competing restoration benefits. This should most certainly include some quantification of recreational benefits and onsite habitat benefits because, as the sensitivity results presented here show, a) these benefits categories provide the greatest portion of overall benefits for the model runs and b) the “optimal” solution often depends on how these benefit categories are weighted.

It is also important for future research to examine the impact of decisions regarding when to begin a CMC restoration. As the model runs show, a difference of 13 years can significantly affect the "optimal" location of acres restored; the amount of benefits that will accrue; and the distribution of dredged material within the CMC that will generate the greatest benefits. Greater resolution in terms of timing should be further examined (for example, is a difference noticeable at a 2-year interval? 5 year interval? 10 year interval?). Also, while the model was used here to prioritize sites, it can also be modified with additional constraints that preclude certain sites due to changes known to exist because of start time differences. For example, the results presented here support the importance of restoring Zone 2b. However, if we ran the model based on a 2040 start year, Zone 2b may provide slightly less benefits while another zone, say Zone 4, provides slightly more. Running the model based on a 2045 start year instead of a 2036 start year may show that Zone 4 surpasses Zone 2b in terms of importance, indicating that restoration at that time should focus on Zone 4 rather than Zone 2b.

It is also important to note that the objective of the model used here was to simultaneously address two separate problems: 1) the need for dredged material placement capacity for the POB; and 2) the need to protect and restore the wetlands of the CMC in the face of threats posed by SLR and other destructive forces. If instead only the wetlands loss objective were addressed, material for restoration could come from a variety of other sources, including some sources much closer to the restoration zones than Bay shipping channels. This would make restoration much less expensive and the dredged material from these sources might be available well before the earliest start year of 2023 for POB shipping channel material; thus the model could be run with lower costs and earlier start years than those examined here. However, although the costs of using material dredged from other places may be much lower than the cost of using material dredged from shipping channels, in many cases dredging from other places may not generate significant independent benefits. This means the cost of such a project would need to be justified purely on the basis of expected benefits at the CMR site.

The model used here was a static model, representative of a snapshot of opportunities and constraints at one point in time. However, by running it at two different points in time and comparing the results we were able to conduct a “comparative statics” analysis that was dynamic in the sense that it showed some of the effects of time on opportunities and constraints and “optimal” decisions. Running a more explicitly dynamic model that shows how constraints and expected costs, risks, and benefits change over time (e.g., where the outputs of one model run are the inputs of the next) would allow for a much more detailed examination of how restoration opportunities will change over time, and provide a more accurate portrayal of real-world restoration options and results. Though such a model would require greater effort and time than the one presented here, it would also provide a far more comprehensive assessment of the CMR which may be necessary as the project gains more attention or becomes more imminent.

Future research should also examine and consider the recommended model improvements presented in this study (see Section 5.2). The model presented here, while providing a significant amount of information and a strong preliminary analysis, is primarily expert opinion-based. Creating a more data-based model would significantly improve the reliability while removing any possible subjective bias currently imbedded in the model. Creating such a model, however, will require a significant commitment of time and money. It is important to consider that the model developed here, or a more detailed version of it, could be used to identify what data is likely to be most and least worthwhile before extensive research is conducted. By determining how sensitive the results are to more specific spatial data, the potential data needs outlined here could be prioritized and the model could be used as a potential tool for guiding future research. For example, it is possible that because SLR is expected to increase dramatically over the next several years, accretion and subsidence rates may become less important in terms of their influence on future sea level. Using an optimization model to determine this influence would then aid in deciding whether collecting spatially detailed accretion and subsidence rates is worthwhile.

On the other hand, if it is determined that the cost of collecting and analyzing this data is prohibitive, but more funding is available than was available for the current study, an alternative approach may be to employ a more thorough and scientifically based method for soliciting and using expert opinion (e.g., ranking of indices); thus arriving at a science-based consensus about the facts and a value-based consensus about how tradeoffs should be made. Additionally, in the final analysis the results of model runs made using a risk-based optimization model would need to be fed into some type of cost-benefit analysis or incremental cost analysis in order to satisfy the requirements for federal spending.

APPENDIX A

Overview of Optimization Software

Crystal Ball® software is an analytical tool that performs simulations on spreadsheet models such as those created in Microsoft Excel®. The forecasts or predictions that result from these simulations help quantify areas of risk so decision-makers can have as much information as possible to make and support their decisions. Crystal Ball allows for quantification of the uncertainty associated with many of these decisions by using what are called “assumption variables.” These are defined by the user and require an associated probability distribution (or range of values). This probability distribution is then used by the model during its trial runs. For each trial, the model chooses a different value from the designated probability distribution and calculates the outputs, referred to as “forecast variables.” These are the results of the model run and thus require the user to input an equation that relates the variables being considered.

