LUMA-GIS Thesis nr 20

Eastern Oyster Aquaculture: Estuarine Remediation via Site Suitability and Spatially Explicit Carrying Capacity Modeling in Virginia's Chesapeake Bay

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2013
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Daniel Patrick Taylor (2013). "Eastern Oyster Aquaculture: Estuarine Remediation via Site Suitability and Spatially Explicit Carrying Capacity Modeling in Virginia's Chesapeake Bay".

Master degree thesis, 30/ credits in Master in Geographical Information Sciences
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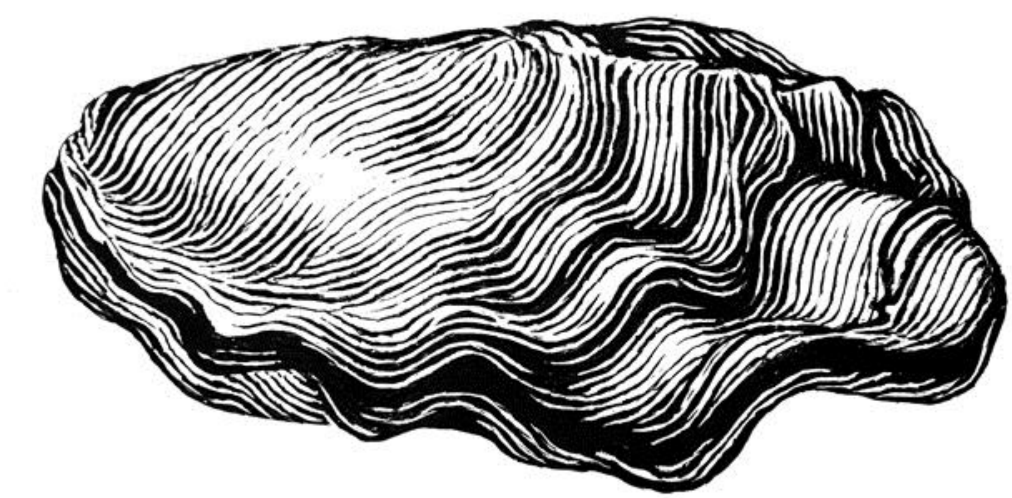

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Abstract

Estuarine eutrophication, the systemic limitation of dissolved oxygen in a body of water, has been increasingly monitored and scrutinized as an environmental concern needing acute and long term remediation efforts. The driving factors of eutrophication are largely attributed to anthropogenic sources within the watershed, sources that are products of modern civilization. Estuarine eutrophication poses significant threats to aquatic ecosystems at micro and macro scales, as well as to coastal economies (EEA (2001) and NSTC (2003)).

This paper addresses bivalve mollusk aquaculture as a managed remediation mechanism for reducing eutrophication through modeling and analysis within the Geographic Information Systems (GIS) paradigm. In realistic application of such mechanisms, spatial delineation of appropriate areas for implementation and potential impacts on eutrophic states must be efficiently predicted; GIS is the ideal platform to bridge data and analyses of interest in this light. Aquaculture site suitability is determined by integrating spatial data in the GIS framework to yield discrete areas of suitable and unsuitable areas. Eutrophic state impacts are determined by juxtaposing suitable areas at their present eutrophic condition against modeled shifts in eutrophic states due to intervention by bivalve aquaculture. In this case, bivalve aquaculture production carrying capacity is used as the benchmark to model effects in eutrophic conditions.

This methodology is applied to Eastern Oyster aquaculture in the Chesapeake Bay of Virginia, USA. The Chesapeake Bay is an exemplary case for this theme as it is the country's largest estuary and has gained notoriety for its eutrophic state. Intensive oyster aquaculture is a burgeoning industry with historical significance to the region as well as presenting an economically viable method for estuarine eutrophication remediation (Shumway, 2011). Oyster aquaculture site suitability, eutrophic conditions, spatially explicit aquaculture carrying capacity, and potential eutrophic state changes are modeled and analyzed in this thesis through the means of GIS.

Acknowledgements

Without the tender fortitude and support from my wife, Maria, this thesis and my general progression in life would be lost at sea. She is the greatest. My parents and friends have always propelled me to greater achievements; I thank them for being superb human beings and I am forever in their debt. I would like to thank my supervisor Petter for providing guidance, encouragement, and assistance in this thesis. Lastly, I would like to thank Sweden for providing this education and for being one of the loveliest places on Earth.

Contents

1. Introduction

The rapid expansion of global aquaculture has been as much an economic boon, as an ecological dilemma. Aquaculture is the fastest growing global food production sector, fulfilling at least 50% of consumed seafood worldwide, and anticipated to replace captured fisheries as the primary supply of seafood. In terms of geographical distribution, aquaculture production is extremely asymmetric, with 89 percent of global production in the Asia-Pacific region and certain other high-value species focused in relatively limited areas (i.e. salmonids in Norway and Chile)(FAO 2012). Traditionally, aquaculture has been perceived through popular scrutiny (largely in the West), as nitrogen-rich effluent, genetic contamination of natural aquatic populations (salmon sea cage aquaculture), and the destruction of sensitive habitats (shrimp farms in mangrove ecosystems) have tarnished the reputation of aquaculture to provide safe and sustainable seafood. Owing to regulation, biosecurity, local-food marketing, seafood safety, and reduced costs, aquaculture is transforming into an industry founded in environmental sustainability (Bardach, 1997).

Perhaps the most exemplary sector of sustainable aquaculture is the culturing of bivalve mollusks, such as blue mussels (*M. edilus*), quahogs (*M. mercinaria*), scallops (*P. maximus*), and oysters (*C. gigas* & *C. virginica*). As most other forms of aquaculture require feed or nutritionally enhanced culture conditions (i.e. shrimp ponds and microbial floc, finfish in RAS or net pens, etc.), bivalves as cultured organisms can be situated in waters replete with 'waste' nutrients, feeding on the suspended matter (Shumway, 2011).

Many of the world's estuaries have been significantly altered by anthropogenic activities in the watershed, commonly leading to excess organic and inorganic material runoff. This net excess material provides the basis for phytoplankton over-production, increasing rates of benthic sediment deposition, degradation in water column light attenuation, and larger shifts in regional food webs/ecological networks. These cumulative issues are collectively referred to as symptomatic and generative aspects of estuarine eutrophication. Eutrophication as an ecosystem response to excess nutrients is problematic to estuarine ecosystems, as not only does the accelerated growth of autotrophic plankton pose ecological trophic imbalances, but consequential dissolved oxygen depletion, toxic/nuisance algal blooms, rising turbidity (loss of macrophytic species abundance), and net reduction of higher trophic level recruitment yield conditions deleterious to estuarine ecological sustainability. Many estuaries worldwide exhibit eutrophic conditions, attributed to anthropogenic intervention in the watershed – where precipitation-based or irrigation-based runoff from upstream land use carries relatively high concentrations of nutrients into the estuary; a veritable dissolved nutrient sink. Solutions to mitigating nutrient runoff abound (buffer wetlands, buffer emergent zones, precision agricultural practices, advanced wastewater treatment, etc.), though in many watersheds these efforts have been vastly underfunded or poorly implemented (EEA (2001) and NSTC (2003)). Innovative solutions to simultaneously reduce nutrient runoff and reduction of ambient estuary nutrient concentrations must emerge as viable mechanisms to mitigate eutrophication, ultimately fostering increased biodiverse habitat conditions and qualitatively cleaner waters. Bivalve aquaculture, employing filter-feeding organisms driven by capital market devices, presents a variety of viable opportunities for the mitigation of estuarine eutrophication (Shumway, 2011).

1.1 Aim and Objective

This thesis seeks to address the issue of estuarine eutrophication by modeling potential production carrying capacity of modern oyster aquaculture in a GIS framework. The Chesapeake Bay, exemplary for its eutrophic state and historically significant oyster fishery, is the area of interest for this study; specifically the southern portion of the Bay falling within the Commonwealth of Virginia's borders. By integrating the manifold environmental data pertinent to oyster aquaculture in a GIS, a multi-criteria evaluation of suitable areas is performed to delineate regulatory and biophysical spatial limitations to intensive oyster aquaculture. Within the study period/data extraction period – January 2009 to May 2012 – environmental data is also analyzed for assessing the spatial distribution of eutrophic states within the Bay. An oyster growth model is employed within a GIS algorithm (tool) to extract production carrying capacity values for discrete areas within the Bay, which then provides potential consequent eutrophic states for each discrete area. This model is validated against production data within the study period. This framework is designed to assist both resource managers and potential farmers select areas most appropriate for native oyster aquaculture, as well as for analyzing historical production data.

1.2 Thesis Structure

Given the objectives of this thesis, the structure, in its presentation of theory, methodologies, findings, and discussions, is somewhat atypical. There are broadly three analytical themes which are integrated holistically, but each methodology and discussion of findings are presented within those sections. The initial analysis is of site suitability for oyster aquaculture. Data sources and the multi-criteria evaluation (MCE) for assigning suitability scores are discussed per suitability element throughout Chapter 7, along with a discussion of the combined results of that multi-criteria evaluation in Chapter 8.

The next portion of the thesis evaluates the spatially distributed eutrophic conditions of the Chesapeake Bay within the study period. This is completed by employing the ASSETS methodology, which is detailed in that section. The ASSETS evaluation provides a baseline for analyzing potential shifts from the current eutrophic status; the results of this assessment are discussed in Chapter 9.1.

The following portion applies an oyster bioenergetics model to the suitable areas determined in the site suitability analysis. The model is used concurrently with limiting metabolic factors, food and oxygen, to determine carrying capacities for the study period and within the suitable areas. The carrying capacity in this manner provides a maximum number of market-size oysters per acre, limited by either available food or oxygen. These numbers then reemploy the oyster bioenergetics model against total food and oxygen to determine potential reductions in those parameters. This yields new potential eutrophic conditions for the suitable growing areas, which is assessed again through the ASSETS methodology to examine potential shifts in eutrophic conditions. These results are discussed in the subsequent section. The methodology and model descriptions are outlined in Chapter 10, with results presented in Chapter 11.

2. Background and Theoretical Basis

2.1 GIS and Aquaculture

GIS provides a robust paradigm for the assemblage, organization, analysis, and synthesis of spatially distributed data. Within a GIS, copious amounts of data from multiple sources can be aggregated and manipulated for streamlined spatial analysis or for use in spatial models; these procedures can even be automated for efficiency or iterative processes. In addition to being able to present data and findings cartographically, GIS is a powerful central tool for scientific inquiry employing spatial analysis. As a tool though, it is only as useful as its operator and their skill in being impeded by the technical limitations of the tool.

The application, development, and outlook for GIS in aquaculture has been well reviewed in Nath, et al. (2000); Kapetsky & Manjarrez (2007); and Ross, et al. (2009). The Food and Agriculture Organization hosts a knowledge portal linking GIS and aquaculture under Fish and Aquaculture management Division's GISFish service. It is an information repository for everything GIS and aquaculture/fisheries. Aquaculture, like agriculture, is both influenced by its proximal environment as well as reciprocating influence on its proximal environment; relevant for geographical study. By integrating multiple pertinent spatial parameters in a GIS, aquaculture can be examined in time and space for innumerous perspectives; i.e. ecological/environmental impact, disease transference, correlating growth and mortality to variables, production capacities, resource planning, etc. Such assessments can collectively give rise to collaborative decision making through synergy of multiple stakeholder interest and broad objectives. One such objective, as will unfold in the following text, is the amelioration of the Chesapeake Bay; once lauded as a seafood superpower, now mandating fisheries closures and suffering the effects of episodic eutrophication.

2.2 Remote Sensing

In the context of this thesis, remote sensing applies to the capture of environmental data by sophisticated oceanographic sensory installations or by sample collection and demarcation of the sample site and time. Both methods provide raw data linked with a specific location, suitable for scientific analysis in a GIS with some degree of pre-processing. Remotely sensed parameters of interest include current velocity, wave height, water column depth, temperature, salinity, chlorophyll-a, turbidity, sediment toxins, and dissolved oxygen. These data, indicated in space by coordinates, can be employed as a basis for studying spatial trends and forming estimates of values between measured points.

3. Study area

Within the contiguous United States, the Chesapeake Bay is the largest estuary in the country, draining over 150 riparian bodies from 6 states with 167,000 square kilometers of drainage area. (USGS – Fact Sheet, 1998). Hosting greater than 17 million people and some of the largest metropolitan regions in US, the Chesapeake Bay also holds the distinction of maintaining the highest land area to open water area for any coastal water body globally; indicating a higher relative anthropogenic impact potential (CBP, "Discover the Chesapeake", 2012).

The extent of the Bay's open waters spans over 300 kilometers, from the mouth of the Susquehanna River at Havre de Grace, Maryland, to the mouth of the Bay itself between Virginia's Eastern Shore and Hampton Roads. A daily influx of 193 million cubic meters of freshwater from upland rivers and an equal volume of diurnal tidal fluctuation of seawater from the Atlantic Ocean impart extremely productive waters; with somewhat static oligohaline, mesohaline, and polyhaline zones. The Bay is relatively shallow for such a vast area of open waters, with an average depth of 6.4 meters, 280,000 hectares with depths less than two meters, and with some trenches reaching 53 meters. Eleven major tributaries drain into the Bay, four of which are within Virginia; the Potomac, the Rappahannock, the York, and the James Rivers (from North to South). In Map 1, the Chesapeake Bay Program provides a succinct outline of the Bay's waters and major tributaries (CBP, "Discover the Chesapeake").

Map 1: Chesapeake Bay and Tributaries (CBP)

Approximately 35 million years ago a bolide meteor collided with the earth's surface, forming a crater that would subsequently become the Chesapeake Bay basin. The configuration of the basin was further manipulated by rising and falling sea levels due to glacial melt and contraction, as well as upland alluvial hydrogeology (USGS, 1998).

Following the latest shift toward warming – 18 to 15 thousand years ago – paleo-indian peoples of the Clovis migration settled within the region and along the Atlantic coast. As glaciers continued to retreat and melt in the north, the Bay's present shape began to resolve, while terrestrial flora and fauna established ecosystems representative of the pre-modern landscape. Only as recent as 5000 years ago, the Eastern oyster (*Crassostrea virginica*) began to colonize the Chesapeake Bay, joining an already robust and diverse aquatic multi-trophic ecosystem (CBP, "Bay History", 2012). As recently as 2000 years ago, the Bay's modern form coalesced and human settlements became permanent in agrarian and fisheries-based modes, though the human population would remain quite low for the next millennia and a half; never exceeding 24 thousand people around the Bay. Native populations cultivated tobacco, corn, squash, beans, and other crops introduced from the Mississippi River valley. Fish and shellfish, particularly oysters, were a staple protein source in the diet of coastal communities (Grymes, 2011).

The first Europeans –Italians, then Spanish - sailed into the Bay in 1524, followed by a private British expedition in 1607. This expedition, funded by the Virginia Company of London, established the first permanent British settlement at Jamestown, near the mouth of the James River in Virginia, motivating what would later become the United States. The Bay's fertile soils and sheltered, abundant waters provided distinct strategic advantages despite initial tribulations of malnourishment, horticultural failure, and sporadic conflict with the indigenous populations. Subsequent expeditions and successful settlement brought many more British to the Bay, establishing increasingly developed population centers, as well as the incredibly profitable tobacco export, while devastating the native human populations through disease and conquest; within 50 years the native population had been reduced to merely 10 percent of its pre-European members (Grymes, 2011).

4. The Eastern Oyster – The Filter of the Chesapeake Bay

4.1 Biology

Crassostrea virginica, also commonly known as the Eastern Oyster, the American Oyster, or the Virginian Oyster, is a sessile bivalve mollusk belonging to the *Ostreidae* family. Its natural habitat is generally characterized by temperate water temperatures of reduced salinity in subtidal or intertidal zones within Western hemisphere Atlantic estuaries; ranging at least as far north as the Gulf of St. Lawrence in eastern Canada to the Central American coasts of the Gulf of Mexico (Gosling, 2003: pp.50-52). Like all bivalves, the oyster feeds by filtering suspended particles, or seston, in the surrounding water, specifically by pumping water into the mantle cavity and capturing particles on the ciliated gill surface. Particles are transported in a mucusoidal medium and then ingested or expelled, depending on particle quality and total particle concentrations. Seston is generally comprised of suspended sediments (silt), phyto- and zooplankton, bacteria, protozoa, decaying organic material, and disaggregate dissolved organic material (i.e. amino acids, sugars, lipids). Since inorganic matter typically exceeds organic matter at concentration within a given volume of water, it becomes necessary for bivalves to select preferential food; where the amount of material filtered and ingested is termed 'clearance'. Cleared matter is then digested and directed to respiration, somatogenesis and/or gametogenesis; food supply is typically the most important and limiting aspect of growth (ibid. pp.87-123).

In natural populations, restoration bars, and in on-bottom culture of oysters, predation can be a significant problem to population sustainability and population growth. Gastropod predation is the most typical for the Eastern oyster, such as the oyster drill (*Urosalpinx cinerea*), or the lightning whelk (*Busycon contrarium*). Crabs, birds, starfish, fish, and worms are other common predators of the Eastern oyster; often substantially reducing populations and recruitment. In addition to predation, Eastern oysters are extremely prone to contracting the protozoan diseases, Dermo (caused by *Perkinsus marinus*) and MSX (caused by *Haplosporidium nelsoni*), particularly in areas coincidentally favorable for oyster growth; i.e. higher temperatures and salinity. These suppressing mechanisms, particularly Dermo and MSX, are the dominant inhibitions to reestablishing successful oyster populations (Ford et al, 1999).

4.2 History

Overexploitation of the natural oyster beds is no new phenomenon. Approaching the end of the 17th century, British settlers had already well-established the practice of harvesting oysters by tong, with the colonial government imposing fishing regulation laws in the 1680s to curb overfishing (CBP, "Bay History", 2012). The plentiful, regenerative populations were ample for regional consumption through artisanal extraction methods, but technological innovation and overwhelming demand quickly altered the population ecology of the oyster. In the early 1800s, oystermen from the New England states had already exhausted the natural oyster beds in the northeast by employing dredges, hauling up several magnitudes greater than the industrial tong used in the Chesapeake Bay. These oystermen then migrated into the Bay, stoking the onset of the so-called 'Oyster Wars', where the Bay became a de facto battle ground between oystermen and state authorities endeavoring to simultaneously regulate the fishery exploitation while mitigating territorial rivalry. Violence and overharvesting compelled Maryland, and later Virginia, to adopt Oyster Navies, the predecessors of modern resource commissions. As the states at the time could not allocate sufficient funding or will to regulate the fishery, the Chesapeake Bay remained as lawless as the open sea throughout the second half of the 19th century, flush with oysters that could match any other rare resource in demand and prize. At the close of the American Civil War and ramping up of the Industrial Revolution, natural oyster beds were harvested at an unprecedented rate, especially with the advent and expansion of trains, motored marine locomotion, manufactured weaponry, harvesting implements, and modernizing processing (canning, etc.). This period generated the ultimate collapse of the oyster populations in the Bay (Kimmel, 2008).

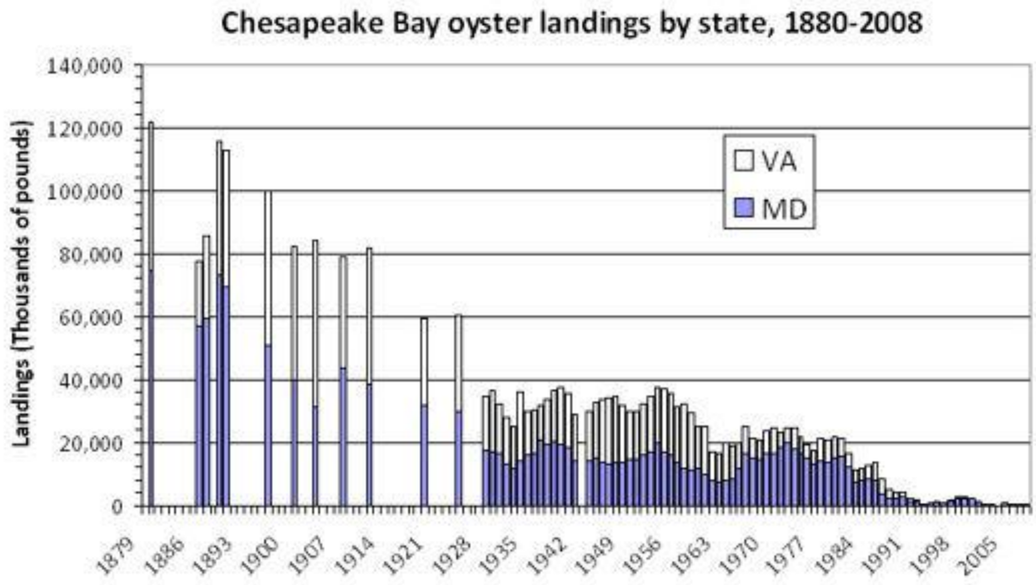


Figure 1 – Historical oysters landings (in thousands of pounds) between Maryland (MD) and Virginia (VA). Since records have been kept, landings have generally decreased. Notice the drastic decreases in the first half of the 20th century and second drop in the latter part of the second half. (Courtesy of the NOAA Chesapeake Bay Office)

Overharvesting not only had the effect of reducing the absolute numbers and recruitment efficacy of the oyster populations, but has complicated the oyster population and Bay ecology through the absence of this integral species. It is said that in the 1880s, the Bay's oyster population could clear the entire volume of the Chesapeake Bay within days, while at present population levels, that same volume would take a year's time. (CBP, "Learn the Issues: Oysters", 2012)

Concurrent soil erosion due to explosive population growth, government deregulation and incentivisation of agricultural development has provided two centuries of unnatural siltation of the Bay, exacerbating and stimulating planktonic eutrophication, smothering benthic oyster settlement, and hindering other regenerative factors. Nutrient and particulate loading in the Bay has been a well-documented and publicized issue, with the net sum effect of reducing spawning habitat (esp. submerged aquatic vegetative beds) and triggering anoxic events. Clearing of forests along the Virginia coast line for tobacco production early in European American history was a tremendous ecological transformation, which among other things introduced extremely heavy soil-runoff and nutrient loading into the Bay. The concomitant reduction in filter feeding capacity (by oysters), increased sedimentary deposition from runoff, poor historical fisheries regulation, and increased planktonic blooming has been the culprit of many collapsing fisheries in the Bay – including the Eastern Oyster, the Blue Crab, the Striped Bass – as well as the wholesale increase of 'nuisance' species such as Sea Nettles and Cownose Rays. As it is in ecology, isolated detrimental effects typically compound with inertia. Increased suspended sediment presents the added exasperation of limiting light penetration into the water column, leading to a reduction in submerged aquatic vegetation; the nurseries and habitats to countless species.

At the period of highest vulnerability (lowest population numbers), in the 1940s and 50s the scourges of Dermo (*Perkinsus marinus*) and MSX (*Haplosporidium nelsoni*) were discovered in the polyhaline and mesohaline zones of the lower Chesapeake Bay. These two culprits would for the remainder of the 20th century decimate oyster populations and population recruitment (CBP, "Learn the Issues: Oysters", 2012). These historical declines in the oyster fishery can clearly be seen in Figure 1, which depicts oyster landings since the late 19th century. The greatest strides in rectifying these extreme limitations has been based in breeding programs, producing strains of oysters more resistant to infection, as well as yielding greater biomass in shorter time, closing the window of mortality. Mortality and infection increase with temperature and salinity, namely in the summer months when oysters are growing at the greatest rate (VIMS: Aquaculture Genetics and Breeding Program, 2012).

5. Justification for oyster aquaculture

Nitrogen and phosphorus pollution are widely attributed to be the principle component contributing to the Bay's poor water quality and ecological health. Agricultural runoff and wastewater deposition account for the majority of nutrient pollution in the Bay, contributing to planktonic overproduction. Watershed efforts to curb nutrient loading into the Bay from anthropogenic sources have met limited success, while historical changes in the landscape may have set a precedent for cyclical nutrient concentrations in the Bay's water and subsequent health (Chesapeake Bay Foundation: Nitrogen & Phosphorus, 2012).

As is true for many shellfish species, oyster aquaculture in recent decades has principally been practiced for the objectives of fishery replenishment and/or fishery relief. A relatively modern perspective for aquaculture of mollusks implicates managed regional or watershed ecologies and the environmental economics behind nutrient deposition into the seas. Filter-feeding organisms provide an essential ecosystem service, removing agricultural and urban runoff pollution and aggregate biological byproducts from the watershed, while converting that pollution into highly valued consumable biomass. Oysters in particular have been found to filter up to 200 liters of water per day (Shumway, 2011, p. 245). In this light, the culture of bivalves can be seen as ecological and economical assets, particularly when pollution is quantified as in nitrogen-trading (cf. carbon trading). An insignificant portion of modern harvests are from natural reefs or from the traditional practice of harvesting wild seed and transplanting them to publically leased growing areas. The vast majority of oyster aquaculture today is derived from hatchery produced triploid seed and grown-out in cages, nets, or by remote setting (VIMS, 2012, "VA Shellfish Situation and Outlook Report 2011"). Triploid oysters are produced in the hatchery by chemical induction, heat shock, or breeding between diploid and tetraploid oysters (FAO: Hatchery Culture of Bivalves, 2004). This development has permitted 18 month growth periods and culturing in the higher salinity waters of the southern regions of the Bay; with faster growth contributed by sterility, focusing growth on somatogenesis.

> *The production and use of triploid eyed larvae and seed is the overwhelming majority reported by growers, and hence produced by hatcheries. In 2011 the percent triploids used in Virginia farms was 95%. Industry reports that the sterile triploid seed is more viable from a commercial standpoint, as the oysters grow faster and do not diminish in quality with seasonal spawning.* (VIMS, 2012, VA Shellfish Situation and Outlook Report 2011, p.3)

The two primary methods of culturing oysters in the Bay are considered intensive or extensive. Intensive culture, employing cultchless/single seed oysters in an enclosure relatively fixed at a specific location, produces high quality, fast growing oysters for the half-shell market. The typical conception of oyster consumption would be 'on the half-shell', where an iced platter loaded with raw half-shell oysters is served. Cultchless oysters are typically produced in culture vessels, such as suspended racks or suspended net bags within the water column. Extensive culture, or 'spat-on-shell', involves combining eyed larvae with old oyster shell, and then remote setting these set oysters in a growing area for the culture duration. These oysters, which resemble naturally grown oysters, in large clusters, are typically directed to the processing industry for shucking and canning. These oysters generally are found in bottles or cans at the market, or are served at restaurants in soups or sandwiches as cooked products (VIMS, 2012, VA Shellfish Situation and Outlook Report 2011). Off-bottom culture furnishes several advantages over conventional bottom culture (See Appendix 3 for examples). The initial capital investment and intermittent labor are notably higher than bottom culture, though mortality is greatly reduced (elimination of predation by crabs or echinoderms, pests like the oyster drill, and depositional smothering) while growth is accelerated due to greater access to food particles and dissolved oxygen. (ACES)

In addition to filtering suspended matter, runoff nutrients, and nutrient enriched byproducts (phytoalgae, etc.), bivalves provide a number of other indispensable ecosystem services. Oysters in natural conditions build and inhabit vast reefs in shallow estuarine waters. These reefs form extremely biodiverse habitat and nursery grounds for aquatic organisms, and essential in food webs including mammals and sea birds. As well, these reefs support wetlands in the stabilization of shorelines, providing significant protective buffers against storms; Paul Greenberg discussed this aspect of coastal protection in the *New York Times* immediately prior to the coastal destruction of Hurricane Sandy (Greenberg, 29 October 2012). Lastly, oyster reefs are living interfaces between the pelagic and benthic zones, where their own metabolic and reproductive activities intricately connect the sea floor and the open waters (Coen, et al., in Shumway, 2011, Chapter 9).