Given the following simplified situation, a decision-maker could use the Crystal Ball program to determine the most likely environmental benefit generated from a wetlands restoration project. Assume the following: 1) restoring one acre of wetland costs, on average, $10,000; 2) one acre of wetlands results in an environmental benefit (e.g., increase in a wetland value index) of 50,000; and 3) there are 100 acres of wetland to be restored. In this case, the cost per acre and the environmental benefit per acre are average values and would be considered assumption cells with an associated probability distribution (or value range). For example, a triangular distribution could be used for the cost per acre such that the average value ($10,000) represents the most likely value with

$0 as the expected minimum value and $20,000 as the expected maximum value. The forecast variable would then associate the two assumption variables and the independent variable (number of acres to be restored) with each other using the following equation:

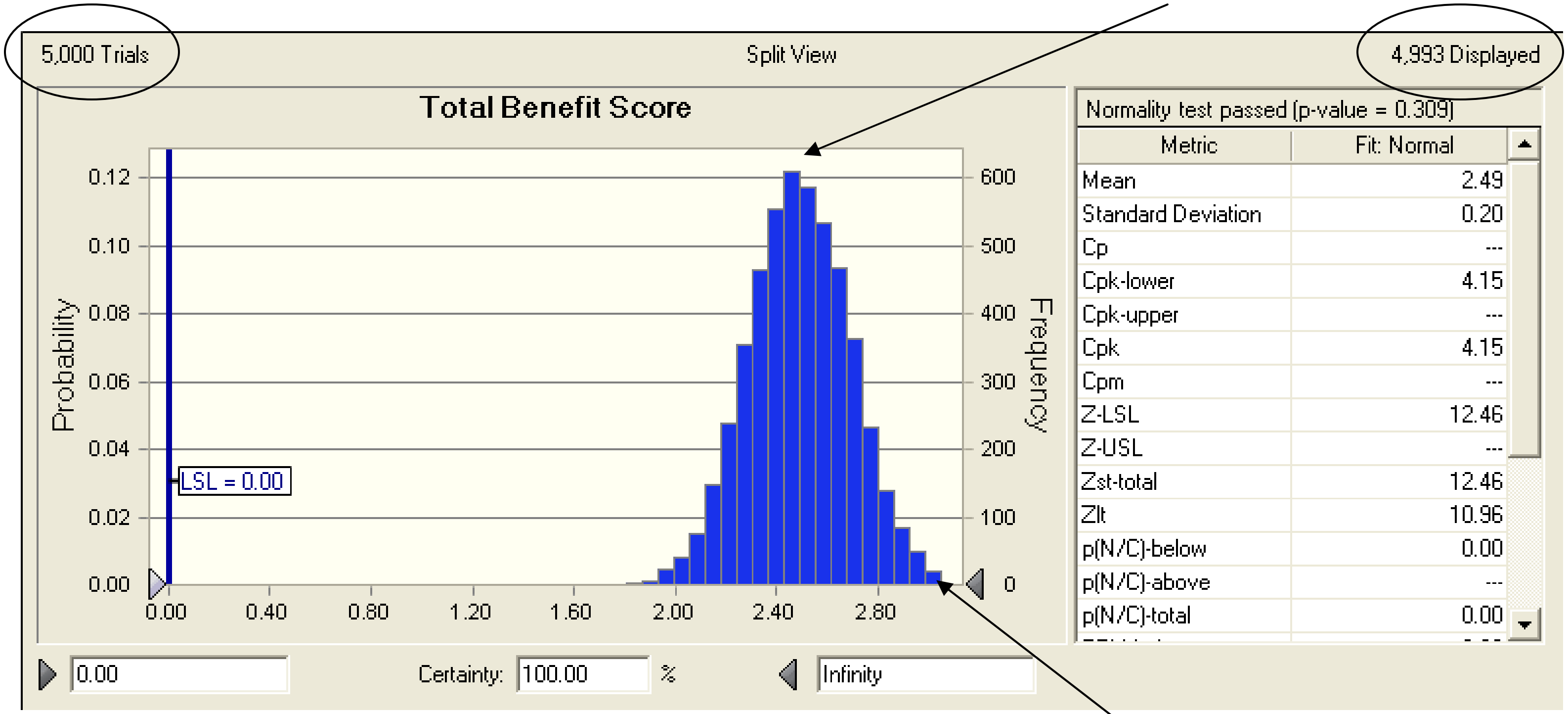
> Environmental Benefits per Dollar spent = [(# of acres) x (benefit per acre)] /[(# of acres) x (cost per acre)]