The oyster industry is fundamental to the identity of the Chesapeake Bay. Due to suppressed population numbers, the industry as a whole is much smaller than in its peak, or even 50 years ago. The transformation of the oyster industry from one of pure extraction, to one more reminiscent of small scale agriculture has resulted in consistently robust growth within the past seven years (i.e. from 800,000 oysters sold in Virginia in 2005 to 23.3 million in 2011). This growth is projected to continue, and will see economically diverse growth as a result. Hatcheries, watermen, equipment manufacturers, marinas, watercraft construction firms, seafood processors, restaurants, among others benefit directly from a strong oyster industry. Countless other interests, economically or otherwise, benefit indirectly from the ecosystem services oyster populations provide (Shumway, 2011).

Oyster aquaculture naturally provides one of those seemingly rare instances where economic and ecological benefits converge. Bivalve aquaculture is essentially a sustainable aquaculture method, though if in a given area or stream segment is over-stocked with these animals, negative feedback mechanisms will outpace the positive and come to dominate the characteristics of that system. The current state of the Chesapeake Bay is largely the result of many negative feedback mechanisms, most of which are anthropogenic; requiring incremental and gradual mitigation tactics to increase its own ecological carrying capacity. Bivalve aquaculture has been widely accepted as such a strategy to ameliorate the Bay, as in for example what NOAA has termed 'blue infrastructure';

> "aquatic priorities in the nearshore coastal zone, such as submerged aquatic vegetation, oyster bars, tidal wetlands, fish spawning and nursery areas, and shoreline buffers." (NOAA Coastal Services Center, 2010)

As such infrastructure is not readily used by the public as other infrastructure typically is, and as it is situated externally from human settlement (underwater), blue infrastructure projects do not receive the funding priorities that conventional infrastructure does. As well, this living infrastructure is subject to a higher degree of degradation due to climate, weather, hydrology, predation, disease, anthropogenic injury, etc. Roger Mann of the Virginia Institute of Marine Science argues that hatchery-based seed production and active for-profit culture of the Eastern oyster is the most feasible method to simultaneously restore oyster populations while increasing the ecological carrying capacity of the Bay (personal communication). Restoration bars managed by public institutions have afforded limited success, due to aforementioned effects as well as unmonitored, illegal harvesting. Aquaculture lends both unvalued ecosystem services of removing excess suspended nutrients while assimilating those nutrients into a valuable seafood product.

The methodological steps taken in this thesis were conceived from the endemic problems of oyster restoration and poor estuary health. The subsequent analyses and tools will endow resource managers and the oyster industry with efficient planning mechanisms for simultaneously maximizing economic return and Bay restoration.

6. Modeling Oyster Production

Numerous efforts to model different carrying capacities of mollusk aquaculture have been conducted to date, particularly in determining potential production carrying capacities; e.g. Carver & Mallet (1990), Bacher et al. (1998), Ferreira et al. (2007), Kaiser & Beadman (2002), Duarte et al. (2003), Grant et al. (2008), Filgueira & Grant (2009). In addition to mere production carrying capacity, perspectives of ecological, economic, and social carrying capacities have arisen in the discussion of aquaculture modeling to better consolidate limiting factors of production other than organism-centered metrics (McKindsey, et.al., 2006)(Gibbs, 2009). Nevertheless, production carrying capacity is generally conceived of as a preliminary step to higher precision resource management, and an indispensable figure set in cooperating with industry stakeholders. In regards to shellfish carrying capacity modeling, Grant and Filgueira (in Shumway, 2011) describe carrying capacity models as essentially three coupled elementary components: a biogeochemical sub-model, a bivalve ecophysiology sub-model, and a physical oceanographic sub-model. The scale and application of such models is disparate, ranging from single box models to spatially enabled models. Currently, it seems that the literature favors localized production carrying capacity models, such as Farm-Aquaculture-Resource-Management (FARM) (Ferreira, et al., 2007), or spatially enabled models calibrated to specific regions, such as Grant, et.al. (2008), Filgueira (2012), or DHI MIKE implementations (DHI Group, Hørsholm, Denmark) . In principle, bivalve production carrying capacity models integrate biophysical factors (i.e. seston, water quality, current velocities, etc.) and functions of population growth.

Considering the filtering mechanisms of bivalves, the rate of filtration, and the net effect on the environment, Cranford, et.al. (in Shumway, 2011), detail the need for an increased quantity and quality of data pertinent to bivalve aquaculture to ameliorate uncertainty due to environmental and seston variability.

> "…site- and time-specific measurements of clearance rates are encouraged whenever possible to improve or to test model applications. These measurements will increase confidence among aquaculture stakeholders on the practical and regulatory applications of population-level clearance calculations. They will also improve ecophysiological and ecosystem model predictions and will increase capacity to address more specific questions related to fine-scale changes in feeding behavior. [….]

> greater spatial resolution within models would permit more quantitative assessments of optimal farm site location/layout and multi-farm interactions, whereas increased temporal resolution will aid in predicting seasonally variable bivalve controls on the phytoplankton." Ibid., p.113

Growth models, and models that integrate growth, aim to apply a set of reasonably accurate functions that ultimately provide a net biomass value, typically driven by food concentrations, respiration and metabolic losses, filtration rates, and environmental variables. Some sessile bivalve population dynamics models will also integrate mortality rates and reproduction aspects. Bivalve food consists of species-preferred suspended particles, largely represented in modeling by a function of measured chlorophyll-α. Filtration rates have been measured for several bivalve species through a variety of laboratory methods, where clearance rates are typically modeled as a fractional efficiency of filtration or by measuring the net reduction in seston over a given time. As not all ingested material is directed to somatogenesis (growth of the body) at a 1:1 ratio, assimilation (or alternatively, 'scope for growth'), as a fraction of that ingested energy, is the efficiency of the organism to convert food into flesh or shell after metabolic maintenance and respiration. Model intricacy varies substantially, with some based merely on functions of dry weight of bivalve flesh, while others incorporate environmental variables such as salinity, temperature, seston concentrations, etc (Gosling, 2003, pp.169-194).

Submerged, non-intertidal rack bivalve aquaculture posits a few limiting factors relative to production carrying capacity, which tends to parallel ecological carrying capacity. The most essential limiting factors are seston depletion and dissolved oxygen availability. Seston depletion will pose a limit on growth, production and density; while dissolved oxygen concentrations also limit the density of animals within a given area. For example, high densities of oysters in warmer, saline waters with high seston concentrations may consume enough oxygen to approach lethal levels, exceeding the carrying capacity for a time and place; particularly if those areas are already oxygen-compromised. Reduced dissolved oxygen levels will also increase the risk of contracting Dermo.

The inherent difficulty in site selection and farm-scale configuration of culture vessels and densities is to maximize return on investment with insufficient knowledge of the environmental limits to production.

7. Intensive Oyster Aquaculture Site Suitability: A Multi-Criteria Evaluation

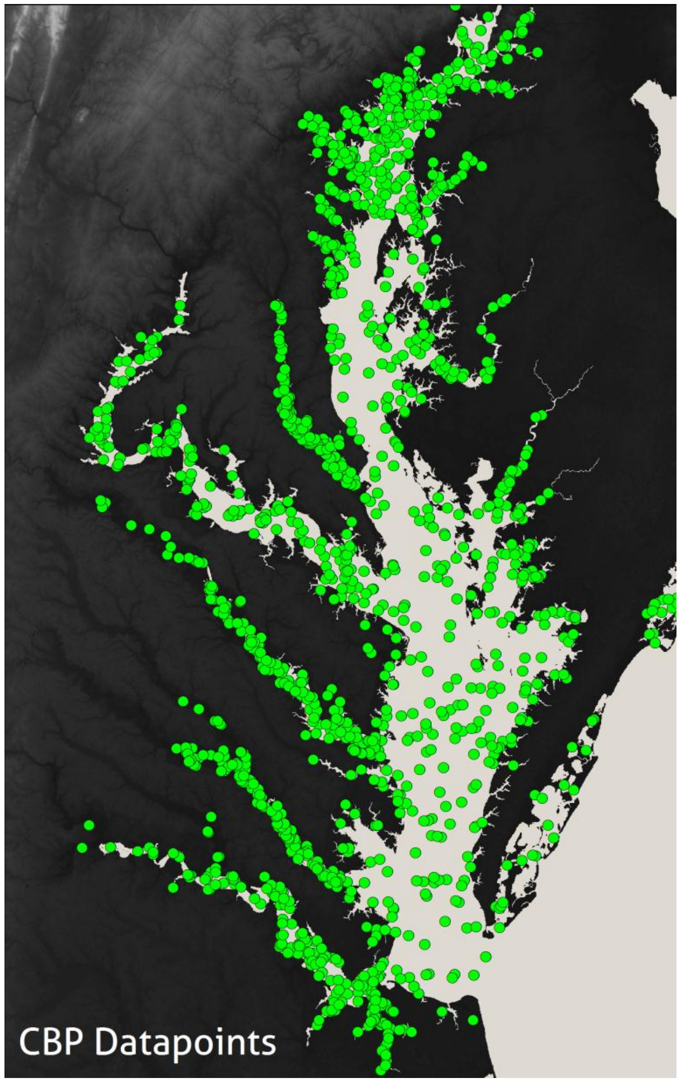
A two-step process was employed for the delineation of areas suitable for oyster aquaculture. Preliminary examination of physical, environmental, and social/regulatory constraining factors within the Chesapeake Bay presented significant limitations to siting. This process is largely influenced by the methodology employed in Silva et al. (2011); in which the authors delineated sites suitable for Pacific oyster culture in the Valdavia estuary of Chile by interpolating low resolution (spatial and temporal) data for use in a multi-criteria evaluation and as model driving parameters for oyster production. Their methodological justifications are befitting to the Chesapeake Bay, as given the expanse of its waters and exceptional competition for resource use, the Bay can be considered relatively data-poor and in acute demand of scrutiny.

An initial step of binary exclusion in regards to regulatory limitations and existing use or zoning for use that is exclusive of shellfish aquaculture (condemned shellfish waters, military exclusion areas, navigable water ways, conservation plots, wetlands, and submerged aquatic vegetation) delimits areas of conflicting development. The subsequent step analyzes biogeochemical and physical attributes of non-exclusion areas for binary suitability; where an area is either suitable or not suitable. Silva et al. (2011) argue for this binary method of selection, vis-à-vis expert systems or assigning weighted values to evaluative inputs, as "…. Aguilar-Manjarrez (1996) has shown with specific reference to aquaculture that experts with similar backgrounds may not be consistent in the assignment of weights or ranking of importance. Different backgrounds bring differing opinions, resulting in a range of outcomes ([Levings et al., 1995], [Longdill et al., 2007] and [Nath et al., 2000])." (ibid). This is particularly relevant to bivalve aquaculture due not solely to their complex interaction with the environment, but owing also to the relative high variability in adaptation and documented limiting factors for survival. Therefore, for each factor set of suitable site localization are treated uniformly.

7.1 Data Sources and Considerations

Environmental data employed in evaluating site suitability and subsequent oyster modeling was extracted from several databases made available by request or was publically accessible. The majority of data used here predominantly originated from four sources: The Chesapeake Bay Program's Water Quality Database (CBP), The Virginia Estuarine Coastal Observing System (VECOS), the NOAA Chesapeake Bay Interpretive Buoy System, and the NOAA Chesapeake Bay Operational Forecast System (CBOFS).

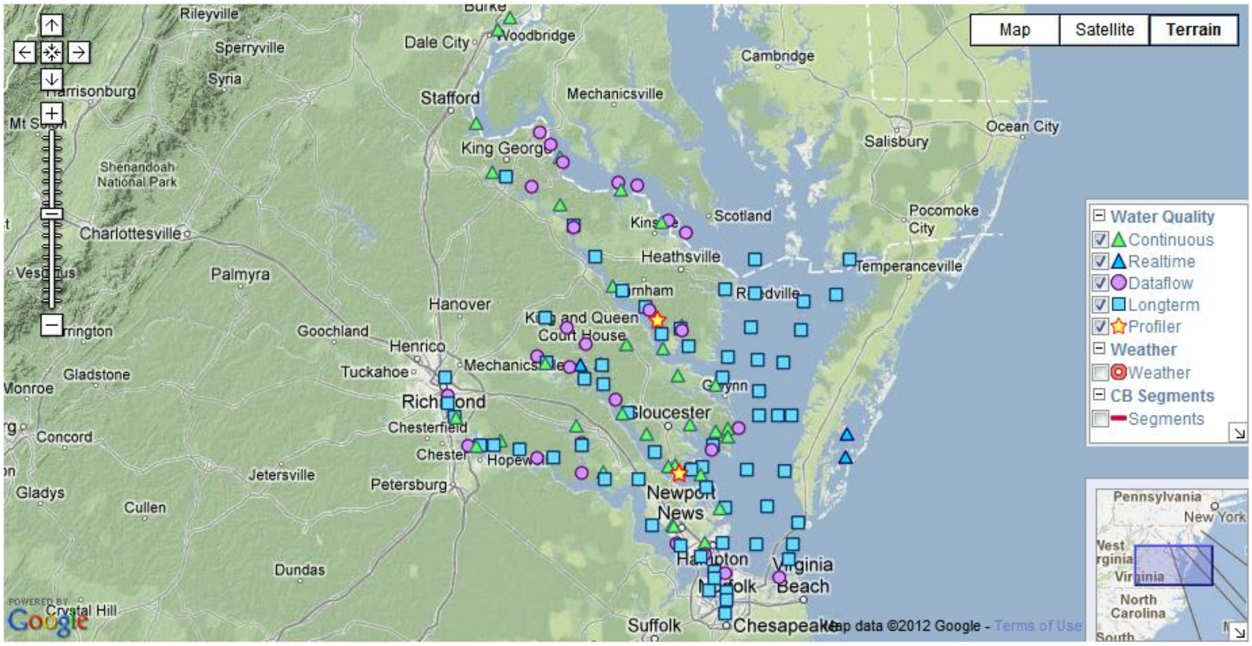
CBP data is hosted on a web-based data system, where monitoring site-specific data can be extracted by date. This data is a compilation of scheduled monitoring/sampling cruises around the Bay, as well as associated programmatic sampling of different parameters with relatively high spatial and temporal resolution; varying seasonally and with annual funding. Sediment toxin data, chlorophyll-a, total suspended solids (TSS), bathymetry, dissolved oxygen, and benthic diversity values were derived from this source (CBP Water Quality). As this data is stored by its 'sampling station', this data source is provided in point-data format. These 'sampling stations', or data points, are presented in Map 2, where water quality samples used in this work were derived.



Map 2: Chesapeake Bay Program Water Quality Datapoints.

VECOS is a web-based geographic data hub for water quality data in Virginia's portion of the Chesapeake Bay and major tributaries. Hosted by the Virginia Institute of Marine Science (VIMS), the data comes from multiple academic and scientific agency sources, though the bulk of the data is sourced from VIMS monitoring programs. Data parameters and testing methods are largely the same, or equivalent, throughout the datasets, though the acquisition is categorically different between datasets; particularly in temporal resolution. Data falls within four program categories: Dataflow, Continuous, Profiler, and Longterm. As the web-based version of this expansive database is intended for individual site-by-site querying, it was necessary to obtain the data as a 'dump' from the database manager. VECOS maintains records for 121 monitoring sites (see Map 3), and all data was obtained between January 2009 and

May 2012 for these sites directly from the database manager via FTP. These data, like the CBP data, are stored as point-data. Map 3 was captured from the VECOS website, presenting the locations of sampling locations.



Map 3: VECOS Datapoints

NOAA buoy data is extracted on a parameter basis by date range. These data are of extremely high temporal frequency (minute) but extremely low spatial frequency (10 sampling locations – see Map 4). Chloropyhll-a, dissolved oxygen, salinity, and temperature were obtained from this source by querying each station for the study period. As before, this data source is stored as point-data, and the sampling sites are presented in Map 4.

Map 4: NOAA Interpretive Buoy Locations (CBIBS)

CBOFS data provided modeled high spatial and temporal resolution hydrobiogeographical data. CBOFS is a local implementation of the Rutger's Ocean Modeling System, a "free-surface, terrain-following, primitive equations ocean model" (Regional Ocean Modeling System, 2012) representing hydrological characteristics at a semi-diurnal temporal scale (to mark tidal fluctuation) and extremely high spatial resolution. CBOFS data was extracted from the NOAA OPENDAPP data stream as NetCDF files, which were programmatically processed for evaluation within ArcGIS 10 (Environmental Systems Research Institute, Redlands, CA, USA, 2011). Dimensions were parsed into tabular attribute data for salinity, temperature, x and y horizontal flow values, and vertical flow values. Salinity and temperature were rasterized by Inverse Distance Weighting with barriers. As the operational forecast system models bidirectional horizontal flows, a tangent flow was calculated in Euclidean space and populated into a new field. The tangent flows were interpolated by in the same manner as all other variables. CBOFS data are validated at a rate sufficient to be considered 'observed data'. For elaboration on the model development and functioning, consult NOAA Technical Report NOS CS 29 (Lanerolle, et al., 2011).

Other data pertaining to biophysical, regulatory, or product quality constraints were procured from several sources, specific to the nature of that particular data. Condemned shellfish growing area data was obtained by portable storage media via post from the Virginia Department of Health Shellfish Safety Division as vector polygon datasets. Shoreline inventory data (shoreline land use) was obtained from the Virginia Institute of Marine Science's online database, as were vector polygon data demarcating Submerged Aquatic Vegetation in the Bay. Wetland delineation was obtained from the National Fish and Wildlife Service's National Wetlands Inventory, as vector polygon data available on the web. Navigable waterways data was made available from the National Register of navigable waterways from the federal office of the US Army Corps of Engineers and the Norfolk regional office of the US Army Corps of Engineers, as vector polyline data delivered by email. Conservation areas were obtained from the Nature Conservancy's online database as vector polygon data. A graphical representation of data sources, type, and suitability classification is presented in Figure 2 (below).

Parametric interpolated data were derived from sources differing in measurement frequency. Some data could be sufficiently dissolved on a daily averaged basis (dissolved oxygen, chlorophyll-a, turbidity, salinity), while others were dissolved on a weekly averaged basis (total suspended solids) and were linearly interpolated on a weekly basis. All data were reprojected or transformed to the NAD83 datum and UTM Zone 18N projection.

Due to the incapacity of ArcGIS to parse some comma-separated data (not to mention unambiguous errors in transforming data spatially within ArcGIS), these datasets were re-parsed by database tabulation within Microsoft Access (Microsoft Corporation, Redmond, WA, USA, 2010) and subsequently projected within ArcGIS. Although the quality of most records were maintained at a standard level, a few values interspersed within the datasets were either entered incorrectly in the VECOS database, or corrupted by ArcGIS in the transformation to dbf format. As a result, the provided date reformatting function within ArcGIS could not be used as it cannot handle anything outside user specification and further corrupts the original dataset; therefore a VB macro was created to parse dates and times.

The process model composed within this thesis is based upon a specific period within the life cycle of an organism that grows quite slowly. After seeding the grow-out enclosures, it is readily accepted that the oysters will be ready to harvest in 18 months. As such, over 18 months of data for this study area have been collected, processed, and analyzed (January 2009 – May 2012).

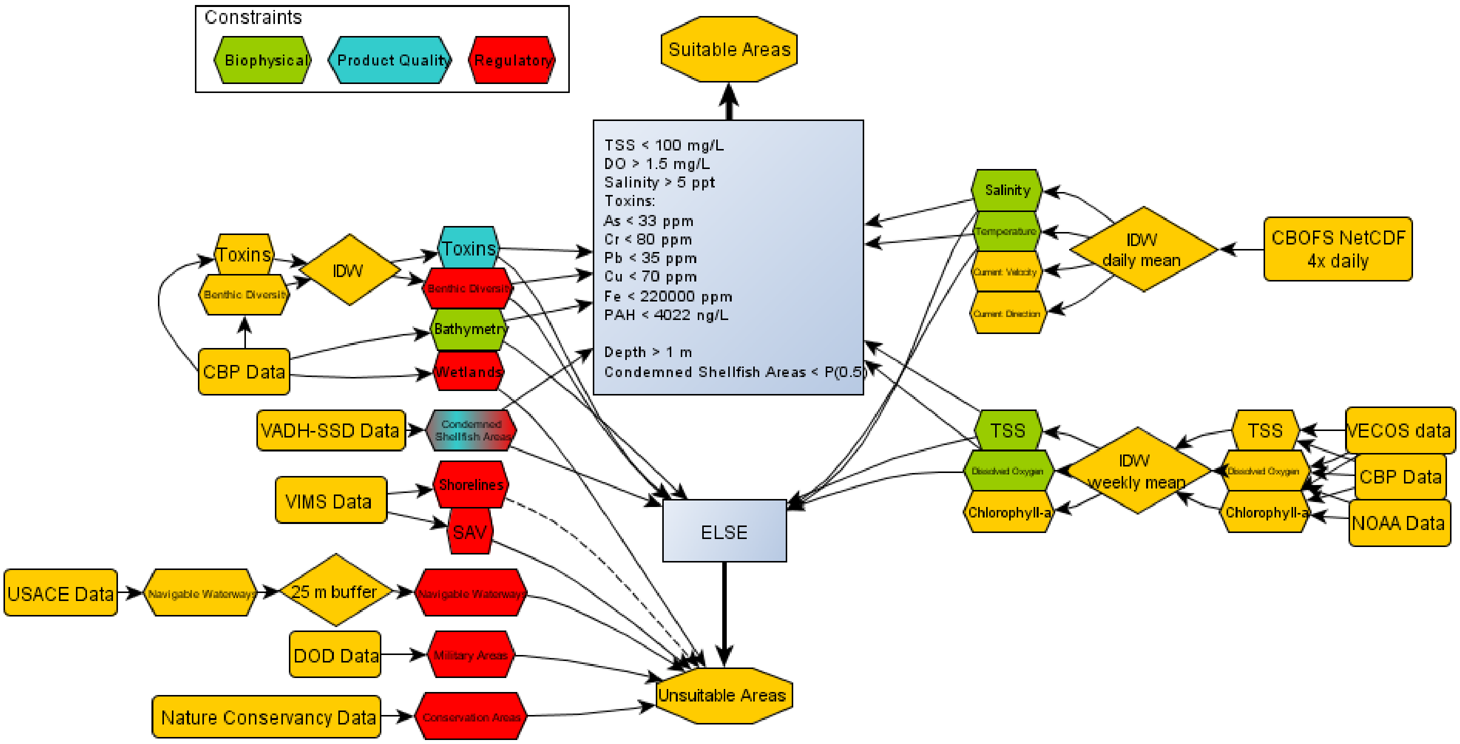


Figure 2: Aquaculture Suitability Data and Limits. Data sources are presented at directed origins, their parameters, and pre-suitability analysis operations. Each parameter was evaluated as a constraining factor, either as a biophysical constraint (e.g. salinity, oxygen, bathymetry), a product quality constraint (e.g. toxins), or a regulatory constraint (e.g. conservation areas, SAV, navigable waterways). Condemned shellfish areas is both a regulatory and product quality constraint. For constraining factors that were limited by an upper or lower limit were tested for that limit, and determined to be suitable or unsuitable for oyster aquaculture.

7.2 Field Measured Modeling Parameters and Suitability Factors

Compiled data were geometrically averaged on a weekly basis and interpolated by means of inverse distance weighting interpolation (IDW) with bounding features. Several interpolation methods were tested (kernel interpolation with barriers, diffusion kernel with barriers, kriging, several polynomial trend methods, and spline interpolation) for least standard error as derived from a sub-sample of validating observed values, finding IDW with barriers the most 'suitable' model given the data resolutions. Other interpolation methods provided system-wide error not significantly different from IDW interpolation with barriers, but their inter-variability of error yielded higher dispersal and validated error significantly greater than IDW. This method provided the most desirable results due mostly to the physiographic structure of the Bay, with many divergent channels and general complexity of inland waterways, as well as spatially complex multiple anthropic interventions in the study area. As IDW bases estimated values on linear distance between input point values, instead of deriving broader functions of spatial variation, in this context IDW has proven to be the most appropriate method for accuracy and efficiency. A simplified boundary feature was constructed based on detailed shoreline data by extending the shorelines inland by one kilometer, eliminating vertices and smoothing with Bezier curves; this reduced processing times from ~32 hours to ~3 hours for most datasets and time periods. In addition, datasets were interpolated on a 1km^2 basis, and then resampled to 100 meters^2 to both reduce processing times and avert peaks/spikes in the surface not uncommon to local interpolation methods (See Persson, et al., 2005 for a review on interpolation error, observation distribution, and density). It must be noted that clearly interpolating such a vast and complicated physical study area will fail to expose nuanced aberrations from the model, but this can be remedied with higher resolution of data acquisition and this framework is intended to be scalable. Distance-based interpolations provide generalized interpretations of the measured parameter over two-dimensional space. Perhaps a future alteration to this framework would be to employ a dynamic localized statistical interpolation (kriging) that respects bounding features if such an algorithm could be made available.

The IDW function is described copiously in the literature, Burrough and McDonnell (1988) detail:

$$Z(x) = \frac{\sum_{i=1}^{n} W_i * Z_i}{\sum_{i=1}^{n} W_i} \qquad \text{(Eq. 1)}$$

and

$$W_i = \frac{1}{D^k} \qquad \text{(Eq. 2)}$$

We find a new value for the point in question, in *Z(x)*, based upon the linear distance (*D*) from the measured point; whose value is represented by Z_i, *i* represents the i^{th} point in an iteration over *n* points. The fundamental variable in the IDW algorithm which modifies the influence of distance as a weight, *k*, is a user-determined exponent that accelerates the discreteness of spatial influence with rising value. With extremely high *k* values, IDW predictions can revert to Vonoroi diagrams / Thiessen polygons; while on the other hand lower values tend to provide 'smoother' interpolations as distance becomes less emphasized. It is largely accepted that the 'best' or 'optimal' value for *k* will depend on a priori knowledge of the parameters distribution characteristics, which is almost always unknown – hence the interpolation, or by testing a subset of sampled points to yield the least error. Bounding features provide a means of restricting points of influence given features that may exist in the landscape that transect points near to each other (i.e. riparian land bounding features). The bounding features create a discontinuity between two points that would otherwise influence the interpolated values in the space between those two points. This is particularly useful in this case as the hydrological configuration of the study area often situates relatively unrelated points in closer proximity to each other than points with higher spatial relation; limiting influence of space to points that lie on the same side of the bounding feature (ESRI, "IDW (Spatial Analyst)", 2011).

Interpolation statistical prediction errors are indicated for each temporally static interpolated parameter (toxins, benthic diversity) by Mean Standardized Error (MSE), Root Mean Square Error (RMSE), and Root Mean Square Standardized Error (RMSSE); where

$$\text{MSE} = \frac{\sum_{i=1}^{n} \left(\hat{Z}(\mathbf{s}_i) - z(\mathbf{s}_i)\right) / \hat{\sigma}(\mathbf{s}_i)}{n} \quad \text{(Eq. 3)}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(\hat{Z}(\mathbf{s}_i) - z(\mathbf{s}_i)\right)^2}{n}} \quad \text{(Eq. 4)}$$

$$\text{RMSSE} = \sqrt{\frac{\sum_{i=1}^{n} \left[\left(\hat{Z}(\mathbf{s}_i) - z(\mathbf{s}_i)\right) / \hat{\sigma}(\mathbf{s}_i)\right]^2}{n}} \quad \text{(Eq. 5)}$$

Where, $\hat{Z}$ refers to the observed value and z refers to the estimated value at point s_i. In general, smaller errors indicate higher accuracy, while the Root Mean Square Standardized Error provides a measure of variability estimation; values approaching one indicate less bias in either over or under estimating variability (ESRI, "Cross Validation", 2010).