As the model performs its simulations, it chooses values from the probability distributions associated with the two assumption cells, calculates the forecasted total benefits value, and stores that value. The model produces a probability distribution of the forecasted total benefit values for each simulation, as well as several statistical measures of the total benefit values (i.e. mean, standard deviation, etc.). The decision-maker could then use these outputs to determine the most likely benefit per acre of wetlands restoration for this project and compare the results with the same analysis conducted for other wetland restoration projects.

However, by itself Crystal Ball does not perform an optimization analysis; it simply helps predict an unknown outcome based on inputted values of what is known. This example assumes the number of acres to be restored is independent of the cost and benefits associated with the restoration – therefore, an optimization of restoration options is not necessary. The OptQuest add-on tool to Crystal Ball is what performed the optimization analysis used for the CMR study. Using the OptQuest tool requires designation of another input, referred to by the Crystal Ball program as a “decision variable.” The value of this variable is determined by the model for each simulation. The model then uses this value to run multiple trials; for each of these trials, it chooses a different value from the probability distribution of the assumption variables. The average of these trials is then stored as the value for that simulation run. Figure 15 provides an example of the probability distribution created by Crystal Ball for the “best solution” simulation taken from one model run. A total of 5,000 trials were calculated; however, only 4,993 trials provided feasible results (i.e. within the cost constraint).

In the case of the model described in this paper, the amount of dredged material used to restore each habitat type in each zone was the decision variable. This determined total costs (a forecast variable) because most cost components depended on the amount of dredged material being transported. This decision variable also determined the amount of acreage of each habitat restored in each zone/subzone; and the acreage restored also affected the total benefits (the second forecast variable) because it was a key variable in the calculations for resulting onsite habitat, offsite habitat and recreational benefits. The dredged material benefit was directly determined by the amount of dredged material used to restore each habitat type in each zone/subzone. The Habitat Use Index values were designated as assumption cells because of the uncertainty associated with whether the habitat restored would provide the maximum use value for each guild. These values affected the total benefits because they were used in the calculations for onsite habitat and offsite habitat benefits.

Most likely outcome.



5,000 Trials

Split View

4,993 Displayed

Normality test passed (p-value = 0.309)

Metric	Fit: Normal
Mean	2.49
Standard Deviation	0.20
Cp	---
Cpk-lower	4.15
Cpk-upper	---
Cpk	4.15
Cpm	---
Z-LSL	12.46
Z-USL	---
Zst-total	12.46
Zlt	10.96
p(N/C)-below	0.00
p(N/C)-above	---
p(N/C)-total	0.00

0.00

Certainty: 100.00 %

Infinity

Figure 15. Crystal Ball optimization output.

Best possible outcome.

Equations Imbedded in Excel Spreadsheet

1. Acreage restored:

$A_T = \overset{i}{\Sigma}\ \overset{k}{\Sigma}\ DM\ [A_{ki}/cy]$

A_T = Total acreage restored across all habitat types and zones/subzones.

i = zone/subzone.

k = habitat type.

DM = dredged material placed by model in habitat *k* of zone/subzone *i*.

A_{ki}/cy = Acres per cubic yard for habitat type *k* within each zone/subzone *i*.

$A_{ki}/cy = (1/FH_{ki})\ (C_{acres})$

FHki = Fill Height for habitat type *k* in zone *i*.

$FH_{ki} = WD_i + MH_{ki} + SLR$

WD_i = Current Water Depth of zone *i* (as estimated by the expert panel).

MH_{ki} = Marsh Height of habitat type *k* in zone *i* (as estimated by available field data or expert panel).

SLR = predicted increase in Sea Level Rise.

C_{acres} = Conversion factor from yd^2 to acres.

A_{CP}[3] $= A_{EM}\ [FRA_{CP}/FRA_{EM}]$

A_{CP} = restored acreage of Channel/Ponds habitat in zone/subzone *i*.

A_{EM} = restored acreage of Low Marsh habitat in zone/subzone *i*.

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[3] The restored acreage of the Channel/Ponds habitat was calculated using a slightly different method, given that no dredged material is directly required in order to restore this habitat type.