The ultimate purpose of an MCE in site suitability analyses is to appropriately integrate several influential geographical variables into a cohesive representation of a study area for multivariate delineation of areas ranging from suitable to unsuitable for a given purpose. For site suitability of intensive oyster aquaculture, three categories of variables were found to be crucial for selecting areas that would simultaneously sustain this culture practice in a biophysical sense (no variable contraindicating oyster survival) while respecting the multiple uses and stakeholder interests in this estuary. Although oyster aquaculture can empirically be conceived of as a sustainable farming practice and pollution-mitigating mechanism, to ensure sustainability of the industry, the practice must first respect opposing interests, allowing sentiment to grow with increasing profitability and positive tangible environmental impacts. Figure 2 (above), presents a general overview of the MCE from data acquisition to suitability determination.

7.2.1 Condemned Waters

The Virginia Department of Health (VDH) Shellfish Sanitation Division maintains a fecal coliform monitoring program within the Bay waters, employing a dedicated team of technicians that constantly draw samples from the water column and test for fecal coliform in the lab. Sections that exhibit fecal coliform counts exceeding the statistical limits as determined by the Food and Drug Administration's National Shellfish Sanitation Program are deemed condemned and closed to shellfish harvesting; where,

> "The fecal coliform median or geometric mean MPN or MF (mTEC) of the water sample results shall not exceed 14 per 100 ml, and not more than 10 percent of the samples shall exceed an MPN or MF (mTEC) of:
> (a) 43 MPN per 100 ml for a five tube decimal dilution test;
> (b) 49 MPN per 100 ml for a three-tube decimal dilution test;
> (c) 28 MPN per 100 ml for a twelve-tube single dilution test; or
> (d) 31 CFU per 100 ml for a MF (mTEC) test." (FDA NSSP 2009 Section II Chapter IV)

Additionally, the VDH closes/restricts harvesting where,

> "Shoreline surveying of properties on the shore documents the presence of failing septic systems – where these are found, we also close nearby shellfish waters. Where significant marina activity exists, we close the nearby shellfish waters in the warmer months (Apr1-Oct31). Where there is a sewage treatment plant outfall, we prohibit nearby shellfish waters from harvesting and lastly where we cannot routinely sample (too shallow, etc) and we know there is shellfish resource or harvesting present, we administratively close those waters." (Daniel Powell, data administrator, email 16.5.2012)

This data is then used by the VDH to regulate the harvesting of shellfish within waters that present a significant hazard for seafood consumption – particularly relevant to human enteric pathogens. Once a section of waterway is deemed 'condemned' for a period of time, the geographical and temporal extent of that section's condemnation are recorded in a database. The VDH was kind enough to provide this database (the program commenced in 2006) for analysis of historical condemnations, in order to test the probability of condemnation for any given location within the Bay; a total of 22 quarterly periods. The VDH classifies closures into five classes: Condemned, Open, Prohibited, Prohibited-Nonproductive, and Seasonally Condemned.

Current regulations state that shellfish harvesters may not sell shellfish from waters deemed condemned, though they may 'relay' their harvest under regulations set by the VMRC. Relaying is a practice utilized by shellfish growers that find their growing area closed or condemned. The harvester will load the mollusks into a cage, where a VMRC officer will seal the cage and accompany the harvester to an open/safe section of water, and transplant the cage here to depurate the shellfish for 15 days (VMRC Regulation 4VAC 20-310-10). Relative to an analysis of site suitability, this avenue provides growers the opportunity to hypothetically grow in condemned waters and then transplant to open waters, but this is in practice somewhat onerous and unlikely that the grower would receive a permit to grow in such conditions. This would in most circumstances apply to a harvest within seasonally condemned waters; as such, this analysis omitted seasonally condemned waters as exclusive to shellfish production.

Thus, all closed sections were converted from vector to raster format at a resolution of 10x10 meters to preserve the extents of these areas. This raster data was then summed and tested for probability of condemnation by the classification of being either closed (1) or open (0). Areas with classifications greater than 11 were considered unsuitable. As shown in Figure 3, closures were found to be largely permanent relative to the recorded period (2006-2012), where out of 6914 discrete closed areas, 90% had been closed for the entire period.

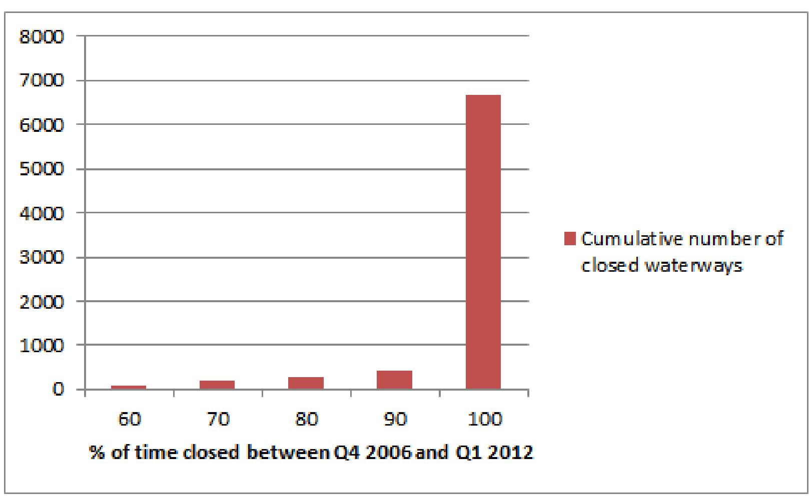
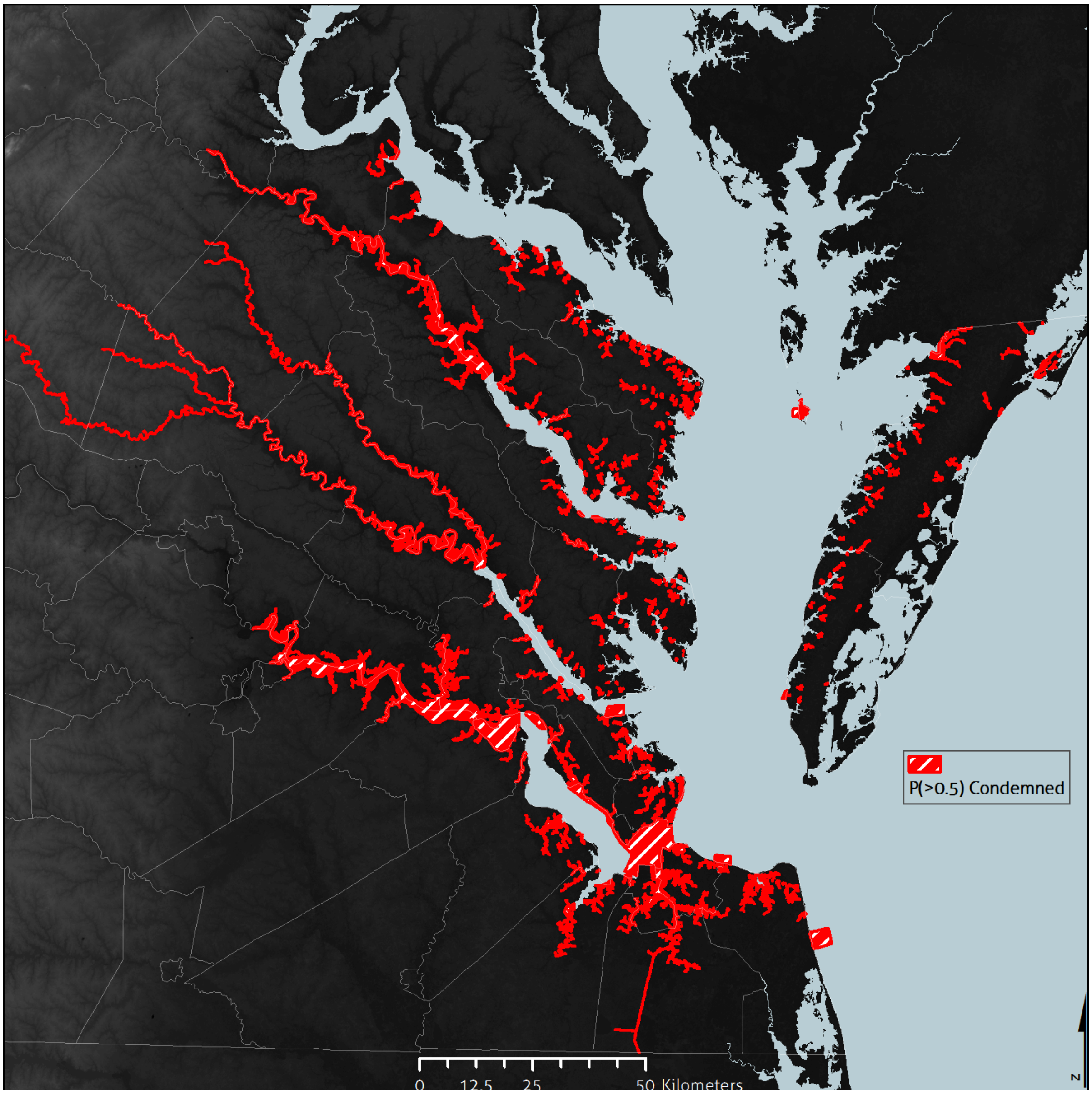


Figure 3: Percentage of Time between 2006 and 2012 Areas of P>0.5 Condemnation. The x-axis refers to the number of discrete areas, and the y-axis refers to the percentage of time the area had been considered condemned between Q4 of 2006 and Q1 of 2012.

For sensitivity, the probability threshold was set to 'chance', or 0.5; resulting in 6669 discrete areas (96.46% of all closed areas) and 71,583 hectares. These areas were thenceforth considered unsuitable for oyster aquaculture in this analysis, as shown in Map 5.



Map 5: Condemned Shellfish Growing Areas. Shellfish growing area closures are notably confined to the upper portions of the Bay's tributaries, as fecal coliform from human sewage or agricultural runoff tends to concentrate 'upstream'. Data source: VA Dept. of Health Shellfish Sanitation Division

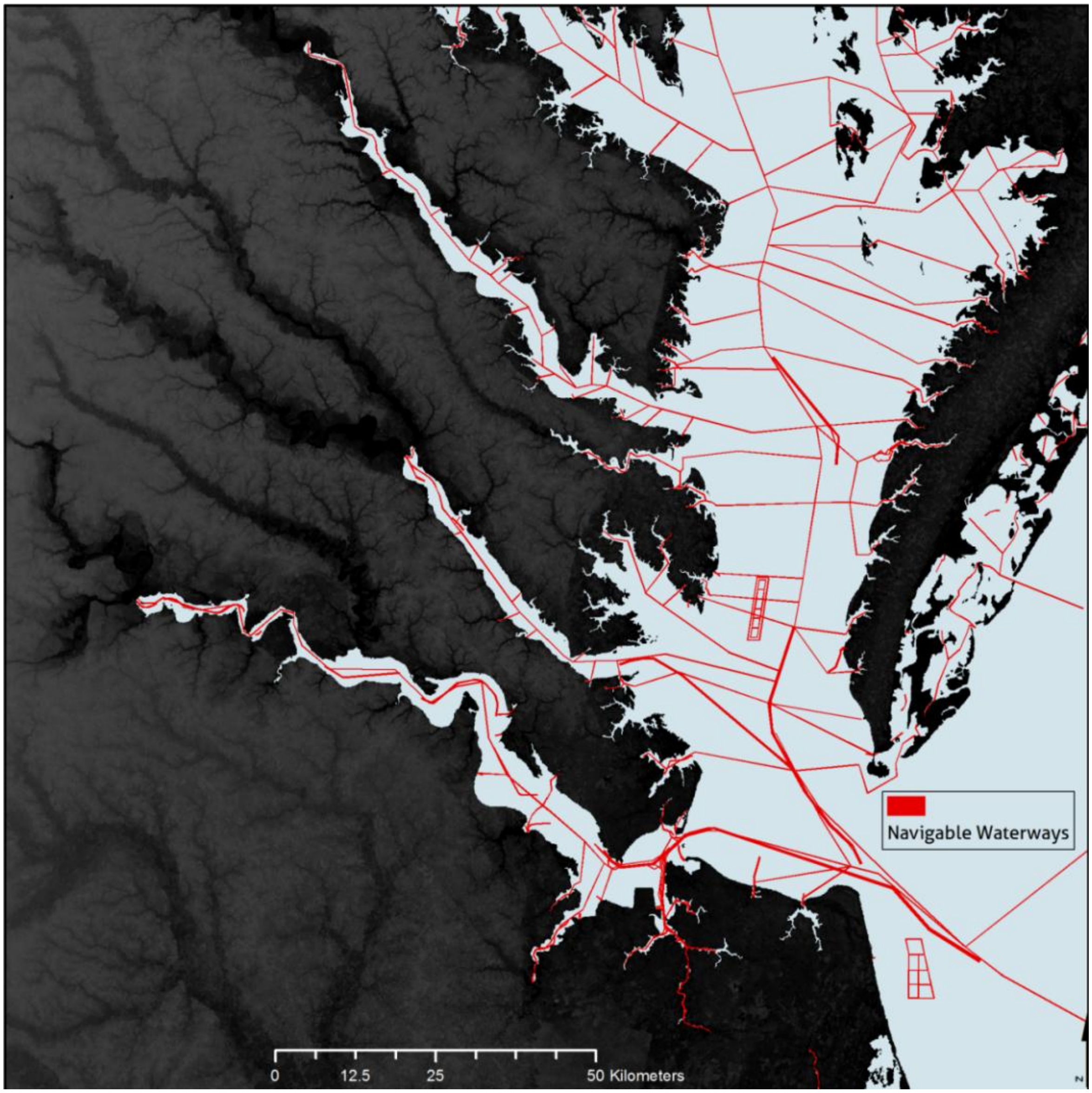
7.2.2 Navigable Waterways

The Chesapeake Bay has historically been valued not only for its great wealth of aquatic resources, but perhaps even more so as an extensive network of navigable waterways for maritime trade. The world's major logistics corporations maintain offices within the watershed, with the port at Norfolk being one of the largest on the eastern seaboard. The world's largest naval installation is also located at Virginia's southern end of the Chesapeake Bay; and with two of the largest metropolitan regions in the eastern United States – Washington DC and Hampton Roads – the Bay is host to vast recreation maritime traffic. In short, the Bay's waters are busy and valuable.

As stated in VMRC Regulation 4VAC20-1130-50. Special Conditions. Part G,

> "Temporary protective enclosures shall not be placed in any area that would impede customary access to navigable waters, from any riparian property, public or commercial landing, or marina facility."

The region's navigable waterways are digitized and maintained by the US Army Corps of Engineers, Norfolk Division (USACE). They were provided by that office upon request. A 30 meter buffer (total of 60 meters) was imposed on navigation tracts, a sufficient channel width for navigation in the Bay; though it should be noted that most navigable channels are far narrower throughout the Bay (Author's personal experience). These areas were then considered unsuitable for oyster aquaculture in this analysis, as shown in Map 6.



Map 6: Navigable Waterways, 30m buffer. Regular ship traffic traverses throughout the Bay. Data source: USACE

7.2.3 Submerged Aquatic Vegetation

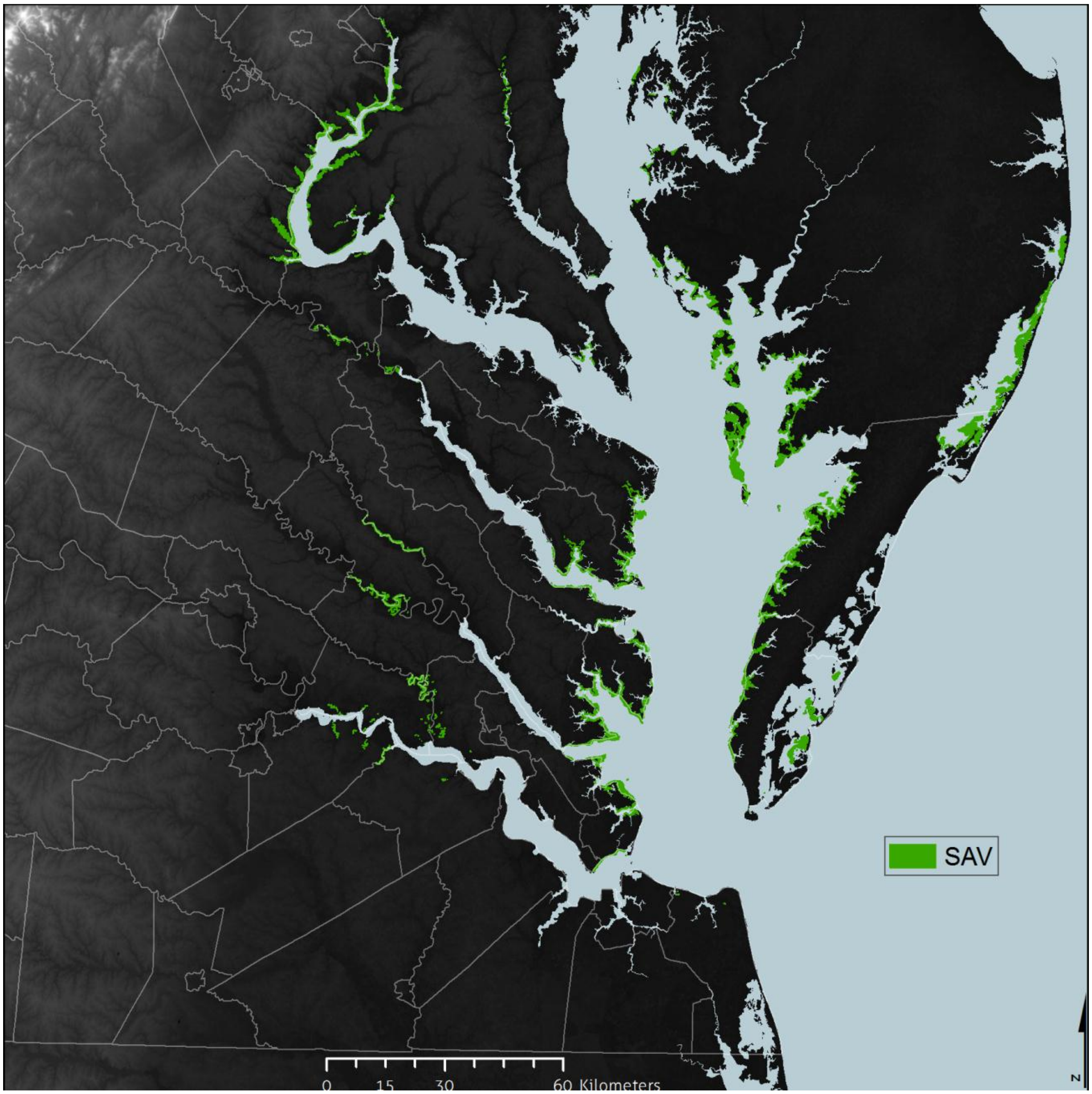
Within estuaries, one of the most significant symptoms and subsequent sources of ecological degeneration is the loss of submerged aquatic vegetation (SAV). SAV suffers a similar fate and provides many of the same ecological functions as oyster populations. Dissolved nitrogen and phosphorus are directly assimilated by SAV, reducing excess nutrient loads and phytoplankton densities. As they contribute heavily to water column clarity (reduced turbidity) and thrive in clear waters, SAV equally languish in turbid waters of high light attenuation. The rhizosphere of SAV also provide the function of keeping sediment consolidated, further contributing to water clarity. Turbidity and SAV proliferation are to a large extent inversely related. SAV also provides nursery conditions and habitat to countless aquatic organisms; suffice it to say that the preservation and promotion of SAV are paramount (VIMS, "Submerged Aquatic Vegetation", 2012).

It is the priority of resource management institutions within the Bay that SAV should be protected and stimulated, and remain exclusive of other uses, including shellfish aquaculture. As stated in VMRC Regulation 4VAC20-1130-50. Special Conditions. Part C,

> "*No temporary protective enclosure shall be placed in or upon submerged aquatic vegetation beds, and consideration, by the Commissioner, for authorizing the placement of protective enclosures in currently un-vegetated areas that are documented as historically supporting SAV beds, shall include consultation with the Virginia Institute of Marine Science, in order to determine the potential for impacts on SAV, within the term of the prospective lease. If SAV colonizes within the boundaries of the area designated for the temporary protective enclosures, the authorization for those structures under this general permit shall remain in effect only for the remainder of the term of the lease. The general permit shall be renewed only upon a finding by the Commissioner that the placement of the temporary protective enclosures, within the lease, will not significantly interfere with the continued vitality of the SAV.*"

Annual surveys are conducted by the Virginia Institute of Marine Science and associated NOAA Seagrant investigators by aerial and boat survey. The most recent comprehensive data available encompassed 2011 surveys, which were extracted from the VIMS-SAV database.

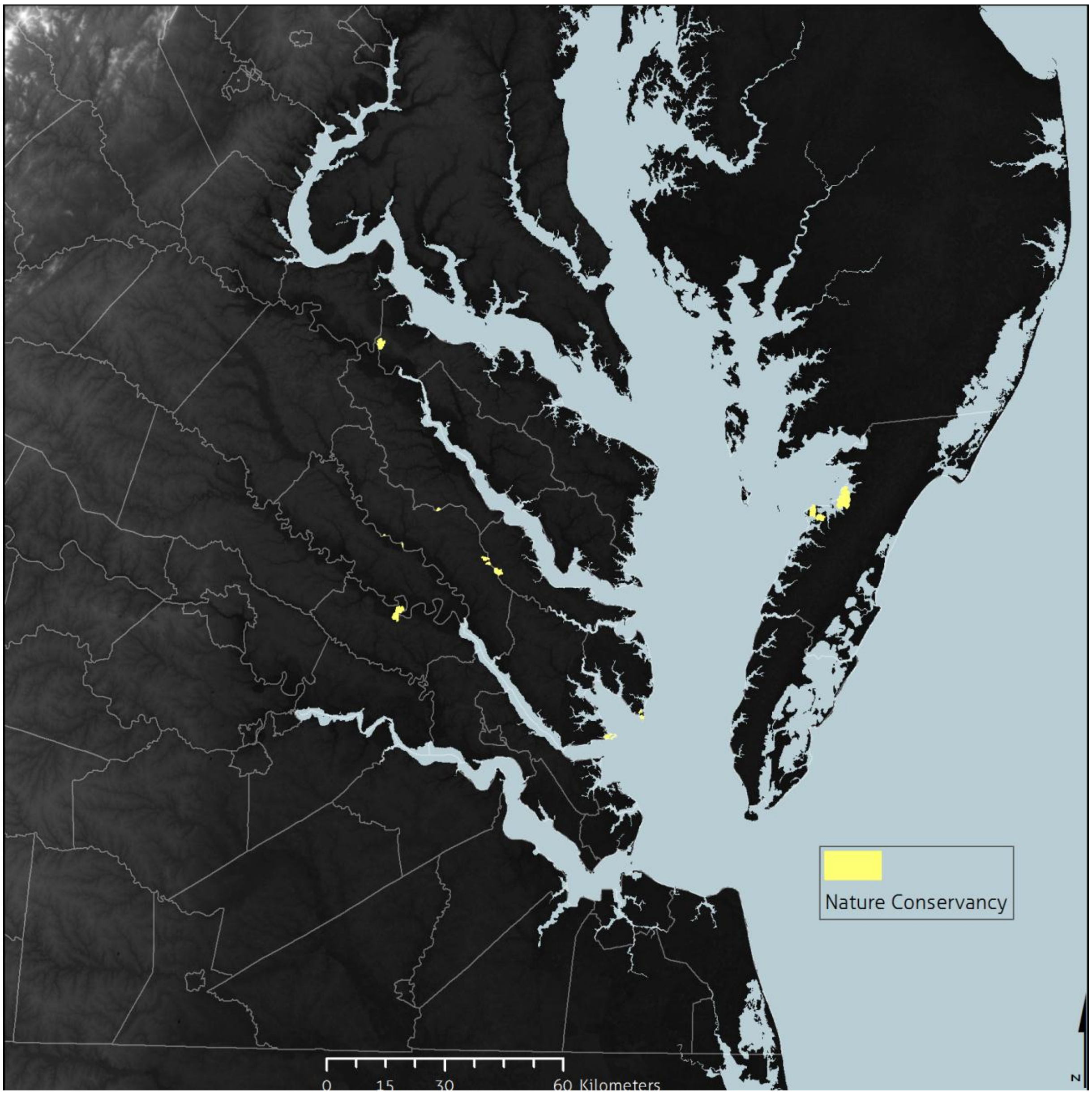
A total of 39564 hectares of the study area exhibited presence of SAV, with a mean discrete area of 10.68 ± 59.37 hectares (n=3682). The exceptionally wide confidence interval is due to the skewed range of areas, where the smallest SAV bed measured 0.01 hectares, the largest continuous bed measured 2785.2 hectares. Areas indicated of SAV were considered unsuitable for oyster aquaculture in this analysis, as shown in Map 7.



Map 7: Submerged Aquatic Vegetation. These vegetative beds are largely confined to areas of low water depth. Data source: VIMS

7.2.4 Conservation areas

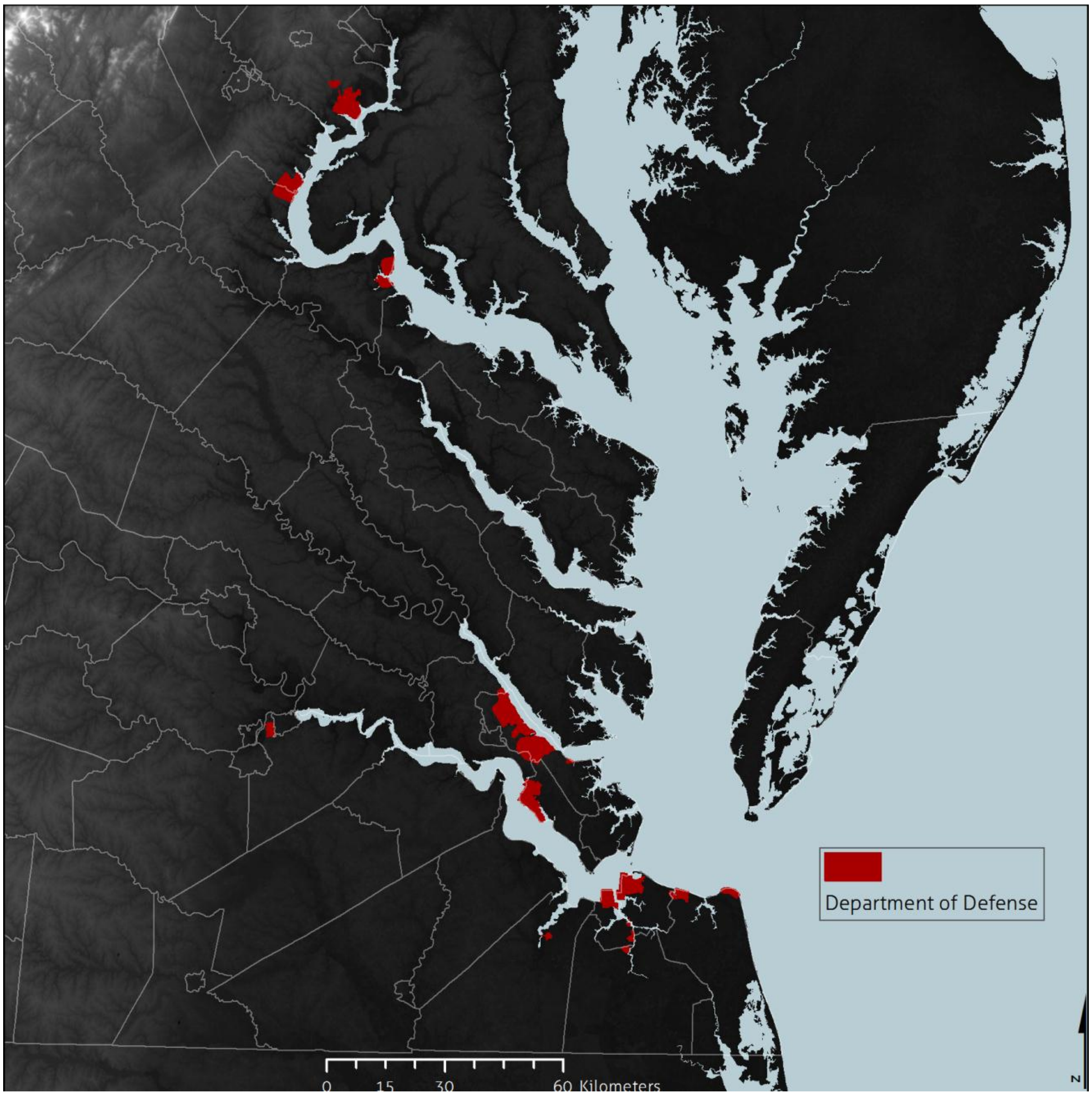
Falling within the scope of sustainable aquaculture and resource management, areas set aside for natural conservation should be respected as areas exclusive of anthropic intervention. A total of 2612 hectares (average of 153.6 ± 183.3 hectares, n=17) are protected by the Nature Conservancy, the largest non-profit environmental conservation organization in the United States. These areas are considered unsuitable for oyster aquaculture, without expressed request of the Nature Conservancy for farmers to utilize these areas, as shown in Map 8.



Map 8: Marine Conservation Areas. Data source: Nature Conservancy.

7.2.5 Department of Defense Regions of Exclusion

A total of 27,172 hectares (average of 1045 ± 1283 hectares, n=26) are maintained as zones of exclusion by the Department of Defense, precluding most other uses. Besides military maritime traffic, these areas may also be exposed to miscellaneous toxins or otherwise hazardous circumstances. These areas are unsuitable for oyster aquaculture as a private enterprise, as shown in Map 9.



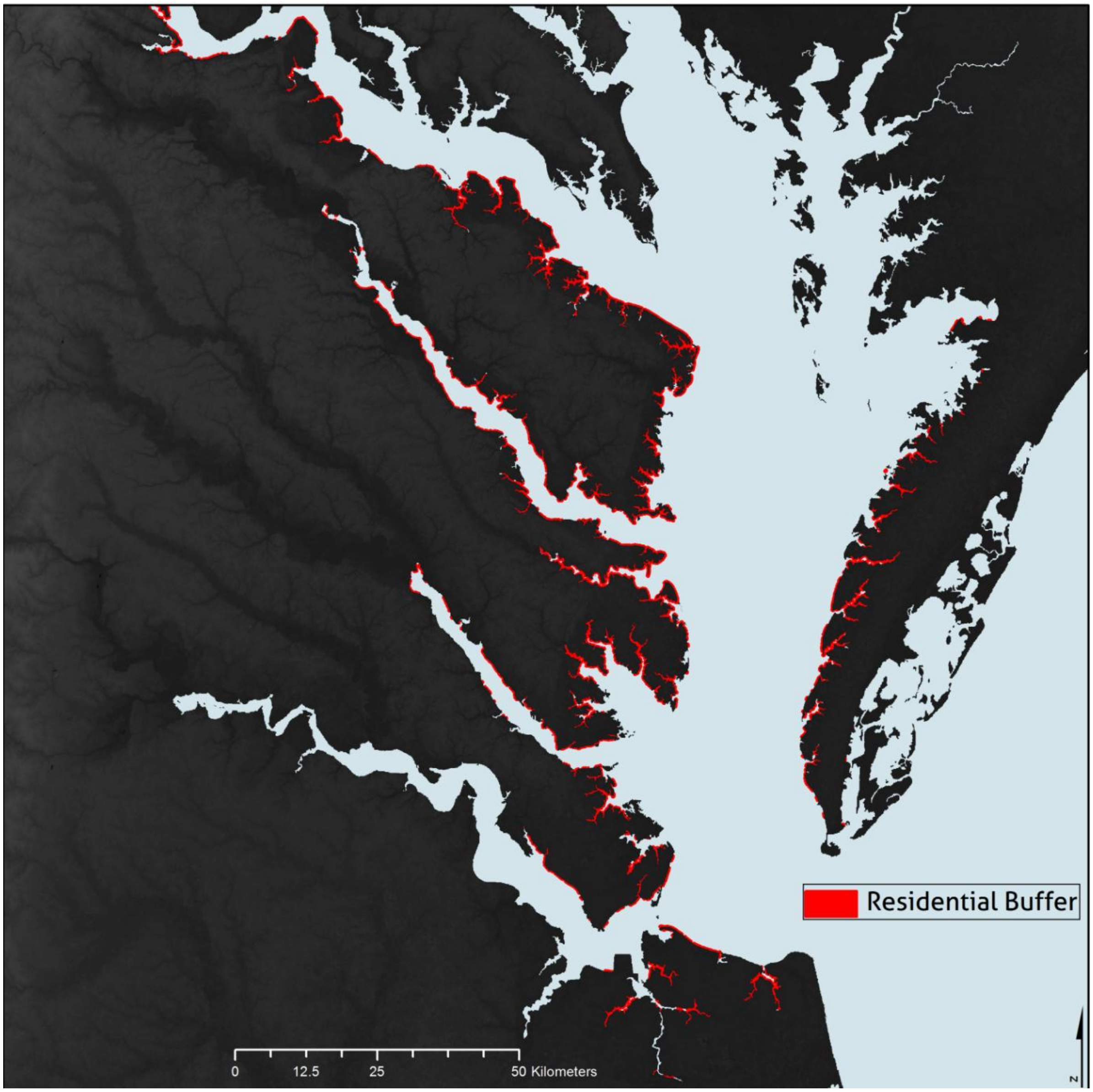
Map 9: Department of Defense Exclusionary Zones. Data source: US Department of Defense.

7.2.6 Shoreline Inventories

As stated in VMRC Regulation 4VAC20-1130-10:

> "*The notification [notification of the use of temporary protective enclosures] shall also include a list of the names and addresses of all riparian property owners within 500 feet* [152.4 meters] *of the area containing the temporary protective enclosures and shall depict the location of their land on a tax map or other suitable map. Riparian Property Owner Acknowledgement Forms for such riparian property owners, may be included with the notification. Such forms shall be signed by the riparian property owner and shall indicate their comments on the notification. Should such forms not be provided in the notification, the Commissioner, or his designee, shall notify the adjacent property owners of the pending notification.*"

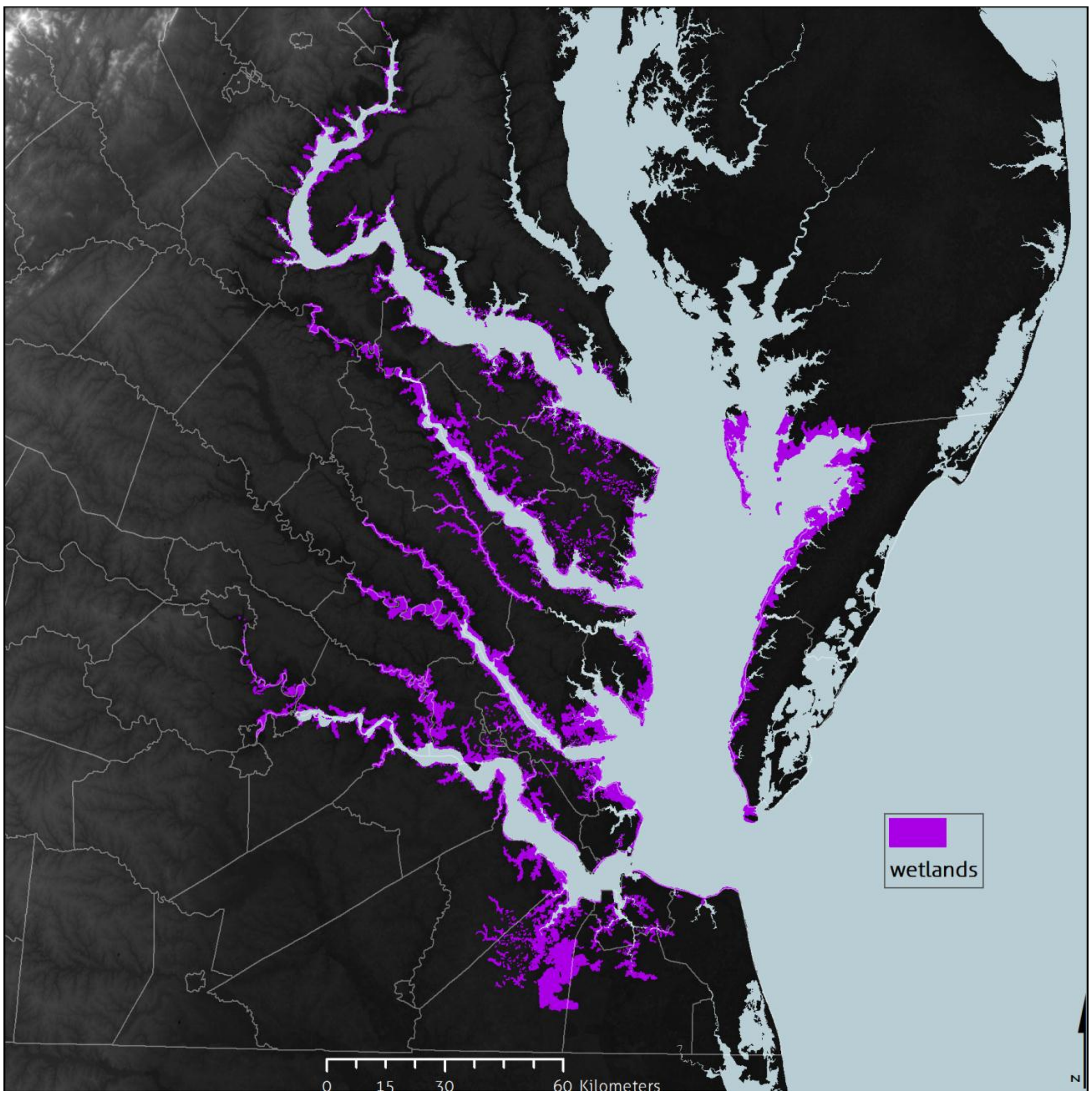
Shoreline inventories were collected for each municipality sharing a riparian or otherwise waterfront boundary with the Chesapeake Bay, with the exception of some municipalities along the James River which could not be obtained. These inventories were collected from the VIMS shoreline database as well as individual county data managers. Shoreline use classifications were reclassified as either residential (including commercial ownership) or other. A 500 foot buffer was applied to residential segments for delimiting areas of potential conflict of interest, as shown in Map 10. These areas are not exclusive of shellfish aquaculture, though they are denoted as requiring additional scrutiny prior to aquaculture development; as such the deficiencies of this database along the James River are not considered to be diminishing in this analysis.



Map 10: Residential Shoreline Land Use. Characteristic of the modern Chesapeake Bay, waterfront property has been developed for single family residential land use. Data source: VIMS

7.2.7 Wetlands

Wetland preservation is a well-grounded policy objective of environmental agencies, resource commissions, and planning bodies. They provide similar ecological services as SAV, with the addition of wild fowl habitat. The exclusion of wetlands from intensive oyster culture however will not necessarily impose much restriction, as wetlands are generally intertidal (exposed sediment at low tides), not continually deep enough for such culture. Wetland delineation was derived from the National Fish and Wildlife Service National Wetlands Inventory. A total of 85925 hectares, mean of 4.57 ± 33.3 hectares within the Bay are host to permanent wetlands, deemed unsuitable for intensive oyster aquaculture, as shown in Map 11.



Map 11: Wetlands are a very common feature of the Bay, and a crucial ecosystem for Bay ecology. Data source: Fish and Wildlife Service National Wetlands Inventory via CBP

7.2.8 Benthic Indices

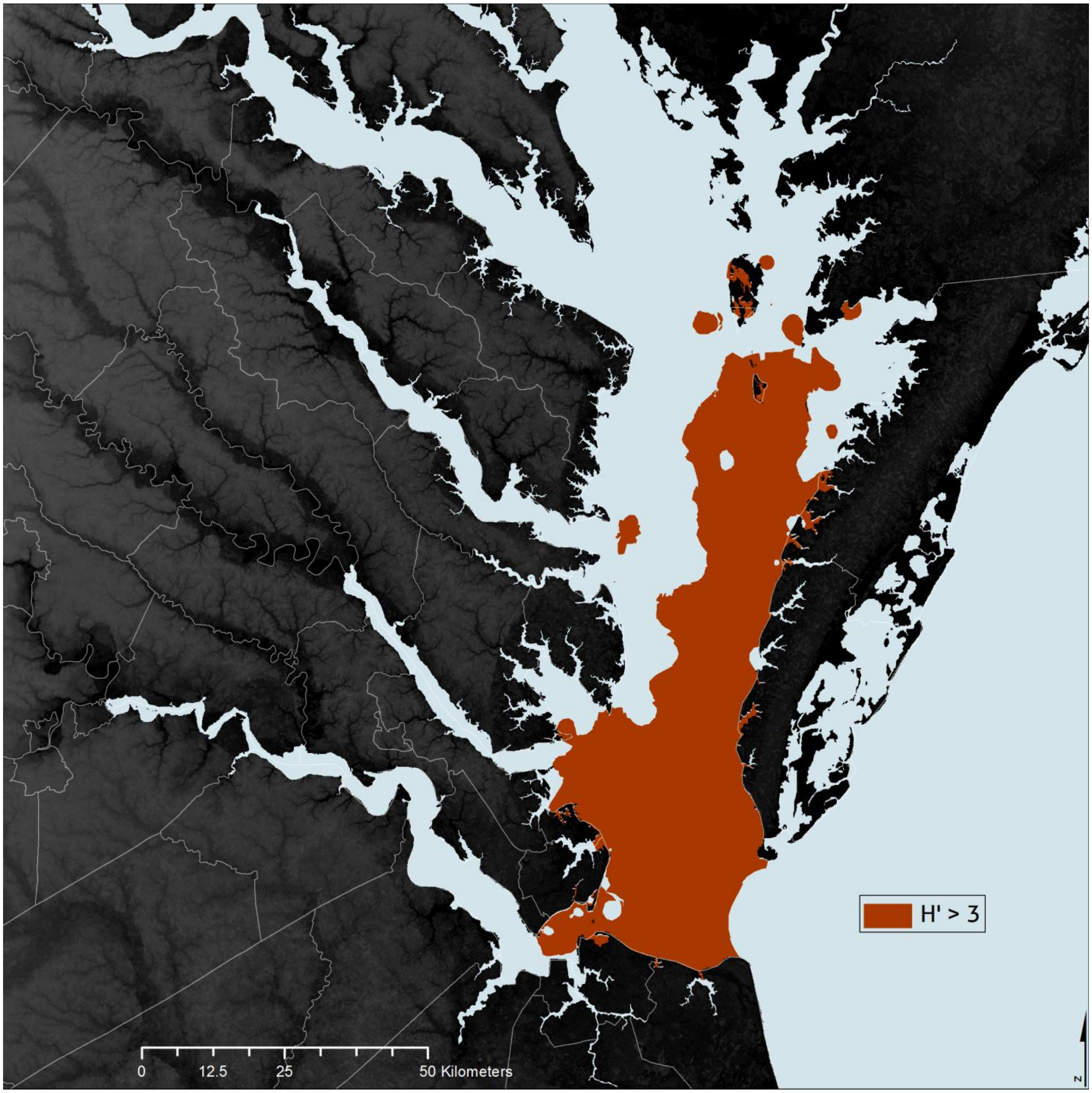
Keeping in stride with the Ecological Approach to Aquaculture, intensification of shellfish aquaculture should not preclude the preservation of benthic biodiversity; an essential ecosystem in estuaries. Deposition of shellfish fecal and pseudofecal (undigested, rejected food coated in mucous) matter has been documented to increase benthic zone anoxic conditions, and subsequently decreasing benthic biodiversity (Castel, et al., 1989). As Silva, et al (2011) has proposed, zones of relative high benthic biodiversity should be treated as ecologically sensitive areas, and excluded from intensive shellfish aquaculture. Several ecological indices are readily utilized in the quantification of biodiversity; Labrune, et al (2006) evaluate several indices in the analysis of oyster bed impact on benthic diversity. Shannon's index (denoted 'Shannon-Wiener Index' in CBP) has found broad use in the ecological literature; Lu et al. (2008) employ Shannon's index in reference to macrofaunal benthic communities influenced by intensive oyster aquaculture in an eastern North American estuary, providing categorical metrics for ecological quality. Although far from perfect, it is computationally efficient, is relatively immune to sample size variation, and has wide recognition.

Shannon's index (H') is formalized as:

$$H' = -\sum_{i=1}^{n} p_i \ln p_i \qquad \text{(Eq. 6)}$$

Where p_i refers to the abundance of the i-th species (Spellerberg, 2008).

Based on meta-analysis Silva, et.al (2011), specify that shellfish aquaculture suitability should be limited within areas exhibiting values of H'>3. Data derived from the Chesapeake Bay Program's Baywide Benthic Database, and interpolated, provided values between 0.52 and 4.65.



Map 12: Areas of High Benthic Diversity, error metrics of the interpolation are provided below. These areas of high benthic diversity are found within the more saline parts of the Bay. Data source: CBP

MSE	0.003
RMSE	0.77
RMSSE	0.97

A total of 811,001 hectares within the Bay were found to exhibit contraindicative benthic diversity properties to development of intensive oyster aquaculture at this time, as shown in Map 12. This will of course be one of the most contentious limiting spatial factors to siting, and will require further examination in relation to the differing practices of oyster aquaculture (as well as other aquaculture practices), though at the moment, the amount of seemingly available area is currently underutilized and should be desired more so than areas of higher benthic diversity. Finally, the flux in benthic diversity as a function of shellfish aquaculture will be an important dialogue in the future, as within this framework, oyster aquaculture will be self-limiting as theoretically it will increase downstream ecological health and subsequent species diversity. At this time however, with the eutrophic states in perspective, areas deemed suitable outside of highly diverse benthic areas are considered in which intensive bivalve culture will do more good than harm.

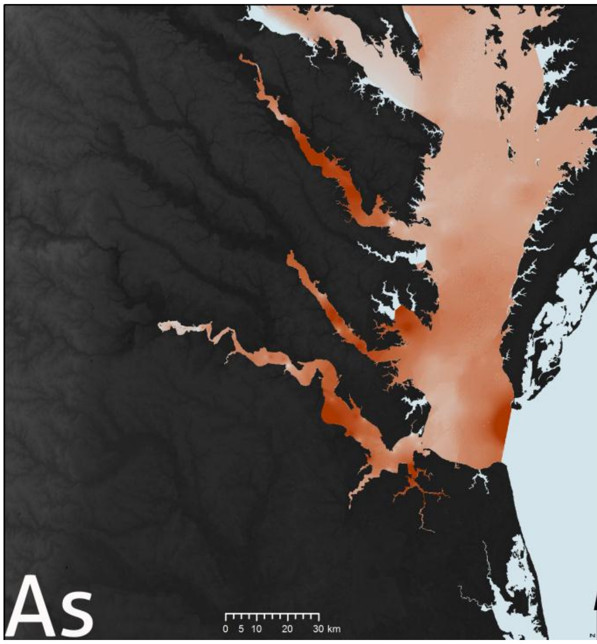
7.2.9 Toxins

Long, et.al. (1990), and the State of Washington (1995) (another bivalve producing state) have determined limiting values of shellfish quality relative to toxicity levels of sediment contaminants that pose risks for bioaccumulation in. Although many different parameters are presented in that literature, and others could pose bioaccumulative risks, the following are provided in the available data to an appreciable extent. The only exception is the delineation of polycyclic aromatic hydrocarbon (PAH) values, where only a few samples had been made available and were insufficient to interpolate; a 2-kilometer buffer was imposed on these points for sensitivity. Toxins data was derived from the CBP Sediment toxins database.

Where

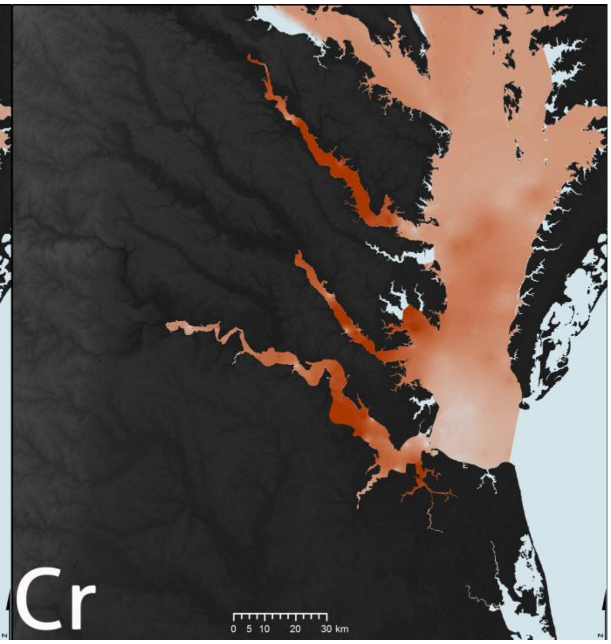
- As = Arsenic
- Cr = Chromium
- Cu = Copper
- Fe = Iron
- Pb = Lead
- PAH = Polycyclic aromatic hydrocarbons

Toxin Interpolation Results



Map 13: Arsenic Distribution

High : 35.9291 Low : 0	MSE: 0.03 RMSE: 4.82 RMSSE: 1.04

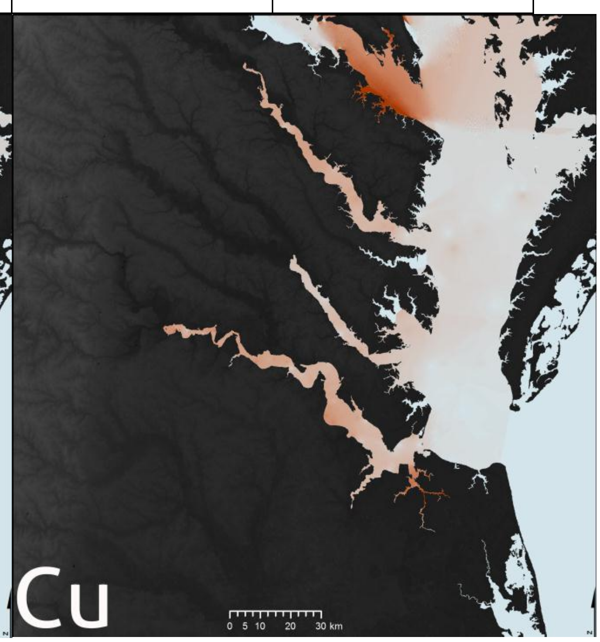


Map 14: Chromium Distribution

High : 80.3827 Low : 2.15416	MSE: 0.04 RMSE: 19.69 RMSSE: 0.99

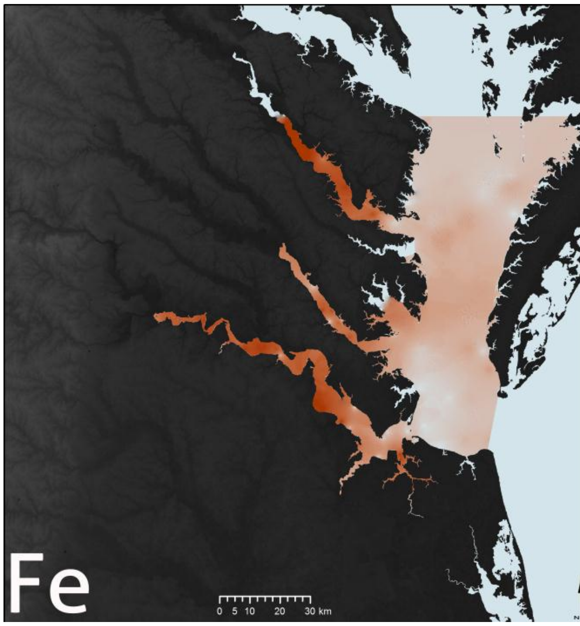
Map 15: Lead Distribution

High : 129.353 Low : 1.86391	MSE: 0.005 RMSE: 21.24 RMSSE: 1.17

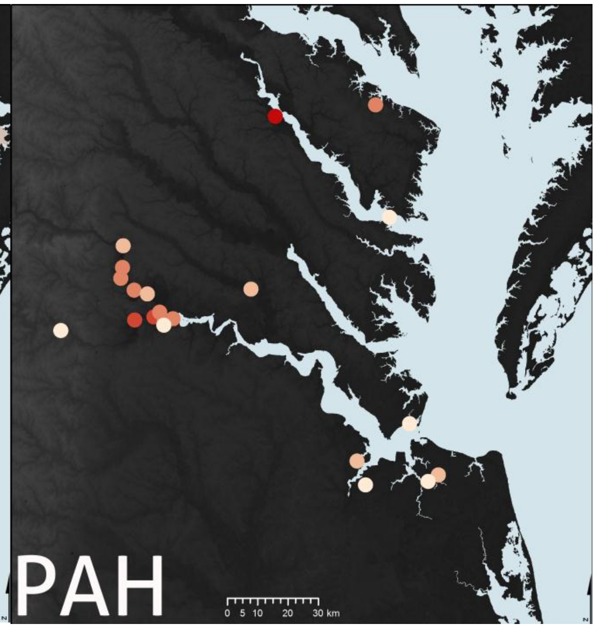


Map 16: Copper Distribution

High : 185.953 Low : 0.922523	MSE: 0.34 RMSE: 22.4 RMSSE: 0.87



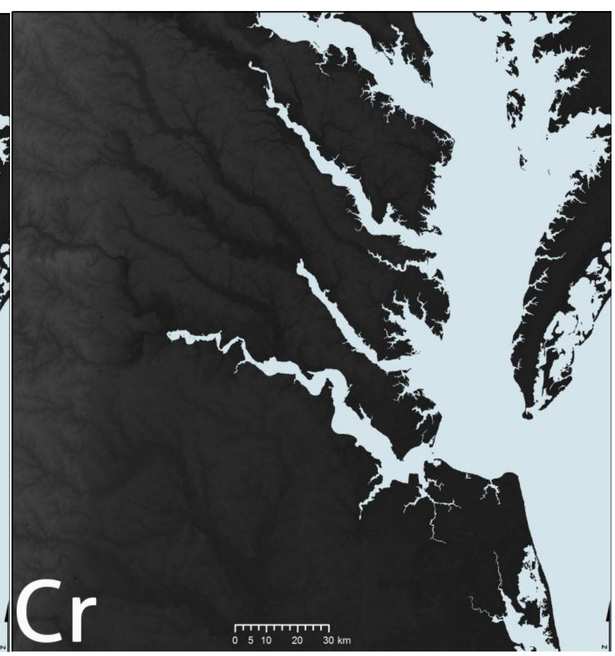
Map 17: Iron Distribution[1]



Map 18: PAH Distribution

High : 56420.2 Low : 1128.84	MSE: 0.087 RMSE: 14892.18 RMSSE: 1.03	11.2 - 351.8 351.9 - 1,276.4 1,276.5 - 3,660.9 3,661 - 7,164.5 7,164.6 - 12,420.1	N/A

Toxin Suitability Results



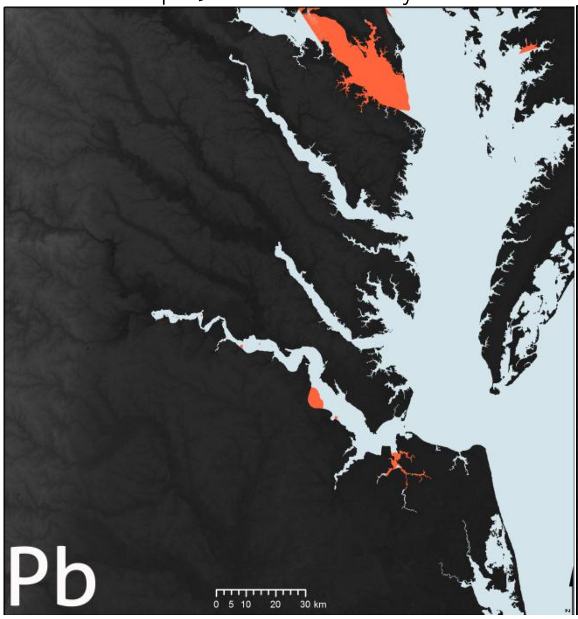
[1] The northern extent of this interpolation is bound by the most northern data points; so as to prevent extrapolation.