FRA_{CP} = Channel/Ponds acreage restored in zone/subzone i, given a full restoration (from expert panel recommendations).

FRA_{EM} = Low Marsh acreage restored in zone/subzone i, given a full restoration (from expert panel recommendations).

2. Benefits

a) Onsite Habitat Benefits:

$$B_{on} = \sum^{i} \sum^{k} [P_{NoHAB}(A_{Tki}) \sum^{l} (HUI_{lk}) (w_l)] + [(1-P_{NoHAB}) (P_{HABSuccess})$$

B_{on} = Total Onsite Habitat Benefits across all species guilds, habitat types, and zones/subzones.

i = zone/subzone.

k = habitat type.

P_{NoHAB} = Probability that no Harmful Algal Bloom will occur

A_{Tki} = Total Acreage restored of habitat type k in zone/subzone i.

l = species guild.

HUI_{lk} = Habitat Use Index value for species guild l in habitat type k (as determined by the expert panel).

w_l = species guild weight.

$P_{HABSuccess}$ = Probability of success even with a Harmful Algal Bloom.

b) Offsite Habitat Benefits:

$$B_{off} = \sum^{i} \sum^{k} \sum^{l} [\text{IF: } (A_{Tik}) \text{ in adjacent zone(s)} > 0; \text{ THEN: } (B_{onlki}) (P_{off}); \text{ OTHERWISE: } 0]$$

B_{off} = Total Offsite Habitat Benefits across all species guilds, habitat types, and zones/subzones.

i = zone/subzone.

k = habitat type.

l = species guild.

A_{Tki} = Total Acreage restored of habitat type k in zone/subzone i.

B_{onlki} = Onsite Benefits of species guild l in habitat type k in zone i.

P_{off} = Percent increase in onsite benefits due to offsite benefits (as determined by the expert panel).

c) Recreational Benefits:

$$B_{rec} = \sum^{i} [(A_{Ti})\,(RS_i)$$

B_{rec} = Total Recreational Benefits across all habitat types and zones/subzone.

i = zone/subzone.

A_{Ti} = Total Acreage restored of zone/subzone i.

RS = Recreational Score for zone/subzone i.

$RS = V_{rec}/V_{rec}^{max}$

V_{rec} = Recreational Value of zone/subzone i (as determined by Loomis and Richardson value tables).

V_{rec}^{max} = Maximum recreational value calculated (here this was the recreational value for Zone 2b).

d) Dredged Material Benefits:

$$B_{DM} = \sum^{i} \sum^{k} DM_{ki}$$

B_{DM} = Total Dredged Material Benefits across all habitat types and zones/subzones.

i = zone/subzone.

k = habitat type.

DM_{ki} = Dredged Material placed to restore habitat type k in zone/subzone i.

e) Total Benefits

$$B_T = P_{success} \overset{i}{\Sigma} [w_B (B_{on} + B_{off} + B_{rec} + B_{DM})]$$

$P_{success}$ = Probability of overall restoration success (estimated to be 60%, based on wave fetch risk as determined by the expert panel).

i = zone/subzone.

w_B = benefit weight.

B_{on} = Onsite Benefits

B_{off} = Offsite Benefits

B_{rec} = Recreational Benefits

B_{DM} = Dredged Material Benefits

3. Costs

$$C_T = \overset{i}{\Sigma} (C_i)$$

C_T = Total Costs across all habitat types and zones/subzones

i = zone/subzone.

$C_i = (DTU * V_i) + (D * LF_i) + (DC_i * V_i * M_i) + (MC * V_i) + (PS * A_i) + (PC * A_i) + (MM * Ai)$.

DTU = Dredging, Transport and Unloading costs at the James Island staging area.

V_i = Volume of dredged material placed in zone i.

D = Dike costs.

LF_i = Total Linear Feet of all restoration cells in zone i (assumed 100-square cells).

$LF_i = [(A_{Ti})/100] [\sqrt{}(100*C_{sqft}) (4)]$

A_{Ti} = Acreage restored in zone i.

C_{sqft} = Conversion factor for acres to square feet

DC_i = Distribution Cost per cubic yard of dredged material to zone i (includes pipeline and booster pumps).

M_i = Mileage to zone i.

MC = Management costs of dredged material.

PS = Preparation Costs for wetland soils.

A_i = Area restored (acres) in zone i.

PC = Planting Cost per acre.

MM = Maintenance and Monitoring Cost per acre.

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