As > 33 ppm
As < 33 ppm

Map 19: Arsenic Suitability

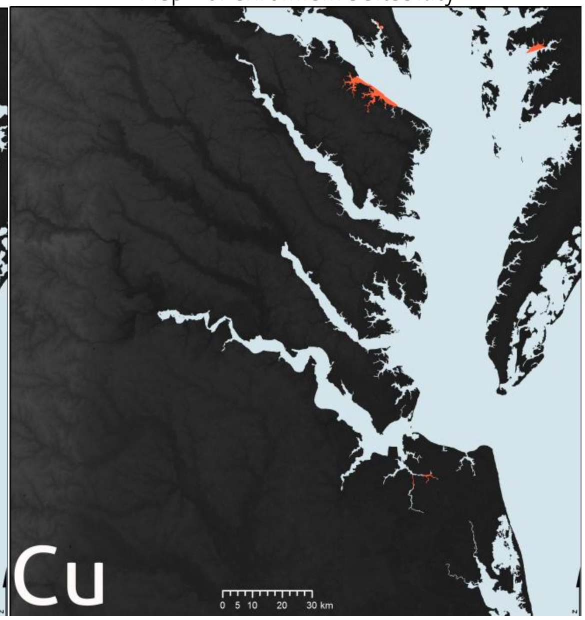
Cr > 80 ppm
Cr < 80 ppm

Map 20: Chromium Suitability



Pb > 35 ppm
Pb < 35 ppm

Map 21: Lead Suitability



Cu > 70 ppm
Cu < 70 ppm

Map 22: Copper Suitability

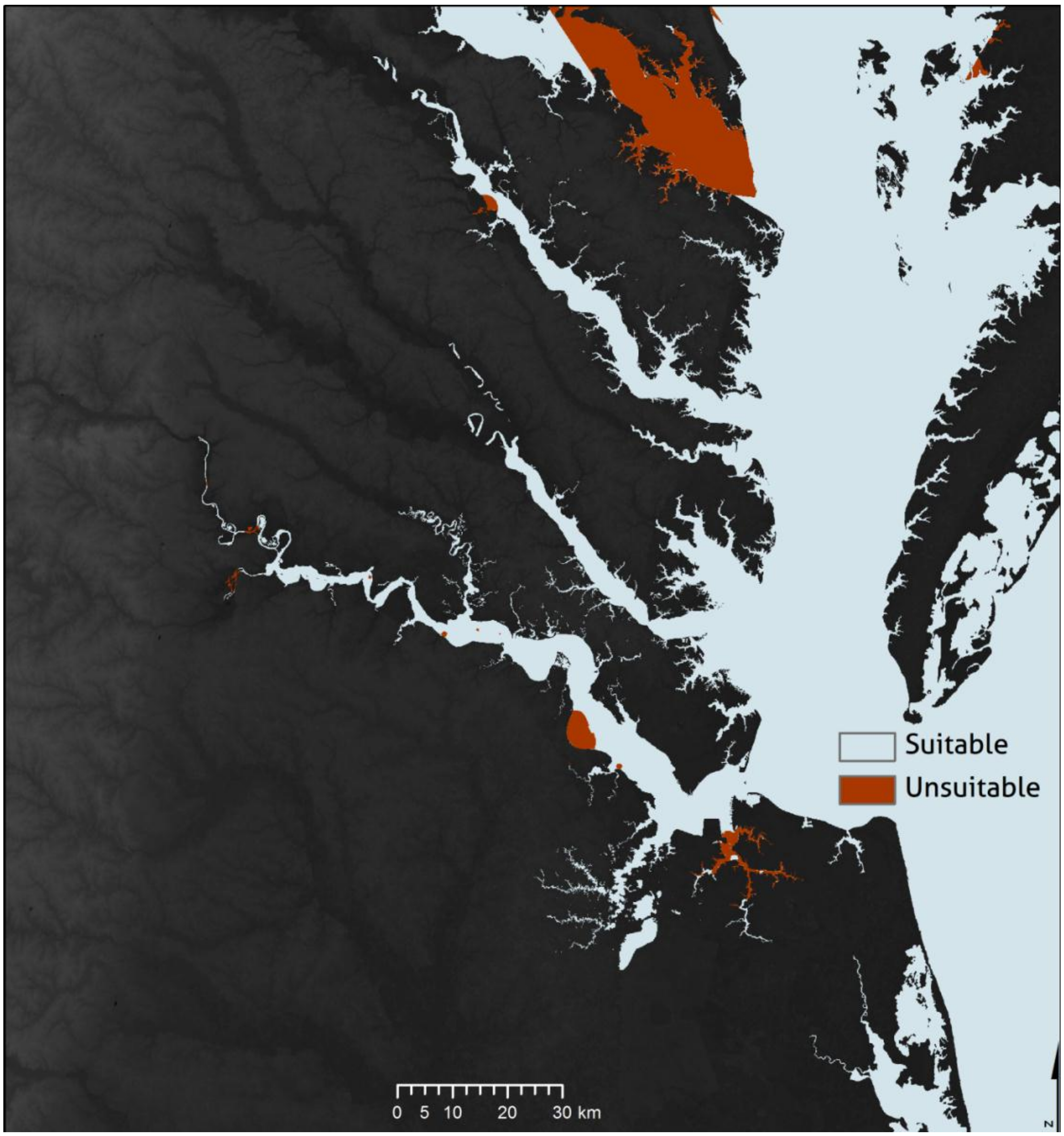
Fe > 220000 ppm
Fe < 220000 ppm

Map 23: Iron Suitability

PAH > 4022 ng/L
PAH < 4022 ng/L

Map 24: PAH Suitability

A total of 257,180 hectares (1,202 ± 11,953 hectares) within the study area provide unsuitable risk to oyster aquaculture due to sediment toxin concentrations; of which 15,825 are Virginian waters (6%), as shown in Map 25. Permitting aquaculture in these areas would pose unnecessary product quality risks to the consumer and health of the oyster.

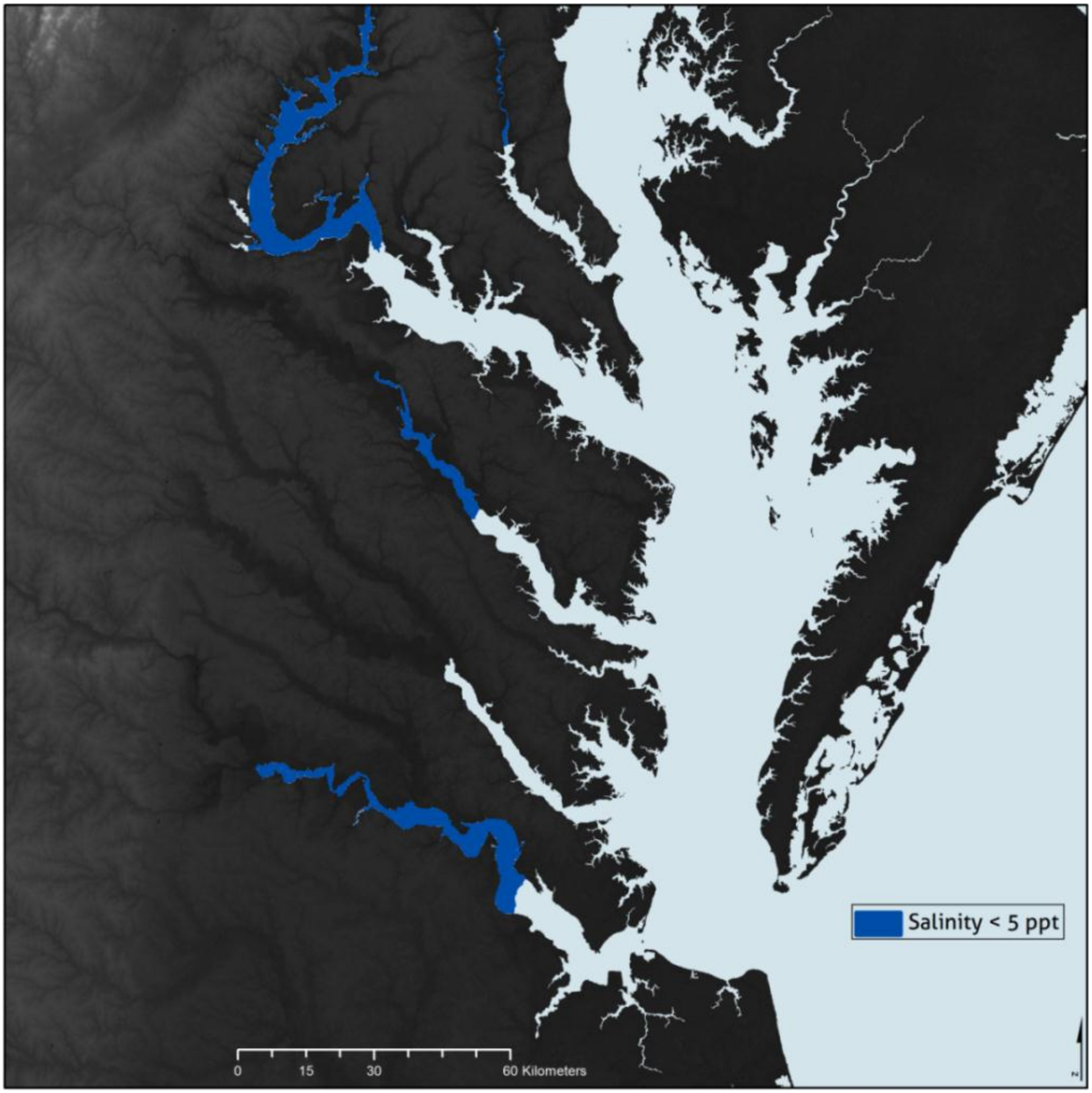


Map 25: Sediment Toxin Suitability. The majority of these high toxicity areas are found within the Potomac River, the James River, and the Elizabeth River at the southern reaches. This can be largely attributed to the urban and industrial area around Washington DC in the north, and productive military industry in the south. Data source: CBP

7.2.10 Salinity

As a basis of marine animal metabolism, dissolved ions in their environment are utilized for every aspect of living; and as such, the concentration and ratio of ions in the saline medium are crucial to the growth and survival of every aquatic organism particular to their habitat. The Chesapeake Bay, like most estuaries has a gradient of salinity, generally decreasing in concentration further inland. Species are generally classified as euryhaline (tolerant to changing salinity) or stenohaline (intolerant to changing salinities, needs a precise range), depending on their adaptability to osmoregulatory pressures (the regulation of ion concentrations and water in the body). Organisms endemic to estuary conditions, such as the Eastern oyster, are by nature euryhaline due to tidal harmonics and precipitation runoff fluctuation; though many euryhaline organisms still can only tolerate certain minimum or maximum limits. C. Virginica has been found to thrive in a wide range of salinities, typically between 10‰ and 30‰, with growth retarding at 7.5‰ and ceasing at 5‰; for a meaningful tolerance of 5-40‰ (Barnes, et al., 2007). These values have been verified globally in populations, and in aquaculture, for C. virginica (Loosanoff (1953); Bataller, et al. (1999)).

Daily interpolated salinity values were averaged for the entire study period, and reclassified as to less than 5‰ or greater. A total of 190,540 hectares were found to exhibit salinity levels, on average, less than adequate for oyster production; of which 52,556 hectares are found within Virginian waters, as shown in Map 26.



Map 26: Salinity Suitability. Data source: CBP, VECOS, NOAA

7.2.11 Dissolved Oxygen

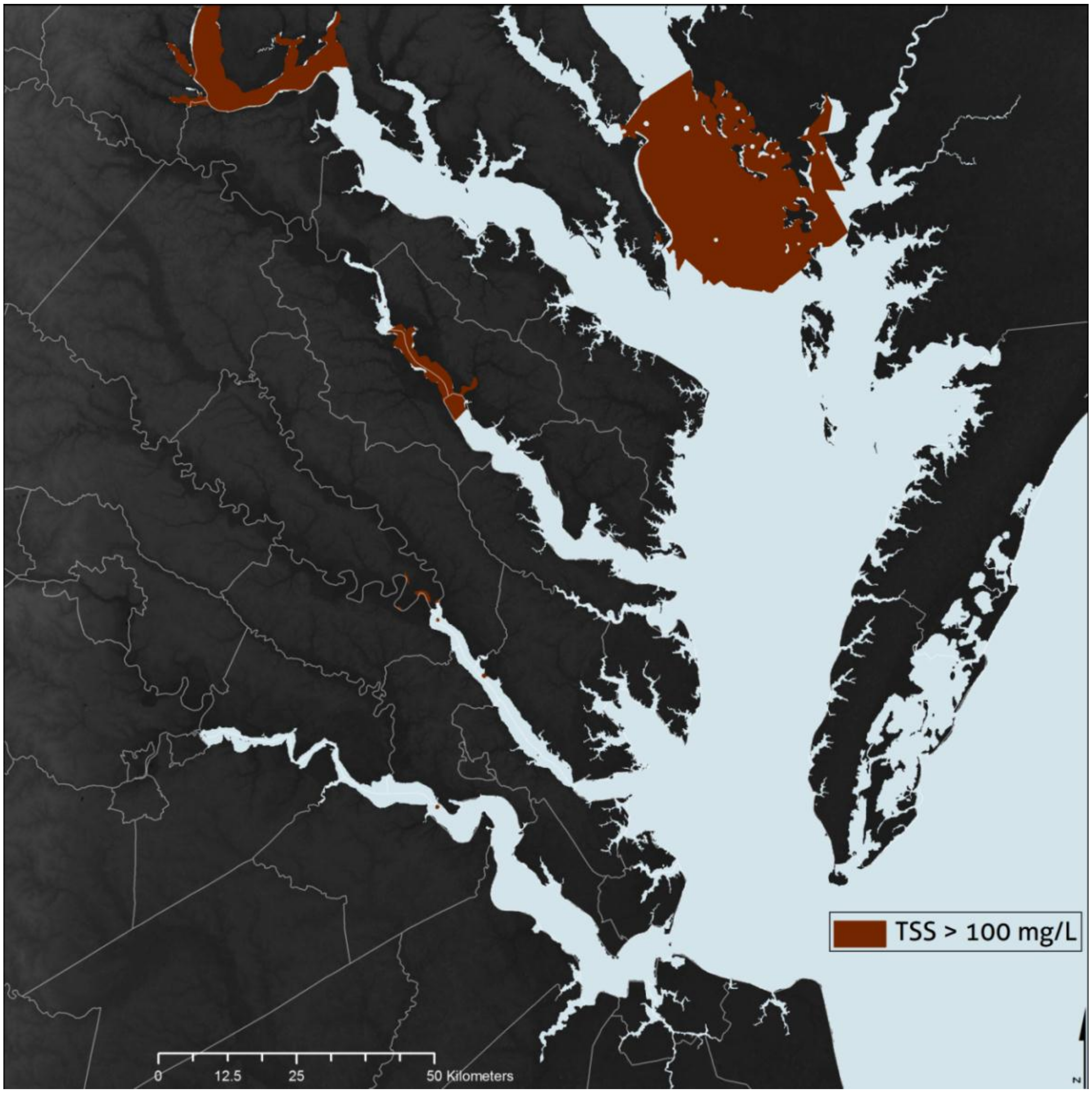
The availability of oxygen to aerobic organisms is broadly considered the most limiting survival factor in aquaculture, whether it is intensive or extensive. Without sufficient oxygen, all other parameters are irrelevant. Baker and Mann (1992) studied the effects of hypoxic and anoxic conditions on juvenile oysters, revealing that in anoxic conditions (<0.07 mg/L O_2) juveniles exhibited mean mortality at 84 hours, while in hypoxic conditions (1.5 mg/L O_2) juveniles exhibited mean mortality at 131 hours. As the Chesapeake Bay is subject to these conditions in certain seasonal and spatial circumstances, the abundance or lack of oxygen presents a very significant variable for intensive aquaculture site suitability. Since the temporal resolution of the spatial dataset is not as precise as these mortality limits, mean interpolated weekly values provide a surrogate for higher resolution. Thus, if a given area meets hypoxic conditions by mean weekly levels, it is deemed unsuitable. Weekly averages were interpolated by IDW with barriers and reclassified to delineate areas exhibiting values less than 1.5 mg/L O_2.Dissolved oxygen measurements were derived from the Chesapeake Bay Program Water Quality Database, VECOS data, and the NOAA Interpretative Buoy Program. Since this variable is relatively easy to measure (electronic probe), the temporal and spatial resolution was quite high.

Repeated scrutiny of the dissolved oxygen data yields no areas exhibiting hypoxic levels for periods consistent with mass mortality. There will at times be isolated or contained, but systemic, eutrophic events where fish kills or otherwise will ensue, though bivalves are evolutionarily well-equipped for such events given they persist for a relatively short time. Some areas provided values lower than would normally be advised in siting aquaculture, though these areas did not exhibit prohibitive conditions for a sustained period. Therefore, no areas are deemed unsuitable due to sustained lack of dissolved oxygen, though lower levels will culminate in reduced growth rates and carrying capacity in the subsequent analysis. Whether oyster densities are limited by food-availability or dissolved oxygen at a given site will arise from the growth model.

7.2.12 Total Suspended Solids (TSS)

Excessive loading of particulate matter has been shown to depress filtration rates in bivalves, and prolonged loading can lead to smothering an oyster population, which will prevent access to oxygen and food. Oysters will begin to produce pseudofeces at relatively moderate levels of seston, increasing positively with seston concentration; indicating reduced filtration efficiency. Cerco & Noel (2005) delimit TSS concentrations above 100 mg/L as the level when filtration ceases; although such a value varies in the literature (e.g. 75 mg/L in Kennedy et al., 1996) and can be modulated by other variables. Given the seasonal, tidal, and weather-related variability of TSS, monthly averages were used to assess areas with persistently high concentrations of suspended matter. Values were interpolated by IDW with barriers on a monthly basis between the aforementioned study period, and averaged for this period to derive characteristic total suspended solids concentrations. TSS values were derived from the Chesapeake Bay Program Water Quality Database and VECOS data with a relative moderate temporal (ranging between weekly and bi-weekly) and spatial resolution (see Maps 2 and 3 for spatial resolution).

A total of 152,282 hectares were found to be persistently overwhelmed with suspended matter, relevant to the culturing of oysters, as shown in Map 27. Of this total, 15,039 hectares are found within Virginian waters.



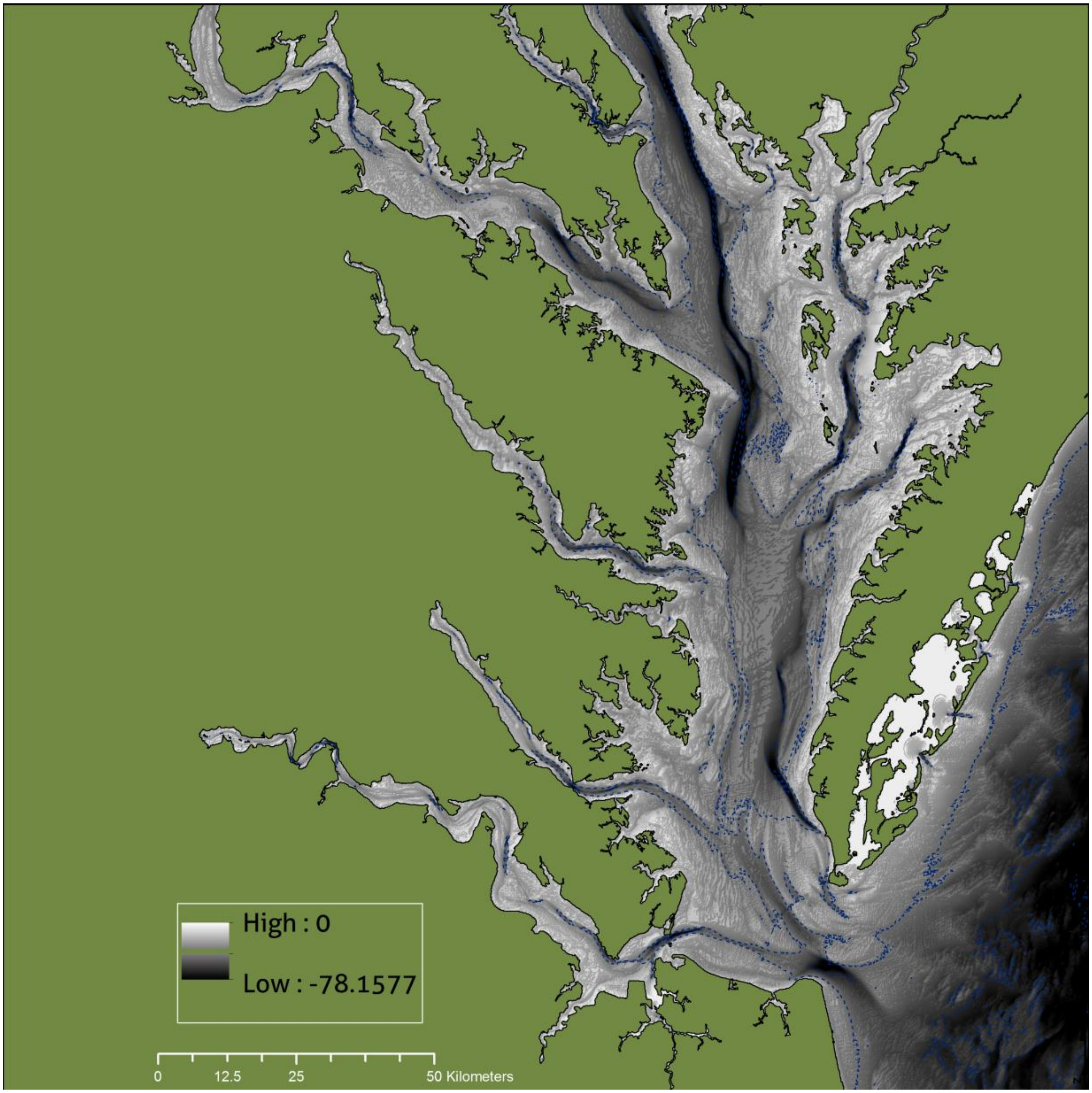
Map 27: TSS Suitability. TSS presence is largely a cause of runoff or steady pelagic mixing. Data source: CBP, VECOS

7.2.13 Bathymetry

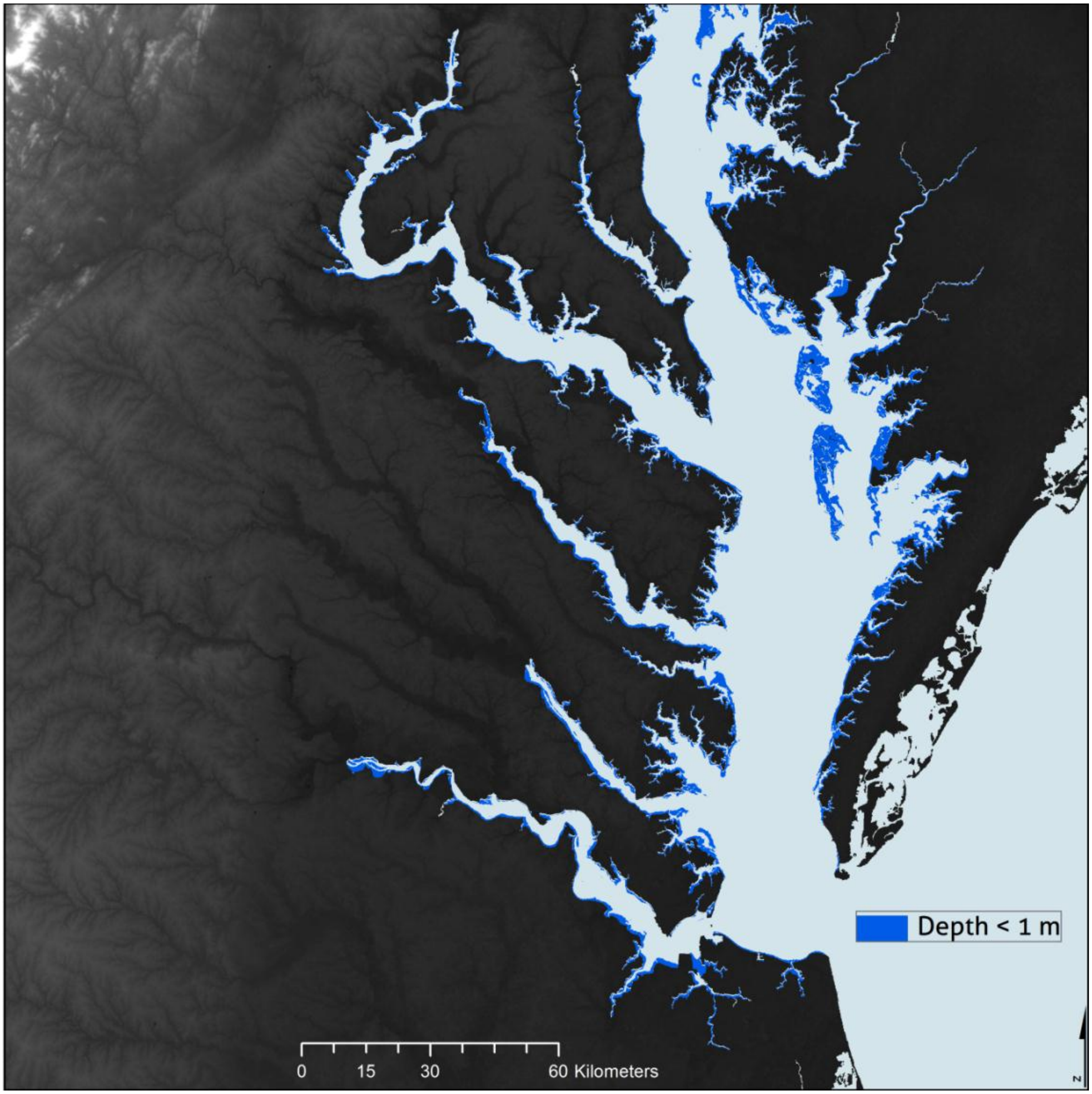
The design of modern aquaculture units permits permanent submersion, where previously this would result in significant bio-fouling of the vessel's screens or orifices, modern materials and design can prevent significant fouling. Conventionally oyster racks would be situated in the intertidal zone, where exposure to air would mitigate the buildup of organic material on the racks, though this practice diminishes oyster growth efficiency (not filtering and consuming suspended food) while posing exposure risks in extreme weather conditions (i.e. freezing air temperatures). Thus, intensive aquaculture can be situated in any mean water depth greater than 1 meter (Fredriksson, et.al., 2010).

Bathymetric data was extracted from NOAA single track and multibeam sonar soundings provided by the National Geophysical Data Center. Depths are adjusted to the Mean Lower Low Water datum; which is "the average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch" (NOAA, "Tidal Datums", 2011). This is the standard datum for recording bathymetric depths in the US. Soundings form a Triangulated Irregular Network and were interpolated into raster format for analysis.

A total of 175,146 hectares (51.4 ± 336.9 hectares) were found to be less than one meter deep at Mean Lower Low tide, and are unsuitable for intensive oyster aquaculture, as shown in Map 28.



Map 27: Chesapeake Bay Bathymetry. Data source: CBP. Interpolated from a TIN.



Map 28: Bathymetric Suitability. Data source: CBP

7.2.14 Omitted suitability parameters

In delineating suitable areas for oyster culture in the Valdivia estuary in Silva et al. (2011), a few other variables were included within the MCE. Temperature, particulate organic matter (POM), sediment type, and fecal coliform concentrations were included in their work, but have not been included here. As *C. virginica* is endemic to the Chesapeake Bay, the ambient temperatures are within tolerance of this organism. Particulate organic matter is not explicitly denoted in the available data sources for this parameter, though as described in Water Quality by Boyd (2000, p. 100), suspended volatile solids are an equivalent term as the residual weight upon ignition of a total suspended solids sample. Chlorophyll-a was also employed to delineate spatial suitability. POM and chlorophyll-a are often used as a surrogates for bivalve food, and under very high loads, bivalves will decrease feeding and has been reported for C. Virginica; though large discrepancies are present between studies on a maximum of sediment (Loosanoff & Tommers 1943). Filtration rates are modulated by the level of suspended matter, and as such these parameters (as food modulated by TSS) are reflected within the growth model later within this work. Due to temporal and weather-related variability of seston concentrations, as well as the redundancy of exclusive factoring with regards to TSS, these two variables have not been included as restrictive spatial elements.

As for sediment type, an analysis of sediment type distribution presented no contraindicating types of sediment in the study area, and given the culture vessels will typically be situated off-bottom, this variable becomes less influential. Lastly, fecal coliform concentrations are the variable which determines shellfish fishery condemnations by the VDH, discussed earlier in this section. Their diligent observation of this variable and assignment of closures is a proxy for direct measurement and delineation of fecal coliform.

Additional regulatory or mixed-use conflicts may arise in siting aquaculture not examined here, and it is recognized that not all could be sufficiently accounted for. Some siting conflicts may stem from situating or affixing growing vessels on the sediment, though many of these conflicts are avoided by employing floating vessels. The Baylor Grounds (public oyster reef) was not included here due to similar reasons.

7.2.15 Turbidity

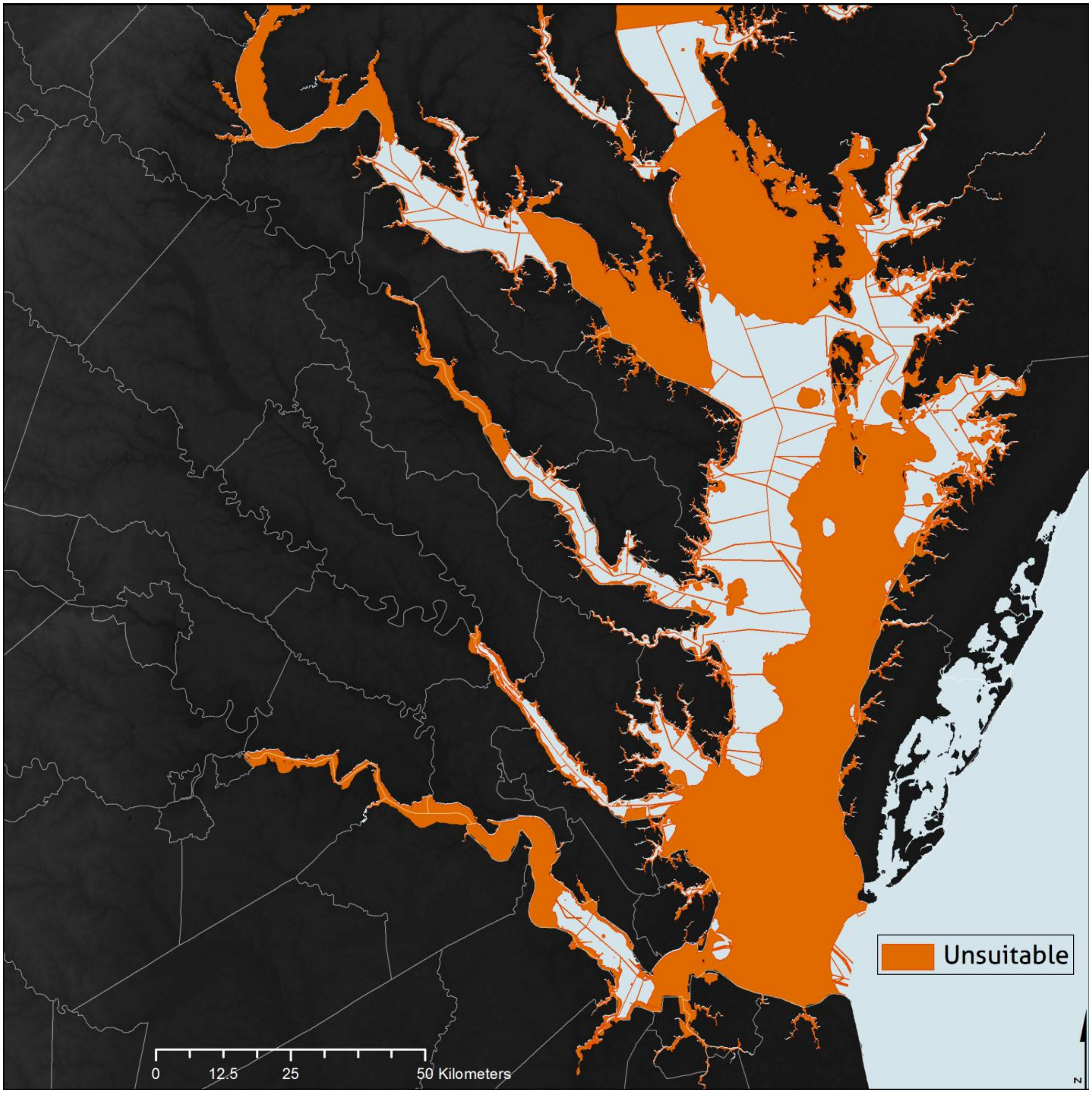
Turbidity (measured in Nephelometric Turbidity Units) has been locally correlated with total suspended solids in numerous case studies (see Earhart, 1984). Turbidity offers a significant advantage as a measurement of seston, if it can be accurately regressed at local scales, as it can be measured at an incredibly high frequency and very low cost compared to traditional measures. This discussion is well documented and debated, so within the scope of this thesis, the promotion of turbidity is only a suggestion for future development. Gippel (1995) extensively investigates the application of turbidity as a meaningful metric for suspended solids in streams and argues that turbidity can be considered a wholly better measurement of solids than conventional measures as the variance in correlation to conventional methods, the high temporal and spatial resolution of turbidity measurement is far less than the variance of conventional measures due to intermittent sampling. Earhart (1984) was able to strongly correlate TSS and turbidity in the northern Chesapeake Bay, while cautioning that proper sampling techniques and local water segment differentiation are crucial elements in measuring solids by turbidity; the characteristics of solids will vary by location and regressed relationships will need to adjust accordingly.

Higher temporal and spatial resolution of suspended matter measurement can greatly increase comprehension and modeling efforts for populations of bivalves and their impact on the environment; namely as aquaculture intensifies and concerted oyster restoration projects develop. A net reduction in TSS is a significant ecological goal for the Chesapeake Bay.

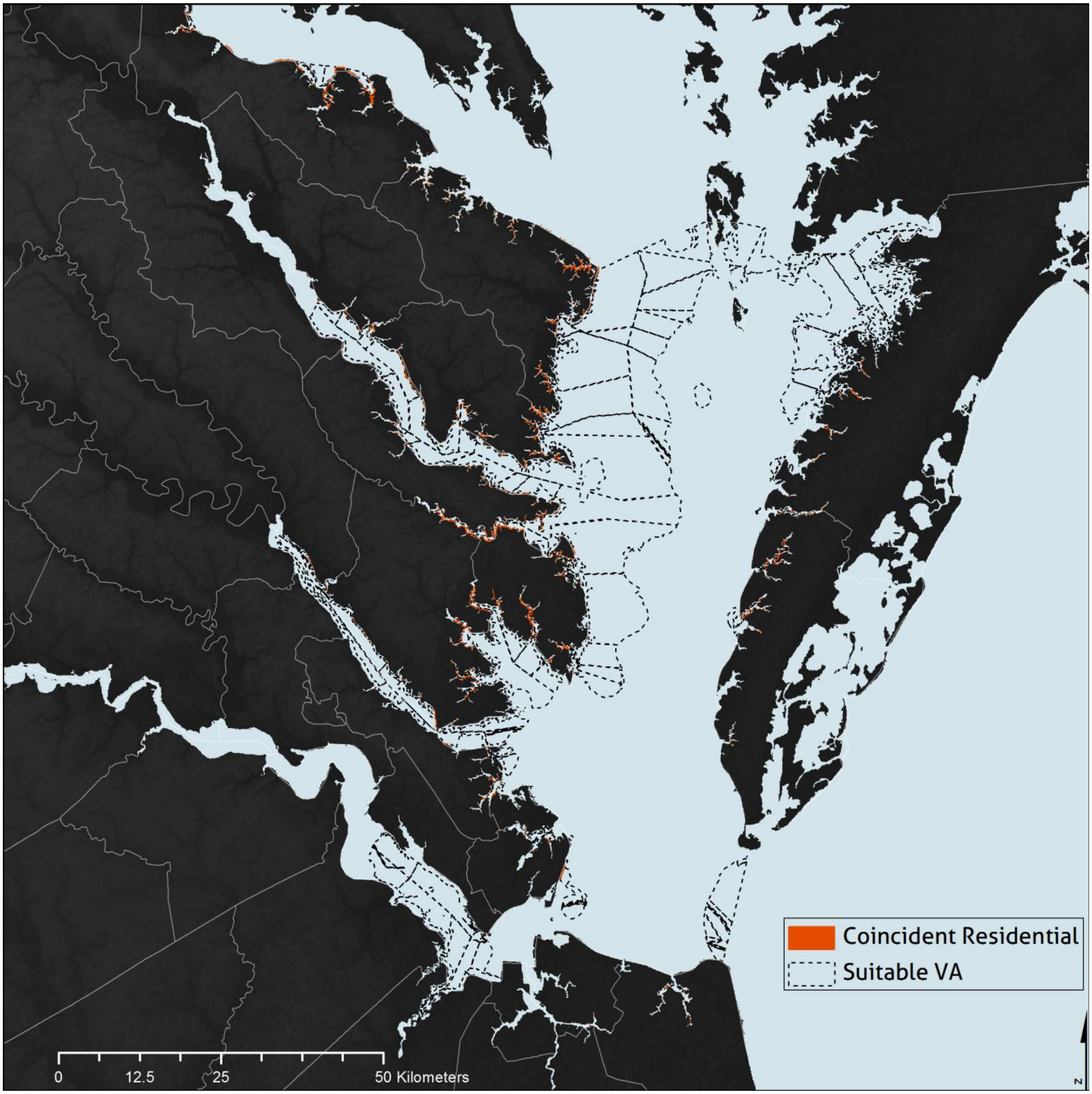
8. Multi-Criteria Evaluation Site Suitability Results

All binary suitability data were combined by a union operation, and then by dissolving the combined features to 'flatten' the analysis space, as presented in Map 29. A total of 777,999 hectares (~68.6% of the open waters) are deemed unsuitable given the contemporary circumstances for intensive oyster aquaculture, making 352,762 hectares suitable for intensive oyster aquaculture. Of the total unsuitable area, 342,043 hectares are Virginian waters (30.1% of open waters and 64% of Virginian open waters). This proportion is simultaneously surprising and distressing, that the majority of the Bay has degraded to conditions unsuitable for intensive filter feeding culture. This brief analysis should provide sobering insight to resource managers, but offer strategic mechanisms for mitigating limiting factors to development. It is true that some limitations are attributed to conservation, and many may see oyster culture as a conservation mechanism, though we cannot proceed to expand intensive aquaculture to preclude conservation without further studies on its net impact on estuarine ecology in regard to conservation areas within the Chesapeake Bay. Within Virginia, 186,281 hectares of open water are considered suitable for intensive oyster aquaculture, as shown in Map 30. Again, it must be reiterated that these areas have been determined suitable by ex-situ examination, and will necessitate the combined scrutiny of the VMRC and the potential farmer. As well, many areas may be 'slivers' of suitability, artifacts of geographical analysis that would otherwise be untenable for development.

Coincidental residential parcels are presented in conjunction with the suitable aquaculture zone. These areas are not necessarily prohibitive of developing intensive aquaculture, but do require additional steps for permit approval, and stakeholder management.



Map 29: Composite Oyster Aquaculture Suitability. Although much of the Bay is currently unsuitable for intensive oyster aquaculture, wide areas are deemed suitable by the constraints explored above.



Map 30: Coincident Areas of Oyster Aquaculture Suitability and Residential Land Use. These areas will require extended permitting due to landowner approval.

9. Production Carrying Capacity Modeling

The Virginia Marine Resource Commission issues permits for rack, cage, and basket type intensive oyster aquaculture. One stipulation to the issuance of this permit is that within the endorsed growing site, each container must not exceed 70 feet^3 (1.982 meters^3), and not exceed 250 containers per acre (per 0.4 hectare); with a maximum of 495.5 meters^3 of growing area per surface acre. This would equate to 495,500 liters of the water column in a given area, and if we limited this to one acre, only 0.12 m of continuous vertical space can be occupied by culture vessels. This is altogether unrealistic unless we are considering floating bag culture. Vertically stacked cultures are provided access to the entire water column, and have proven to improve production by better exposure of the shellfish to three dimensions of the water column. Vertical stacking and interspacing also provides more optimal culture arrangements owing to particle transport dynamics and oxygen depletion by the shellfish. Two culture methods are displayed below in Image 1 and 2.

Image 1: Vertical Oyster Racks: Portsmouth, Rhode Island, USA. (Webster 2007)

Image 2: Floating Cage Culture, Maryland, USA (Webster, 2007)

This modeling exercise is based on functions that determine the maximum oyster biomass a given area can maintain. Given this absolute maxima, seeding densities can be derived and employed as management and culture values to increase site-specific profitability. Although this is limited to retrospective analysis – as environmental factors cannot be reasonably forecasted 18 months in advance – farmers will be able to analyze their own historical seeding densities and harvest data to procure trends of their culture practices. For example, a farmer can compare their seeding and harvest data (densities, mortality, etc.) with the modeled production carrying capacity of that same growing area; answering questions such as:

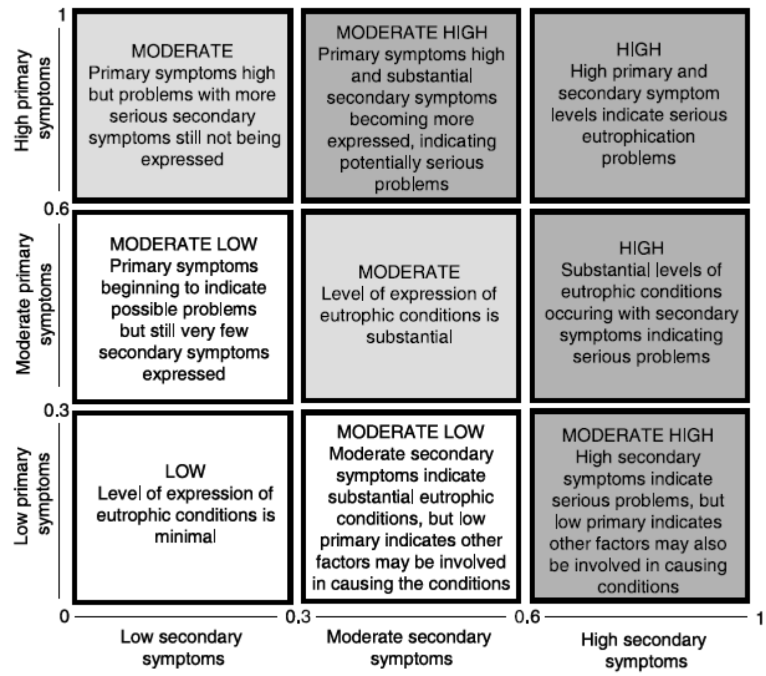
- Can I increase seeding density in this given area for increased harvests?
- Have some of my seedings been too dense, resulting in diminished dissolved oxygen levels and increased mortality?
- What other areas provide potential high turnover rates, i.e. good conditions for oyster culture?

This model however does brush over some significant considerations for farmers. Many other economic, physical, or logistical issues may weigh into exploiting the information provided by this model. Some areas may be relatively difficult or expensive to access, some may provide multiple use conflicts not indicated here, and some may exhibit unforeseen higher rates of pathogenesis.

9.1 ASSETS

The Assessment of Estuarine Eutrophication Status (ASSETS) is a portable Pressure-State-Response investigative tool for assessing eutrophication in estuaries worldwide, augmenting the U.S. National Estuarine Eutrophication Assessment (NEEA), first implemented and developed by NOAA to assess eutrophication along the eastern seaboard of the United States. In response to global anthropogenic estuary nutrient and sediment enrichment, and non-standardization of assessing the eutrophic statuses of estuaries, this framework was developed as a cooperative venture between NOAA and The Institute of Marine Research (IMAR) in Portugal. It has been employed to assess 157 estuarine systems globally.

The methodological process of ASSETS is graphically outlined in Appendix 1. The ASSETS methodology is elaborated in detail in Bricker, et al. (2003). Fundamentally, ASSETS transforms system-scale quantified eutrophication metrics into a qualitative index that can be applied for comparative studies, resource management, or to moderate estuarine multiple-use regimes (i.e. shellfish aquaculture). As detailed in Figure 3, the ASSETS framework utilizes two symptomatic levels of eutrophication, primary and secondary, and assigns a weighted value to the selected representative parameter within the index of eutrophic conditions. Primary and secondary symptoms are assigned into a matrix and provide an estuary system state condition: low, moderate, or high. ASSETS has been successfully integrated into shellfish aquaculture production modeling (Ferreira, et al. (2007); Ferreira, et al. (2009); Silva, et al. (2011)) in order to measure the effect shellfish aquaculture imposes on eutrophic conditions differentially by sub-modeling influent and effluent primary and secondary symptoms. This exercise specifically utilizes chlorophyll-a concentrations as a primary symptom, and dissolved oxygen levels as a secondary symptom for each discrete zone of interest; similar to Ferreira, et al. (2007), Ferreira, et al. (2009), and Silva, et al. (2011). In essence, higher concentrations of chlorophyll-a and lower levels of dissolved oxygen will result in higher eutrophic conditions (i.e. higher ASSETS scores), while inverse conditions will result in lower eutrophic conditions. Shellfish aquaculture is interesting here as the bivalves will reduce chlorophyll-a concentrations (through ingestion), though they will also reduce dissolved oxygen levels (through respiration).



PRIMARY SYMPTOMS

Chlorophyll a

IF Concentration	AND Spatial coverage	AND Frequency	THEN Expression	Value
Hypertrophic or High	High	Periodic	High	1
	Moderate	Periodic	High	1
	Low	Periodic	Moderate	0.5
	Very low	Periodic	Moderate	0.5
	High	Episodic	High	1
	Moderate	Episodic	Moderate	0.5
	Low / Very Low	Episodic	Low	0.25
	Any Spatial Coverage	Unknown	Flag A	0.5
	Unknown	Any frequency	Flag A	0.5
Medium	High	Periodic	High	1
	Moderate	Periodic	Moderate	0.5
	Low / Very low	Periodic	Low	0.25
	High	Episodic	Moderate	0.5
	Moderate / Low / Very Low	Episodic	Low	0.25
	Any Spatial coverage	Unknown	Flag A	0.5
	Unknown	Any frequency	Flag A	0.5
Low	Any spatial coverage	Any frequency	Low	0.25
Unknown	Unknown	Unknown	Not included in calculation at zone level	

		IF	AND	AND	THEN	
		Observed	Spatial coverage	Frequency	Expression	Value
SECONDARY SYMPTOMS	Dissolved Oxygen	Anoxia	High	Periodic	High	1
			Moderate	Periodic	High	1
			Low	Periodic	Moderate	0.5
			Very Low	Periodic	Low	0.25
			High	Episodic	Moderate	0.5
			Moderate / Low / Very Low	Episodic	Low	0.25
			Unknown	Any frequency	Flag A	0.25
		Hypoxia	High	Periodic	High	1
			Moderate	Periodic	Moderate	0.5
			Low / Very Low	Periodic	Low	0.25
			High	Episodic	Moderate	0.5
			Moderate / Low / Very Low	Episodic	Low	0.25
			Unknown	Any frequency	Flag B	0.25
		Biological stress	High	Periodic	Moderate	0.5
			Moderate / Low / Very Low	Periodic	Low	0.25
			Any spatial coverage	Episodic	Low	0.25
			Unknown	Any frequency	Flag C	0.25

Figure 3: ASSETS Classifications (Bricker, et.al., 2003, p.48). Observed values are classified by the parametric concentration, and dependent on spatial and temporal extent. For example, if the concentration of chlorophyll is high and the dissolved oxygen level is low, the ASSETS score will cross values of 1 for the primary symptom and 1 for the secondary symptom, yielding a High eutrophic condition.

As the Chesapeake Bay has been at the center of attention of estuarine eutrophication, studies employing the ASSETS methodology have scrutinized the state of the Bay. The most recent ASSETS evaluation of the Bay exhibits very favorable conditions for eutrophication, with overall eutrophic conditions of 0.44 in primary symptoms scale and 0.79 in secondary symptoms scale; yielding the highest categorical score for eutrophication (ASSETS: Chesapeake Bay Mainstream, 2011); reflecting the Bay's prominently poor state and ecological demand for filter feeding populations.

Implementing this process on present mean measured values, in the scale of data acquisition (January 2009 – May 2012), yields a preliminary portrait of the Bay; in effect, the bottom line. Under the premise of mitigating nutrient enrichment pressures, shellfish aquaculture should in the least maintain the eutrophication potential of the given area, and optimally alleviate eutrophication conditions. Weekly interpolated values for dissolved oxygen (DO) and chlorophyll-a (CHLA) where processed by reclassifying values as:

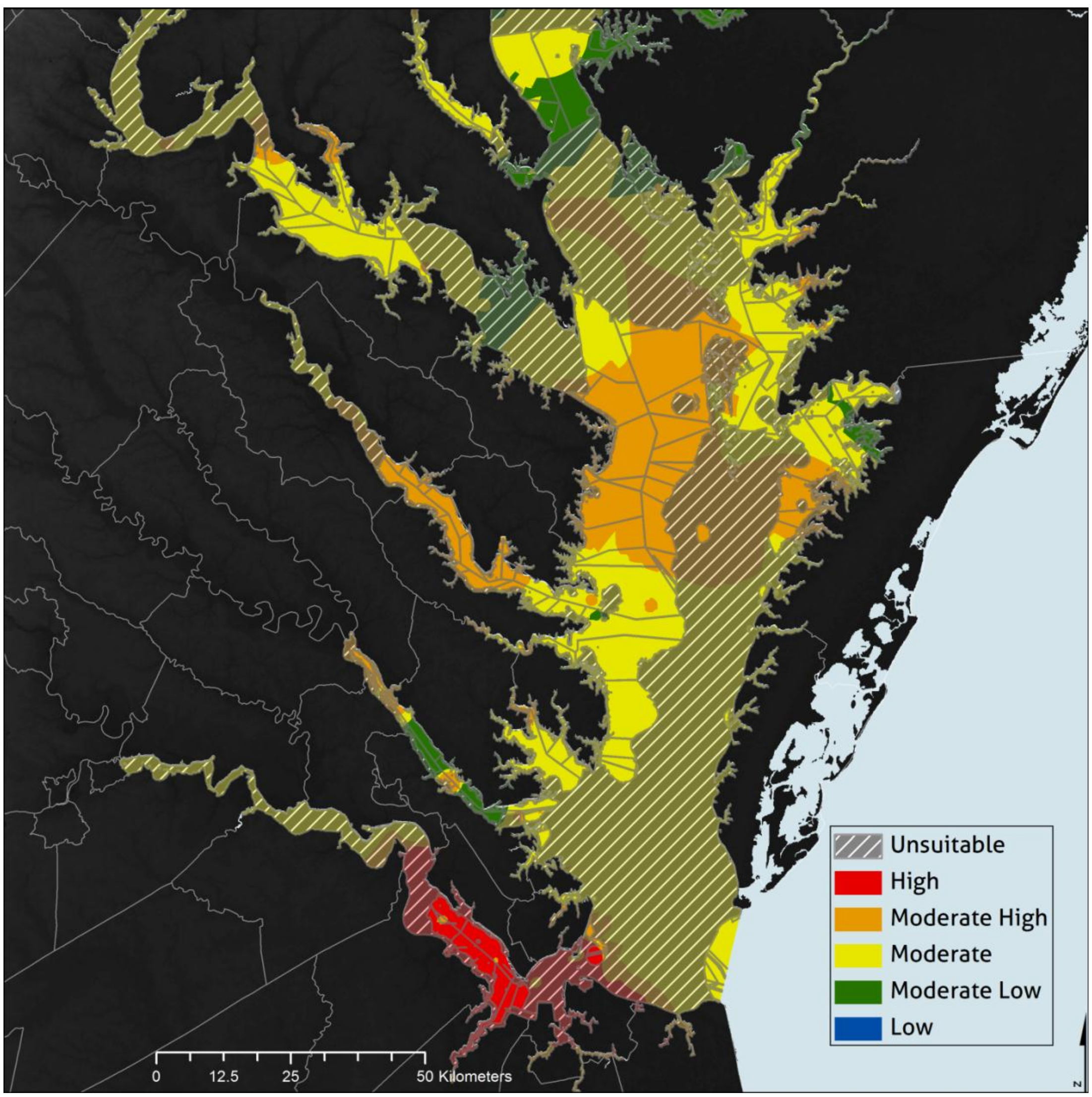
CHLA <= 5 μg/L : ASSETS = 0.25
5 < CHLA <= 20 μg/L : ASSETS = 0.5
CHLA >= 20 μg/L : ASSETS = 1.0

DO <= 2 mg/L : ASSETS = 1.0
2 < DO <= 5 mg/L : ASSETS = 0.5
DO >= 5 mg/L : ASSETS = 0.25

Reclassified rasters were then averaged for the study period and transformed to vectors. Vector polygons were dissolved to reduce computation resources and artifacts. Dissolved oxygen and chlorophyll-a vectors were intersected and overall ASSETS scores assigned based on corresponding primary and secondary symptom states as such:

		Primary Symptom		
Secondary Symptom		<=0.3	>0.3 AND <=0.6	>0.6
	<=0.3	Low	Moderate Low	Moderate
	>0.3 AND <=0.6	Moderate Low	Moderate	Moderate High
	>0.6	Moderate High	High	High

Table 1: Eutrophic state matrix



Map 31: ASSETS Evaluation over Study Period. Most of the area exhibits either Moderate or Moderate-High eutrophic conditions

Within the areas suitable for intensive oyster aquaculture, we find a variable spread of initial eutrophic conditions. As indicated in the following table, over half of the suitable area within Virginia (52%) yields either 'High' or 'Moderate High' scores. For resource managers and planning commissions, these areas would be prioritized for eutrophic mitigation, and perhaps administer incentives for oyster aquaculture within these areas through tax credits, capital investment, or other mechanisms.

ASSETS Condition	Hectares	% of Suitable Area
High	29,406	14.6
Moderate High	74,900	37.27
Moderate	89,385	44.47
Moderate Low	7,291	3.63
Low	0	0

Table 2: ASSETS results

Thus, by assessing average chlorophyll-a and dissolved oxygen concentrations for the entire study period, and transforming those values into ASSETS scores, the spatial distribution of eutrophic conditions is presented in Map 31.

10. Applied Shellfish Growth Modeling in GIS

The Farm Aquaculture Resource Management (FARM) model, conceived by Ferreira, et.al., is a localized box model parameterizing seston depletion to determine production carrying capacity, optimized with a Cobb-Douglas function for maximum profit yield and providing ASSESTS eutrophication values as a function of shellfish seston reduction (Shumway 2011, p. 147)(Ferriera, J.G., et al. 2007). The FARM model has been employed in several estuaries worldwide, modeling several different bivalve species. FARM integrates several sub-models (individual shellfish growth, population dynamics, seston and dissolved oxygen reduction) for simulating nutrient reduction and profit maximization. An adaptation of the framework of this model is implemented here as a predictive measure, and evaluated with the field data. As FARM is not calibrated for *C. virginica*, a species-specific growth and population dynamics model has been employed to simulate both growth and seston depletion as a function of biomass. Additionally, FARM is not GIS 'enabled', in that situation of aquaculture would impact downstream aquaculture by depletion of seston and dissolved oxygen. The model constructed here does neither, but is intended for farmers to evaluate potential growing areas and their own production areas distinct from others. Naturally, this aspect of coupling seston depletion, oxygen consumption, and a three dimensional hydrodynamic transport model with this GIS-based model would be the next developmental stage of modeling oyster aquaculture in the Bay.

As an exercise to begin implementing a GIS-based model calibrated for the Chesapeake Bay, the field data is used to derive relationships between regularly captured remotely sensed data and oyster culture parameters. In this endeavor, the data processing and integration carried out within this thesis could provide a platform for resource managers and industry to collaboratively assess intensive oyster aquaculture. Two anonymous oyster farmers have supplied culture data between 2009 and 2012, which are used in this thesis as evaluation points for integrating a widely accepted growth model within a GIS framework.

10.1 Oyster Growth and Bioenergetics Model

Powell, et.al. (1992), assembled an intricate time-dependent post-settlement (after the oyster has attached itself to a substrate and is growing to the adult stage) population dynamics model to accurately simulate oyster (*C. virginica*) filtration, assimilation, respiration, somatic growth, reproduction, and recruitment. Their work was adopted for this modeling exercise with the exception of reproduction and recruitment aspects. Triploid oysters are bred for sterility, focusing all energy on somatic growth, and as no formal growth models exist yet for triploid eastern oysters, somatic tissue production is considered the only product of assimilation and respiration. Recently this model was employed in Apalachicola Bay, Florida, USA to model oyster restoration bars in relation to shifting seasonal and annual hydrodynamic properties by coupling the model to an invocation of the Princeton Ocean Model, finding relatively strong correlation to field data ($r^2 = 0.84$) (Wang, et.al., 2008). Here the growth model is applied to discrete one-acre segments within the suitable growth areas in order to estimate relative production carrying capacities and regulatory limits. These discrete areas were constructed by overlaying a geographical 'fishnet' over the suitable areas and data is extracted by corresponding coverage. Lastly, predicted production carrying capacity values are imposed upon the ASSETS parameters to estimate potential changes in eutrophic states by calculating the relative reductions of chlorophyll-a and dissolved oxygen by the carrying capacity maxima, as shown in Figure 4.

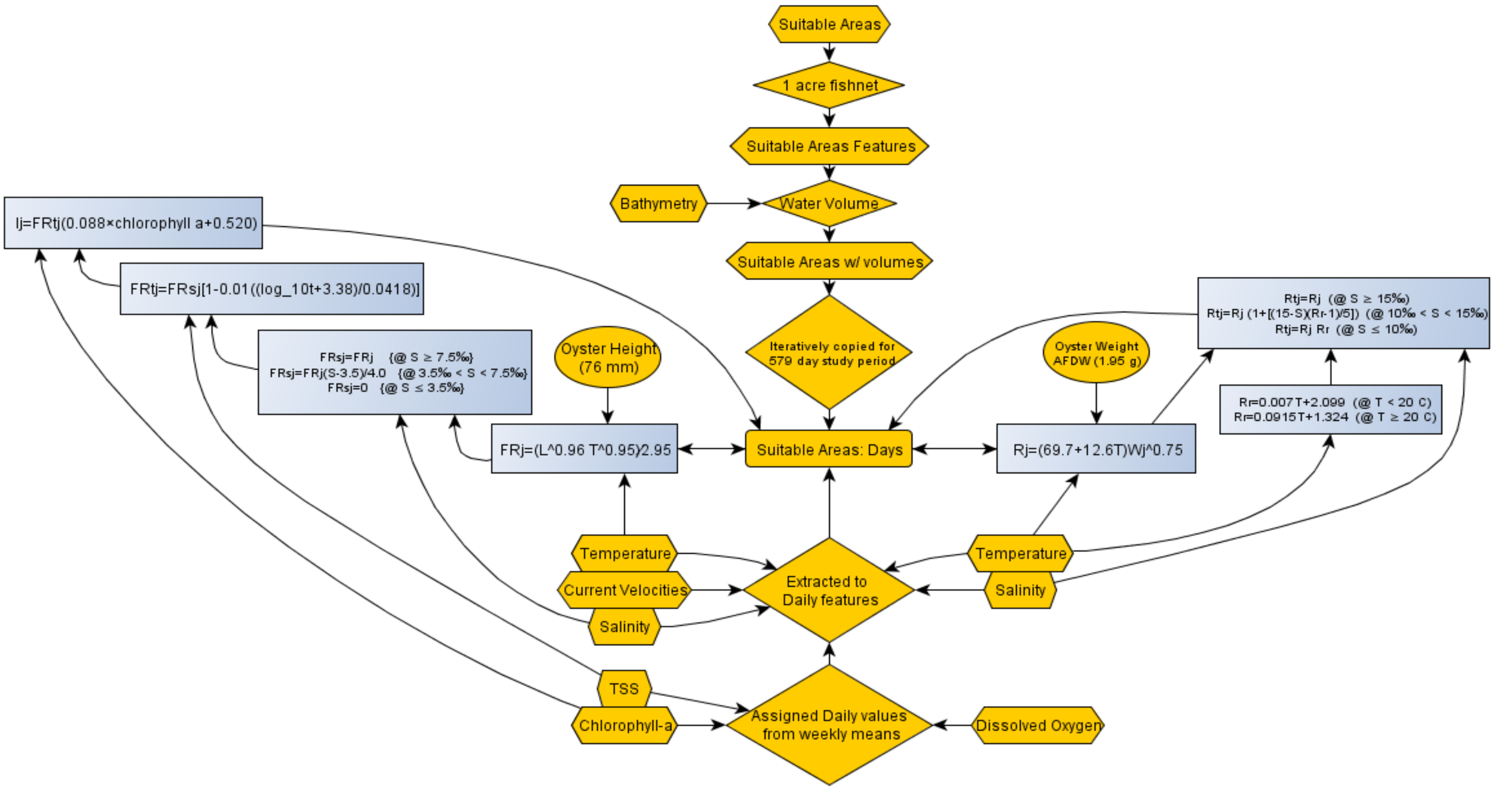


Figure 4: GIS Implementation of Oyster Bioenergetics Model. Respiration and Ingestion model parameters (temperature, salinity, TSS, chlorophyll, and oxygen) were derived and interpolated into daily values. Within the suitable growing area, these daily values drove the bioenergetics model at a fixed oyster size to determine daily rates of respiration and ingestion. These rates were then used to limit concentrations of chlorophyll and oxygen to determine a maximum amount of oysters in a given area.

A preliminary examination of discrete growing area carrying capacities, limited in input by the regulatory maximum per unit area, can help illuminate environmental limiting factors in culture as well as eutrophic responses to culture.

Dissolved oxygen depletion was examined as one limiting factor by evaluating a static maximum biomass level, determined by culture vessel volume regulatory limits and the ideal harvestable size, for a growing season. All suitable areas were examined for sufficient flushing rates; where it is conceptualized that if the water current within a discrete area is slower (< 89.965 m/h or 0.0486knots), per hour, than its diagonal length, oxygen depletion will compound the culture will become self-limiting. On a daily average, none of the suitable areas exhibited such conditions. Of course this type of analysis could delve into the hydrodynamics of the vessels in the water column and gradient depletion within the discrete areas, but this effort is dedicated to future work at the estuary-scale. If we consider the maximum volume of culture vessels permitted within a growing area (495.5m^3 per acre, from VMRC Regulation 4VAC20-1130-50 (2012)), we can determine a harvest-ideal maximum biomass for this given volume by shell dimension and functionally-derived ash-free dry oyster weights (ash-free dry weight refers to the dewatered organic content; which is a standard measure of aquatic organisms). The ideal harvest shell height, which is the typical measure for harvestable oysters, is 76mm (Powell et al, 1992). Specific to triploid oysters, Harding (2007) determined relationships between shell height, shell width, and shell inflation. [2]

$SW = 0.48SH + 22.65$ (Eq. 7)

and

$SI = 0.44SH - 6.23$ (Eq. 8)

Where SH refers to shell height, SW to shell width, and SI to shell inflation. Thus, a model oyster would be 76 x 59.13 x 27.21 as SH x SW x SI, for a box volume of ~ 122.28 cm^3. If every bit of the regulated space were filled with such oysters, an estimated 4,052,225 oysters would be able to be situated in an acre (495.5 m^3 / 122.28 cm^3). This number however is far beyond what is typically harvested in a given area, as growers will tend to spread their culture vessels over many acres; though this will provide a helpful benchmark for further analysis and industrial development.

[2] Other literature may refer to shell height as shell length or width; shell width may be referred to as length, and shell inflation may be referred to as height or thickness. For a diagrammatic explanation, see Figure 5.

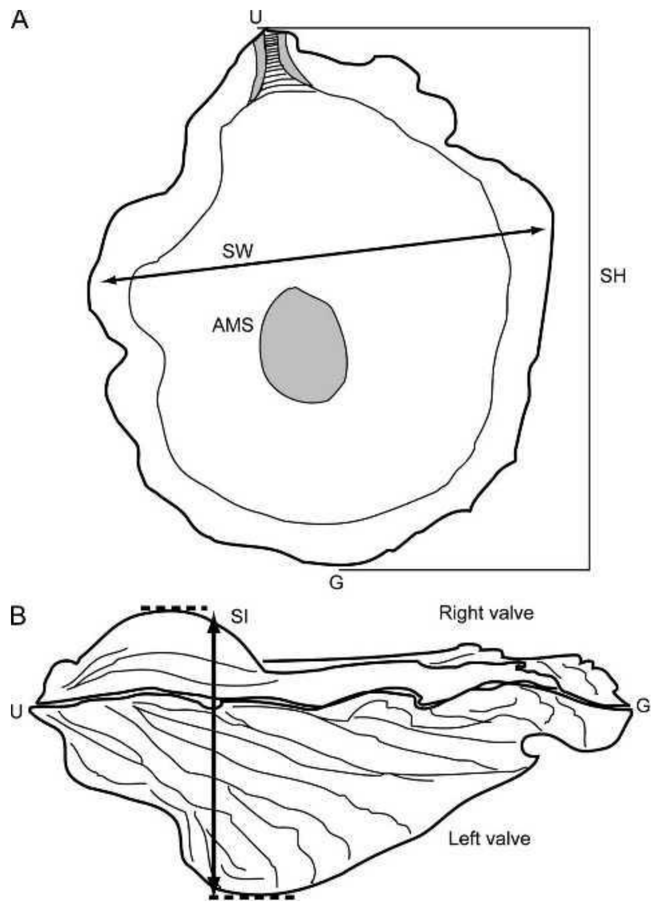


Figure 5: *Sketches of a Crassostrea shell with the umbo (U), growth edge (G), and adductor muscle scar (AMS) shown as reference points. Morphological measurements made for each shell are shown including shell height (A: SH, mm), shell width (A: SW), and shell inflation (B: SI).* (Harding, 2007: p.962)

The corresponding ash-free dry weight (AFDW) for an oyster of 76mm in height according to Powell, et al. (1995), is 1.95 grams;

$W = (1.3258 \times 10^{-7})L^{3.81}$ (Eq. 9)

Where W refers to AFDW and L to shell height.[3] There is a regulatory maximum of 7800 kg (AFDW) of 76mm oysters permitted in a given acre.

Oyster respiration, the energy used to maintain homeostasis, is modeled as a function of AFDW, temperature, and salinity. Temperature was found to modulate respiration as would be expected in a poikilothermic organism (a cold-blooded organism), logically at a threshold of 20°C (in Powell, et al. 1992 from Dame, 1972). Salinity also modulates respiration across an

[3] This is a correction to what is reported in Powell, et al. 1992, 1995, and subsequent incarnations of the oyster model, which was reported by personal email from the co-author J.M. Klinck; where $L=(W/1.3258\times10^{-7})^{-3.81}$

ideal gradient, discretized in Powell, et al. (1992) at 10‰ and 15‰. These modulations address the nature of oysters to alter their respiration rates given their environmental conditions; i.e. oysters will decrease their rate of respiration in colder temperatures or lower salinities, and salinity levels will affect the modulation of temperature on respiration.

$R_j = (69.7 + 12.6T)W_j^b$ (Eq. 10)

Equation 10 is the base respiration function, where R_j refers to μl dissolved oxygen consumed per hour per gram AFDW, W_j refers to AFDW, and b=0.75. As dissolved oxygen levels are typically reported in mg/L, values were transformed to μL by a factor of 1/700 (Pitkin, 2000, p.397).

Temperature (T) modulation:

$R_r = 0.007T + 2.099$ *(@ T < 20°C)* (Eq. 11)

$R_r = 0.0915T + 1.324$ *(@ T ≥ 20°C)*

Salinity (S) modulation:

$R_{Tj} = R_j$ *(@ S ≥ 15‰)* (Eq. 12)

$R_{Tj} = R_j(1 + \left[\frac{(15-S)(R_r-1)}{5}\right])$ *(@ 10‰ < S < 15‰)*

$R_{Tj} = R_j R_r$ *(@ S ≤ 10‰)*

R_{Tj} refers to the modulated rate of respiration function, the amount of oxygen consumed (in μL) per gram of AFDW per hour.

Oyster feeding is represented by the rate of filtration of a modeled seston value. Like respiration, filtration is modulated by environmental variables. Temperature and salinity pose direct relationships to filtration, where optimal conditions approach estuary maxima of each parameter. Furthermore, filtration is negatively affected by an overabundance of suspended matter (turbidity). Temperature and salinity values were derived from the processed CBOFS data, while TSS (for turbidity) and chlorophyll-a values were derived from the composite water quality data.

$FRj = L^{0.96}T^{0.95}/2.95$ (Eq. 13)

Equation 13 is the base ingestion function, modulated by the subsequent equations; where *FRj* refers to ml of water filtered per individual oyster per minute, *L* refers to oyster length (mm), and *T* to temperature (°C).

Salinity (*S*) modulation:

$FRsj = FRj$ *(@ S ≥ 7.5‰)* (Eq. 14)

$FRsj = FRj(S - 3.5)/4.0$ *(@ 3.5‰ < S < 7.5‰)*

$FRsj = 0$ *(@ S ≤ 3.5‰)*

Turbidity (*t*) modulation:

$FRtj = FRsj[1 - 0.01\left(\frac{\log_{10} t + 3.38}{0.0418}\right)]$ (Eq. 15)

Ingestion:

$Ij = f \times FRtj$ (Eq. 16)

Equation 15 represents the modulated rate of filtration, the amount of water filtered (in mL) per individual per minute. Equation 16 is the modulated ingestion function, where *f* refers to the measured food index value (in mg/L). Given that chlorophyll-a has a much higher frequency of measurement than an indexed value of all available organic, inorganic, and free constituent digestible material, Soniat, et al. (1998) provides a regression function based on chlorophyll-a that approximates total available liable carbohydrates, lipids, and proteins. This function is also employed in Wang et al. (2008). Although this function permits easy approximations of available food, it should necessarily be adjusted and verified for different segments within the Chesapeake Bay as the composition of seston will vary somewhat within the estuary.

Food index:

$f = 0.088 \times chlorophyll\ a + 0.520$ (Eq. 17)

Where chlorophyll-a is represented in μg/L and f is the total available feed in mg/L.[4]

By reducing the volumetric amounts of available food or oxygen to null at a fixed oyster size, the modulated ingestion function and respiration function can derive a maximum number of individuals per discrete area by modeling food and oxygen reductions.

10.2 Modeling Spatiotemporal Production Maxima

Parametric driving values were extracted to a 'fishnet' representation of 1-acre discrete areas within the suitable production area by iterative sampling on a daily basis. Salinity and temperature were available at this resolution via the CBOFS model, while dissolved oxygen, chlorophyll-a, and TSS were replicated over their respective averaged period to represent daily values (weekly for chlorophyll-a and oxygen, and bi-weekly for TSS). Figure 4 (above) provides a graphical representation of data processing and oyster modeling, while Figure 5 (below) provides a graphical representation of how the oyster bioenergetics model is used to determine carrying capacities.

So as to establish maximum sustained biomass, with respect to this model we find either dissolved oxygen or food as the limiting factors. These values were calculated by scaling dissolved oxygen values to the volume of each discrete area by extracting bathymetric values over each discrete area as well as setting all depths greater than two meters at two meters. After both daily iteration sets (*Rtj and FRtj*) were compiled, individual rates were evaluated to the gross amount of each parameter in another set of iterations, to limit each towards zero; in which the lowest maximum biomass levels for the study period were adopted as static maxima. These 'maxima' were then cross-evaluated to determine sites being predominantly oxygen or food limiting. As these limits were set by rates, to approximate hydrodynamics of dissolved oxygen and seston levels, a 'refresh' factor was implemented to match rates of ingestion and respiration; by which if the unit area exhibited currents slower than the consumption rate, the

[4] This marks the first notice of errata in Soniat, et al., 1998, where chlorophyll-a is stated in 'uL/L'. Soniat confirmed the error via email.

parameter was scaled to match the current speed. For respiration, if average daily current velocities were less than 89.965 m/hour (0.0486 knots), the total dissolved oxygen was multiplied by: $1/(Current\ Speed\ \times 0.0486)$. For ingestion, if average daily current velocities were less than 89.965 m/minute (2.818 knots), the total 'food' amount was multiplied by: $1/(Current\ Speed\ \times 2.818)$. Current velocities were extracted from daily CBOFS modeling data. Carrying capacity results are presented in Chapter 11.

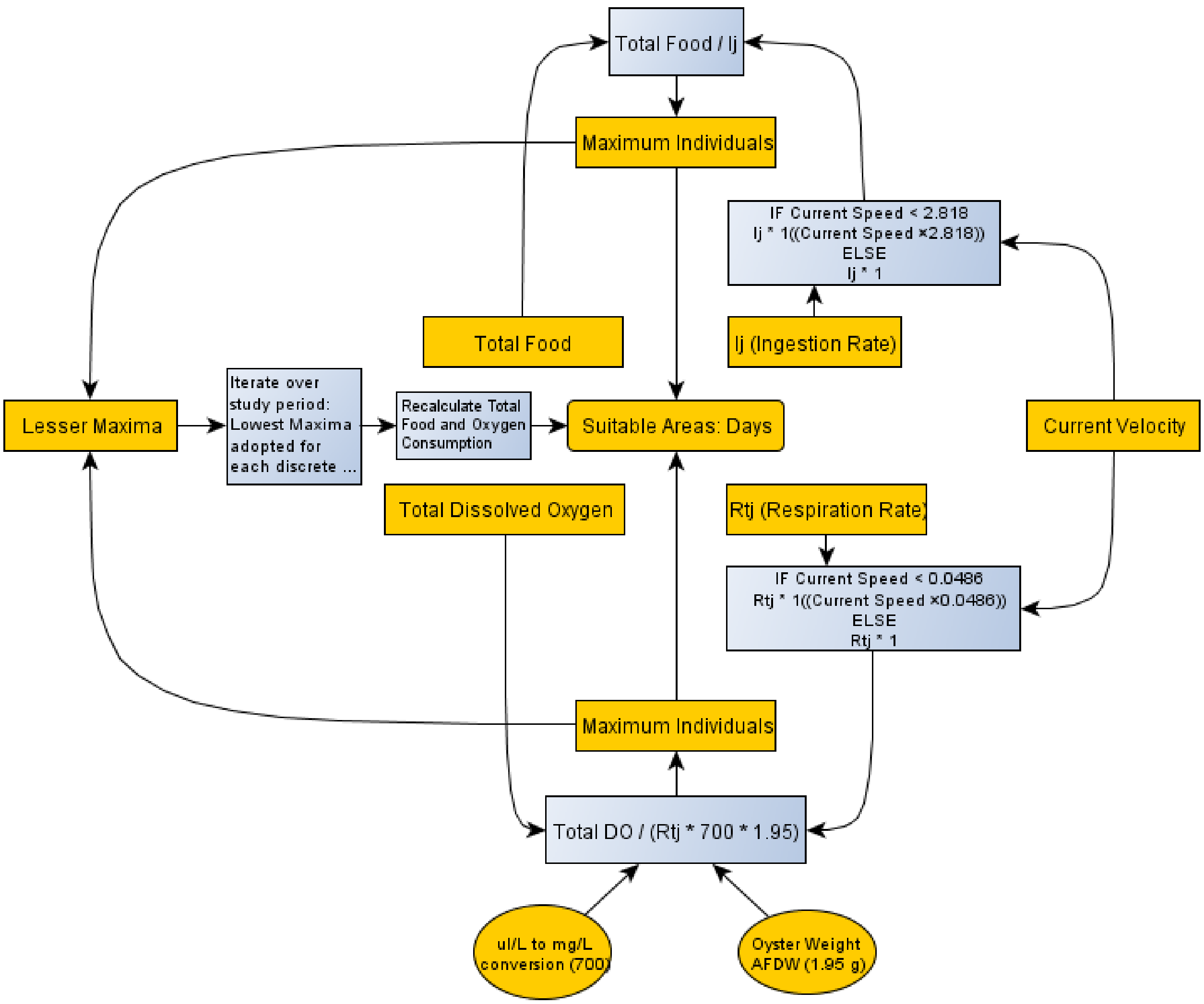


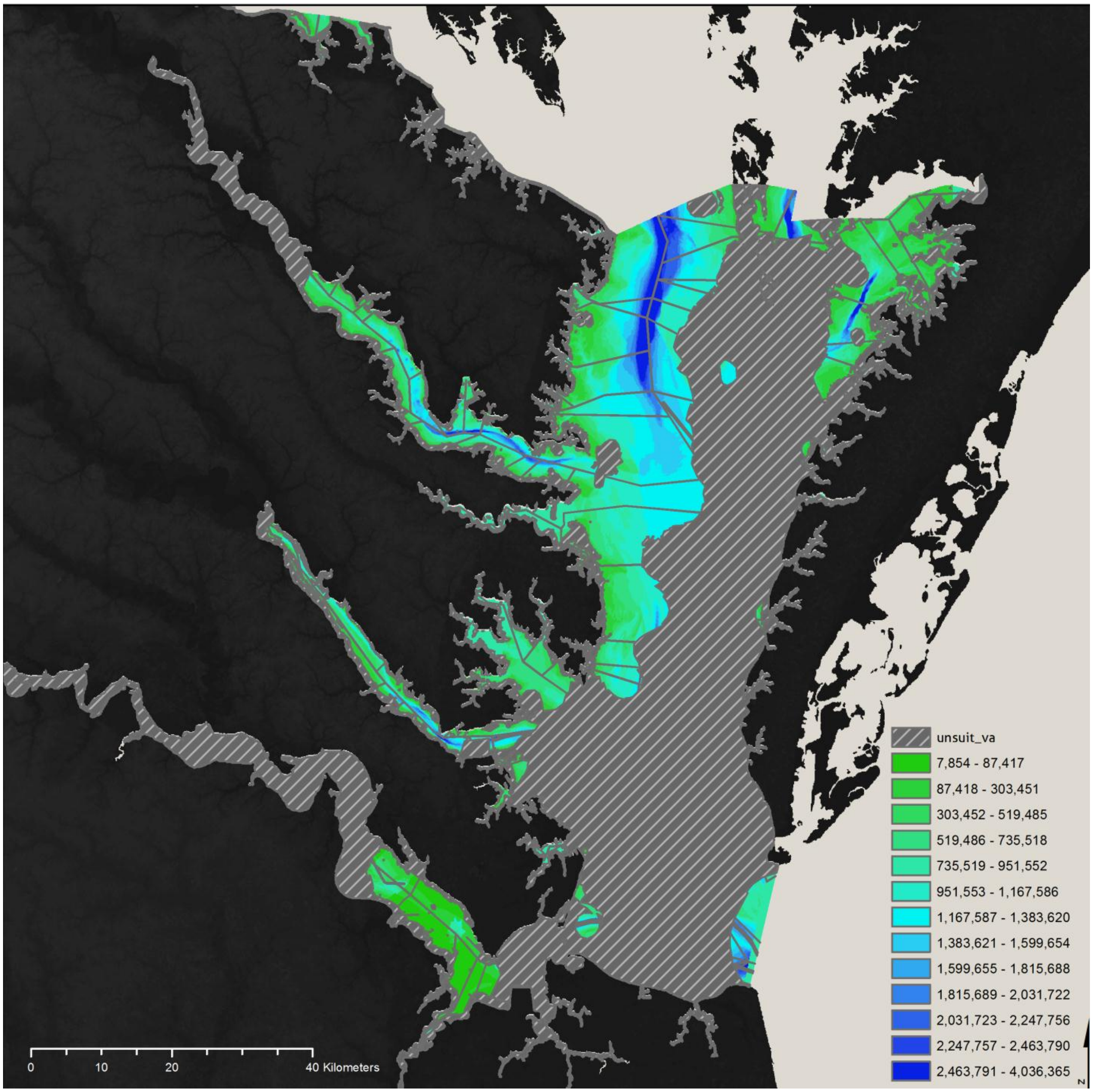
Figure 6: Determining Production Carrying Capacity. Daily rates of ingestion and respiration were determined for the study area by discrete acre areas. Total available food and dissolved oxygen, based on a volumetric scaling, were calculated daily for the discrete acre areas. Total food and oxygen were limited daily by maximizing consumption of either ingestion or respiration. The study period minimum of each daily maxima was adopted as the carrying capacity for each discrete acre area.

10.3 Changes to the Eutrophic States of Suitable Growth Areas

The carrying capacity values were then evaluated for a potential change in ASSETS score over the study period. The inherent contradiction in maximizing biomass as limited by food or oxygen is a mass net reduction in dissolved oxygen, where even though reduced chlorophyll-a levels may yield better ASSETS primary conditions, heavily reduced dissolved oxygen levels can negate the benefits. We must remember however that the biogeochemical and ecological dynamics of reducing seston within the water column with bivalve aquaculture are much more complex than what is provided here. Bivalves ingesting (removing) seston and respiring will reduce dissolved oxygen levels, though the bulk of material that is removed by ingestion will consume less net biological oxygen demand (planktonic and bacterial respiration); thus somewhat offsetting oxygen consumption of the bivalves. Then what is the value of modeling production carrying capacity in this light? Well, first we can use these modeled values to evaluate current production levels and targets. From the perspective of oyster farmers, they may learn that certain areas of interest to them may be able to maintain a higher density while others should be kept at lower densities in order to balance investments, and adjust resources to that end. From the resource managers' and regulating agencies' perspectives, a greater understanding is gained of how to direct incentives to specific areas for remediating poor estuarine conditions; and what limiting effects may impede regional aquaculture industrial growth. Potential ASSETS score shifts are presented in Chapter 11, sub-section 1.

11. Carrying Capacity Results

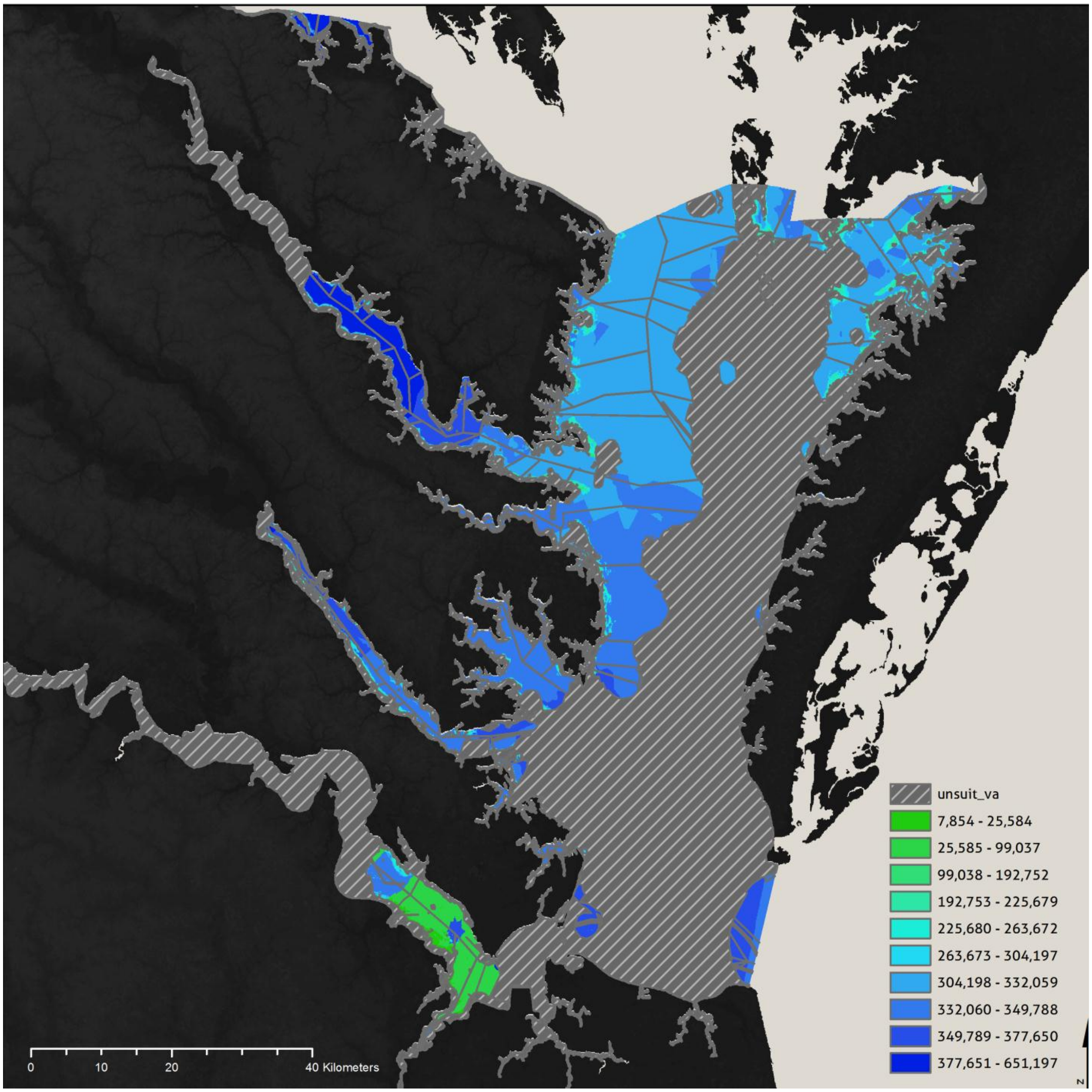
Analysis of food and oxygen availability as limiting factors in the oyster bioenergetics model (Chapter 10.1) yielded absolute minimal carrying capacities for the regions deemed suitable for intensive oyster aquaculture. The vast majority of these suitable areas are limited by food availability. A patch of the James River, which was among the areas most affected by eutrophic conditions in the initial ASSETS analysis, is limited by dissolved oxygen. The separation of carrying capacity between the two factors was often so great, on average, that the mass consumption of dissolved oxygen could be considered trivial compared to food limitations. This is a relatively positive finding, as growers can exceed these carrying capacity values to some extent, adopting sub-optimal growing conditions for higher densities (as food is limiting, the oysters will have less available food if the production carrying capacity is exceeded). This is however an unrealistic scenario as discussed previously; the area exploitable by growers is so vast that sacrificing food availability for their oyster 'crop' instead of dispersing the cohort over a broader area would rarely be an option. Thus, the seemingly high capacities for dissolved oxygen should provide comfort to growers and resource managers that approaching food-limiting capacities will most likely not risk anoxic eutrophication. In addition, while this analysis does not account for biological oxygen demand of fecal depositional decomposition, this supplemental net oxygen consumption will not press the carrying capacities over the precipice.



Map 32: Carrying Capacity: Total Individual Market-Size Oyster per Acre by Bathymetric Volumes and Constant Concentrations of Limiting Factors

Limiting Factor : Population Stats	Minimum	Maximum	Mean	Standard Deviation
Food	8059	5,049,073	875,643	633,266
Dissolved Oxygen	7,854	488,040,960	40,158,597	38,082,049
Combined	7,854	5,049,073	852,007	650,949
Adjusted to regulatory Maximum	7,854	4,052,225	851,475	648,116

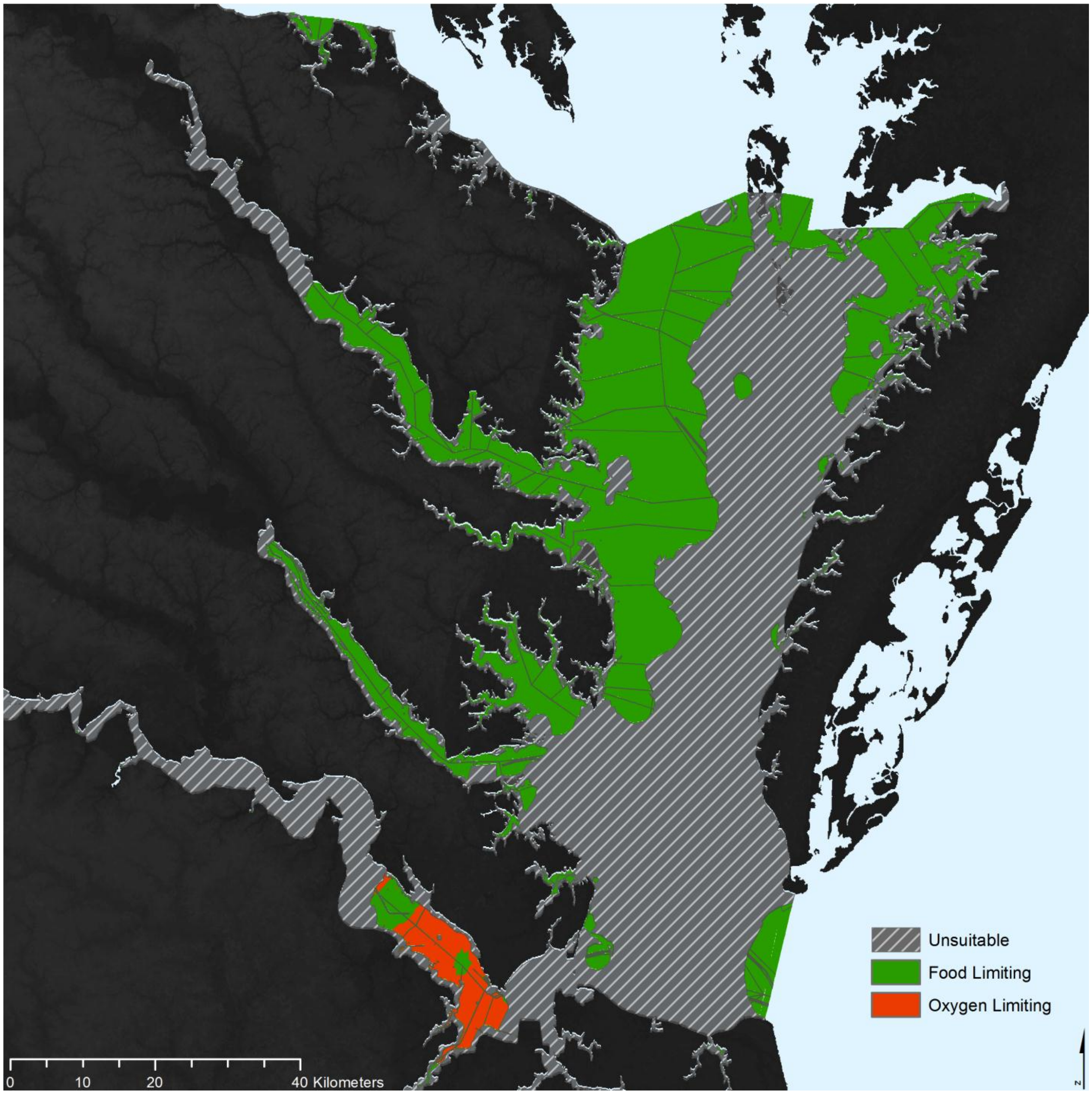
Table 3: Carrying capacities, maximum number of oysters per acre, based on limiting factors



Map 33: Production Carrying Capacity: Total Individual Market-Size Oyster per Acre by Depths of 2 Meters or Less and Constant Concentrations of Limiting Factors

Limiting Factor : Population Stats	Minimum	Maximum	Mean	Standard Deviation
Food	8059	653,730	328,681	38,196
Dissolved Oxygen	7,854	82,491,992	10,662,719	7,065,264
Combined	7,854	653,730	309,718	79,321

Table 4: Carrying capacities at a depth of ≤ 2 meters, maximum number of oysters per acre, based on limiting factors



Map 34: Capacity Limiting Factor: Food as the limiting factor is much more prevalent than oxygen

Limiting Factor	Percentage Area
Food	94.14
Dissolved Oxygen	5.86

Table 5: Carrying capacity limiting factor analysis

It is evident that bathymetry heavily influences this method of determining carrying capacity, as greater volumes linearly increase food or oxygen availability. Clearly this is a limitation of extrapolating food and oxygen concentrations without integrating a three-dimensional hydrodynamic model, though it should be noted that the waters in the Bay are well-mixed; where greater mixing tends towards linear approximations. Band statistics between modeled capacities and bathymetry provided a 0.68 Pearson's correlation coefficient. Obviously the configuration of culture vessels in a given site will depend on the hydrodynamic characteristics of that site; owing to gradients in food and oxygen. A more realistic approximation of production carrying capacity based on current culture methods assesses each discrete area with a maximum culture depth of two meters, as shown in Map 33. Sites with MLLW depths between one and two meters will employ either stationary cages or floating cages, while sites with MLLW depths greater than two meters will most likely employ floating cages that will not extend deeper than two meters (author's personal experience). Therefore, production carrying capacity is based simultaneously on biophysical capacities and the practicality of extending contemporary culture practices. In addition, modeled parameters are far more accurate at depths up to two meters as most field measurements are performed between one and four meters (VECOS and CBP metadata). Thus, the two-meter-limited carrying capacity model is a much better approximation of real production carrying capacities for a given area.

11.1 ASSETS Reassessment: Potential Eutrophic Shifts

Hypothetical production carrying capacity maxima in practice would provide system-wide transformation in current eutrophic trends, previously discussed in the assessment of present ASSETS values. Simultaneous reductions of seston (represented by chlorophyll-a) and dissolved oxygen at capacity scales adjust eutrophic state scores. Summary statistics of median remaining levels (present levels minus modeled reductions) of dissolved oxygen and chlorophyll-a are presented in the table below. Daily modeled ASSETS values were reclassified and intersected to determine overall ASSETS values for the study period.

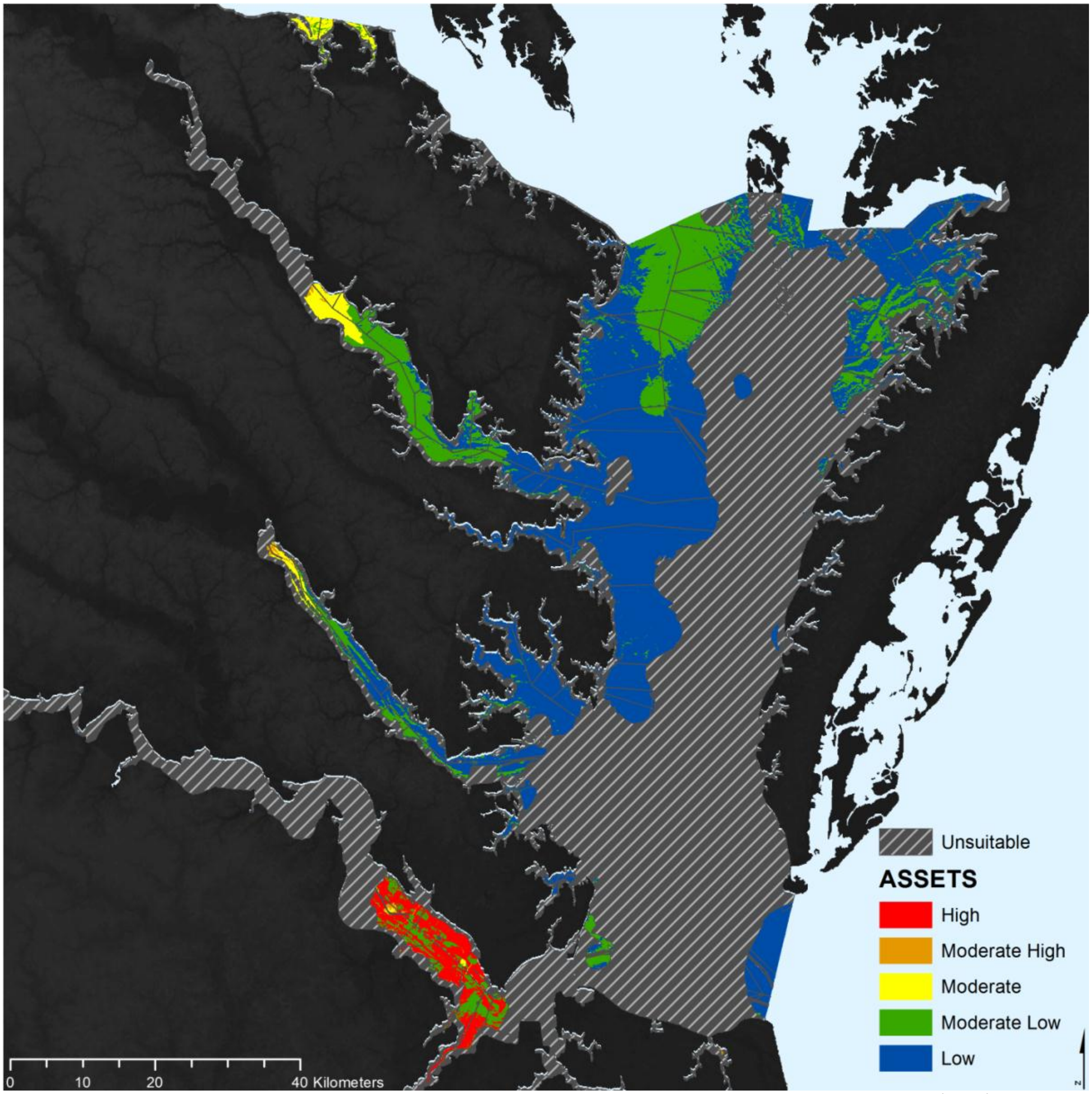
Parameter	Minimum	Maximum	Mean	Standard Deviation
Dissolved Oxygen (mg/L)	0.97	11.89	8.69	1.37
Chlorophyll-a (ug/L)	0.4	32.83	14.67	11.41

Table 6: Summary statistics of parameters used for primary and secondary symptoms: The average dissolved oxygen value is notably high, as is the spread of chlorophyll values.

As presented in Map 35 and Table 7, the resulting ASSETS assessment of modeled carrying capacity impacts is in stark contrast with the current eutrophic condition of the Bay. While none of the suitable growing area was originally exhibiting 'Low' eutrophic conditions, we find over 65% of that area with potential for 'Low' conditions. This should not entirely be surprising as the ASSETS scoring basis favors chlorophll-a presence (and inversely the absence) as a primary symptom for eutrophic conditions. As limiting values for the primary symptom were significantly less than for the secondary symptom in most of the suitable area, we would expect the ASSETS scores to improve along these lines. Nevertheless, this provides weight to the argument for supporting intensive bivalve aquaculture.

ASSETS Score	Hectares	% of Suitable Area
High	15010	7.47
Moderate High	1612	0.8
Moderate	5377	2.67
Moderate Low	47589	23.68
Low	131391	65.37

Table 7: ASSETS scores given carrying capacities applied; as most areas are limited by food, which the presence of food is the primary symptom of eutrophication, significant shifts are possible. Where the current state exhibits mostly Moderate or Moderate High eutrophic conditions, most of the study area exhibits Low eutrophic conditions with extensive oyster aquaculture.



Map 35: Potential ASSETS Scoring as Applied to Oyster Carrying Capacities: In contrast with Map 31 (p.65), most of the study area exhibits high potential for remediating eutrophic conditions. In this context, employing oyster aquaculture as a remediative mechanism can be seen as a viable option in some places.

Surveying the suitable areas, we see that the portion within the James River is relatively unchanged in eutrophic state (High). This was an area limited predominantly by dissolved oxygen and with quite low capacities for intensive aquaculture. Given that much of this area has the potential to shift eutrophic states in present conditions, it is recommended that this area should be particularly scrutinized for intervention with oyster aquaculture.

12. Uncertainty, Error, and Sources of Error

As with any geographical representation of environmental conditions, error in measurement, generalization, georeference, reprojection, and further manipulation will necessarily propagate. The methodological steps taken in this analysis have attempted to meticulously document error in quantitative and qualitative space. The extent of this error is however relatively unknown in respect to reality, which provides a case for terming variance in modeling and geographical analysis, 'uncertainty'. Each and every source of error, whether small or large, will propagate and confound the analytic results.

Error in raw data, as obtained from the various data sources discussed in Chapter 7, can significantly confound the further processing and utilization of that data. Fortunately, all of the data sources maintain high standards of quality control. Data that had been identified as inaccurate or 'suspect' were not included in this work. Nonetheless, it is impossible to be absolutely consistent and accurate in field measurements.

Interpolation of discrete zero dimensional data (points) into two dimensions bestows a considerable source of uncertainty. The process of interpolation should aim to verify modeled values by segregating observed values into one set of drivers and one set for verification, in order to test the interpolation model for fitness. This process may be repeated iteratively to produce a more statistically representative model, as is employed for example in Monte Carlo Simulations. Spatial interpolations within this thesis were employed to produce parametric coverages as drivers for modeling oyster metabolism, and as inputs, the entire analysis should be conceptualized as 'theoretical', considering initial uncertainties in the input datasets. Nevertheless, interpolations were applied to minimize error by seeking the least mean standard errors of residuals while approaching root mean square standardized error values of one; to reduce over- or under-estimation of variability in prediction.

The ASSETS model as described and employed in Chapters 9 and 11 is a simplification of eutrophic conditions in the Bay. Obviously the temporal variation of eutrophic states will fluctuate according to precipitation, solar radiation, nutrient inputs, etc. which do not necessarily correspond with one another. By assessing the eutrophic states on an averaged basis of the symptoms, this thesis attempts to smooth out those variations in order to provide a broad picture of the Bay's eutrophic conditions in reference to bivalve carrying capacity. An estuary-scale analysis which models the effects of bivalves with higher temporal resolution would be interesting, and would further contribute to this knowledge base.

Other aspects of bivalve allometry, metabolism, survival, and relative mass balances not included in this modeling exercise will necessarily play a role in observable variance. The extensive literature on the growth of bivalves largely attributes a handful of relatively available parameters to calculate oyster population dynamics, but the complexity of aquatic ecosystem dynamics will always lend a degree of uncertainty. Seawater chemistry, fluctuating microbiological compositions, bivalve innate immunity responses, watershed-scale anthropogenic influence, differing culture and management practices, genetic variation, and other micro and macro 'stochastic' effects contribute to variance not measured in this analysis.[5] Nevertheless, as mentioned previously, the parameters used in this analysis have been extensively employed to model shellfish growth, survival, recruitment, and ecosystem-scale assessment; and have proven to sufficiently represent these processes as verified in previous studies employing the same model.

Lastly, and in general, modeling any aquatic biological, biophysical, or biogeochemical processes are going to transform in reference to climate change. With rising seas we will witness fundamental alterations in the relationship that built human civilization maintains along the coasts with the sea. Evolving social and ecological priorities will provide changing insights into shellfish aquaculture as an element of infrastructure as well as situational constraints to aquaculture development. Transformation of seawater chemistry, increasing ambient temperatures, decreasing salinities, and pH/CO_2 shifts will contribute to future reconsiderations of model parameters. As with most models of this sort, the basic functions and relationships will require reassessment in the least, and optimally strive towards greater accuracy and precision.

[5] The author recognizes that stochasticity is merely a convenient representation of factors that exhibit randomness but have real causality in a fractal sense, and are generalized in order to fulfill a modeling paradigm.

13. Conclusions and Final Remarks

The aim of this study was to increase an understanding and provide decision support to growers and resource managers on the spatial suitability of oyster aquaculture, as well as its potential to alleviate eutrophic conditions through a GIS framework. This thesis has integrated processed remote sensing data with two models, ASSETS and an oyster bioenergetics model, to illuminate potential production carrying capacities distributed in space and the potential rectification of eutrophic conditions within a major estuary. Such an analysis would not be possible without the use of GIS, in fact, GIS provided all of the tools necessary for this analysis. This thesis contributes to the already vast base of GIS application in environmental modeling and decision support through the demonstration of implementing a site suitability analysis, carrying capacity modeling, and eutrophic state change modeling. In most practical terms, this thesis provides valuable production and resource management data to the industry and regulatory actors, as well as a framework to build upon.

Although the demand for high quality shellfish is currently undersupplied, a rapid, extensive, and intensive growth in shellfish production may adversely affect the market economics. As Ferreira, et al. (Chapter in Shumway, 2011), explain in reference to modeling production carrying capacity, "an increase in seeding density results in a standard Malthusian curve of diminishing returns as seen in the total physical product…" Market dynamics for fresh oysters will markedly shift with increasing supply at some point, as well as with varying quality and consumer preference. However, this is difficult to project at this time as the supply of fresh local oysters is far outpaced by demand, lending considerable prospect for industrial growth.

In addition to market sustainability of the product, growers will also need to weigh the risks of increased densities and production. With greater initial investment, pushing the envelope may prove to be unwise when we consider that there currently is copious space for 'thinning out' any given growing area, and isolated mortality-related events (extreme weather, Harmful Algae Blooms, other pathogen outbreaks) could devastate any cohort of oysters. Although, if a grower were only allotted a limited number of permits for aquaculture, this grower will be able to adjust their spatially-limited production based on carrying capacities of the permitted areas. Individual growers will necessarily asses the risks and potential returns on investment for a particular area, with production carrying capacity as an essential parameter for approaching the biophysical limits of that growing area. The analytical results of modeling production carrying capacities and shifts in eutrophic condition, which can be adopted to some extent as a proxy for ecological well-being, illustrates the growth potential for oyster aquaculture in the Chesapeake Bay.

GIS as a tool for spatial analysis of environmental parameters and distributed modeling offers numerous advantages to the aquaculture industry as well as governmental agencies in this light. It is incredibly difficult to assess carrying capacities at local scales by in-situ measurement and case-by-case appraisal. General regulatory mechanisms in shellfish aquaculture may drastically over- or underestimate the realities of any given site, leading to regulatory inefficiencies, inequities in economy and ecology, as well as fundamental difficulties in administering incentive regimes to bolster economic growth and ecological remediation. Compiling spatial data and leveraging it to reveal spatially explicit characteristics of the Chesapeake Bay in this manner lends credence to the utility of GIS.

This modeling exercise provides supporting evidence to aquaculture advocates and resource managers looking to integrate oyster aquaculture as part of regional infrastructure and as a tool for mitigating diminished estuary conditions. Along with other mechanisms, in time a managed, industrial approach to employing filter feeding organisms in the scheme of improving estuary conditions can simultaneously provide compounded economic stimulus and improved conditions for natural populations of oysters to recolonize their habitat.

14. References

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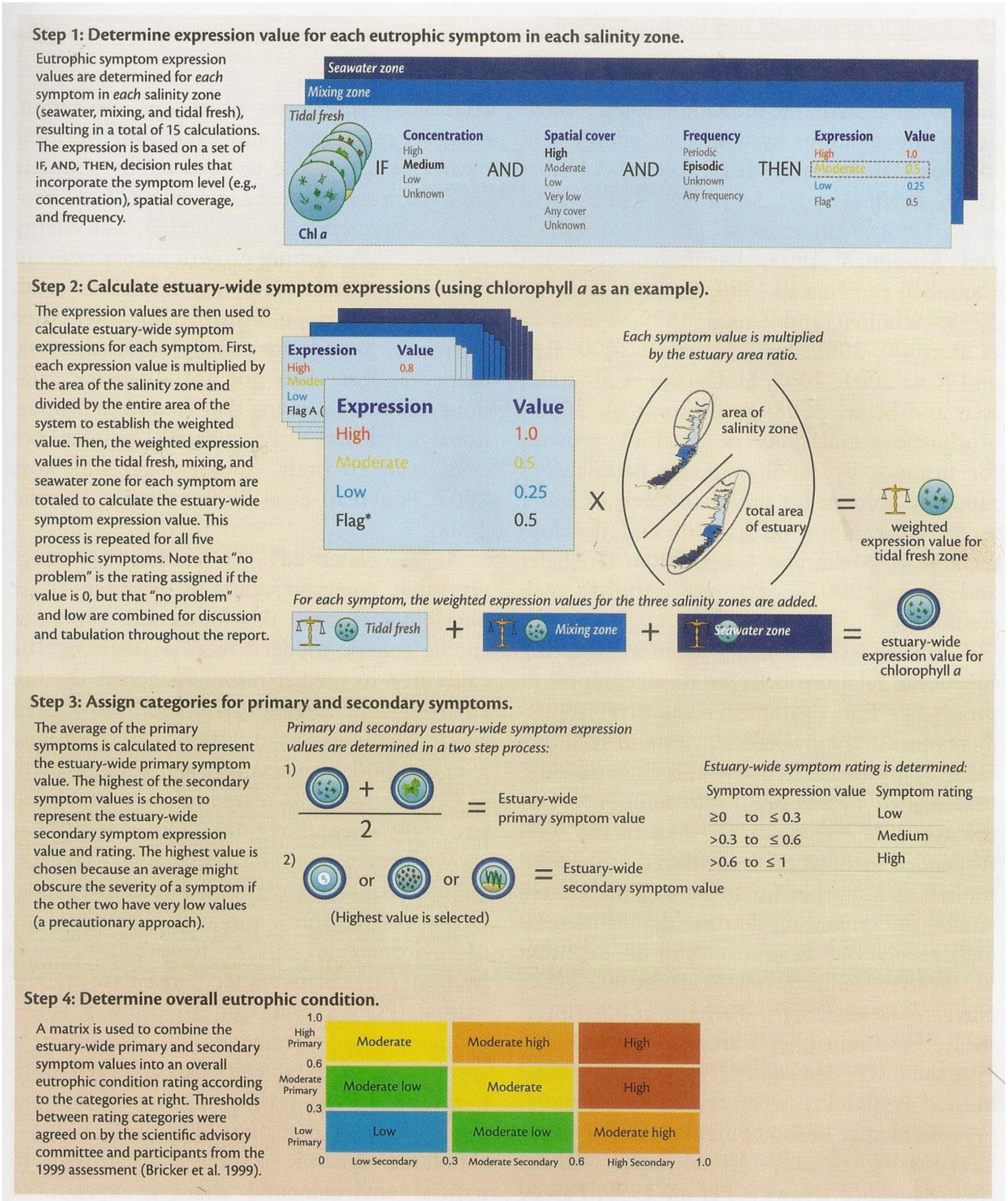
Appendix

1. ASSETS Framework



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