Role of Aquaculture for Chesapeake Bay Ecosystems and Food Security

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Executive Summary

This case study addresses the wicked problem of seafood production in coastal Virginia and the adjacent Chesapeake Bay and its tributaries. The Chesapeake Bay has historically supported a thriving fishing industry, but declines in wild fish populations due to overfishing, nutrient pollution, and climate change make relying on fishing infeasible. Aquaculture provides an opportunity to maintain or increase seafood production in the Chesapeake Bay area without stressing wild fisheries. Aquaculture has multiple benefits including being a resource-efficient method for producing animal protein, stimulating local economies, and allowing fishing communities to maintain working waterfronts. Shellfish aquaculture can have a net positive impact on surrounding ecosystems by filtering water and sequestering nutrients and carbon. Aquaculture also has potential drawbacks. It is a young industry with developing technological and political frameworks. Environmental issues like habitat destruction, over-fishing of small pelagic fish for fish feed, and effluent discharge can be caused by aquaculture if farmers do not have environmental sustainability in mind. The public has mixed opinions on aquaculture. Some consumers prefer wild seafood due to the perception that wild-caught fish is healthier and better for the environment. Coastal aquaculture contends with opposition from the fishing industry, coastal residents, and recreators who view it as a threat to their way of life.

This case study assesses the potential for aquaculture to augment or replace wild seafood production in coastal Virginia and the southern Chesapeake Bay. The benefits and drawbacks of different forms of aquaculture to the economy and ecosystems are considered. Recommendations are made to the Virginia Marine Resources Commission (VMRC) and the Virginia Department of Agriculture and Consumer Services (VDACS).

Decision Space

Interested stakeholders include fishermen, fish and shellfish farmers, regulators, consumers, environmental nonprofits, researchers, and coastal residents and recreators. Stakeholders have differing opinions on aquaculture. Fishermen generally oppose it, farmers generally support it, and other stakeholders have mixed views. All stakeholders share some common goals. These include supporting local food production, maintaining a local seafood industry, supporting small local businesses, and having a healthy Chesapeake Bay ecosystem. These goals culminated in a goal statement: Our goal is to have an ample supply of domestically produced seafood and a healthy Chesapeake Bay ecosystem that can support sustainable fisheries and aquaculture in coastal Virginia.

Aquaculture must operate within the rules of the system. Ethical rules, socioeconomic rules, and regulatory rules that define the decision space are described. Aquaculture operations must take into account the values of participating stakeholders, demands of capitalism, and local, state, and federal regulations. They must balance an ethical and regulatory requirement to protect the environment with maintaining a profitable business.

Wicked Problem

Seafood production in coastal Virginia is a wicked problem for the following reasons:

- There is no clear right or wrong solution.
- The characteristics of the problem are highly variable.
- There is a “no stopping rule.” The problem is never truly solved, and adaptive management will need to be employed.
- There is no immediate test to determine if solutions are good.
- The problem is caused by humans, and humans are also trying to fix the problem.

Understanding the System

Currently shellfish aquaculture dominates the aquaculture industry in Virginia. 70% of Virginia aquaculture operations are oyster farms and Virginia is the nation’s top producer of hard clams. Indoor finfish aquaculture of freshwater fish species is practiced some inland areas. Most of these facilities use recirculating aquaculture facilities. Examples of large indoor facilities include Blue Ridge Aquaculture and Pure Salmon (in development). Some outdoor pond-based aquaculture of freshwater fish species also exists, but it is very limited. Shellfish aquaculture has a net positive effect on the environment. Indoor finfish aquaculture can have a neutral or negative effect depending on the practices employed (energy and water use, fish feed source, waste discharge, etc.) Aquaculture in Virginia is influenced by the environment outside the system also. Influences include climate change, the price of seafood and supplies, media, and federal and regional regulations.

Fragilities and Hazards

Fragilities are characteristics of the coastal Virginia seafood system that make it vulnerable to stressors. Fragilities include the life requirements of fish and shellfish, the geological and hydrological structure of the Chesapeake Bay, the lack of oyster reefs in the Bay, the seafood industry’s dependence on coastal infrastructure, and the dependence of the industry on economic success. These fragilities affect how the system can respond to hazards. Hazards include overharvesting, disease, nutrient pollution, market volatility, and climate change (which causes sea level rise, increased water temperature, ocean acidification, extreme weather, and salinity changes). A range of hazard scenarios, from worst case to best case, are examined. The worst case scenario will occur if no action is taken to address hazards. This scenario involves total collapse of wild fish populations due to overfishing, regular nutrient pollution at the highest observed rates leading to increased eutrophication and dead zones, and sea level rise causing flooding of coastal communities. The best case scenario is characterized by recovered wild fish populations, expansion of aquaculture to meet seafood demand, nutrient pollution reductions, and climate stabilization. This scenario can only be achieved with significant effort to address human-driven hazards.

Foresight and Possible Futures

Hazard scenarios are used to map possible futures for the system. The possible futures range from transformation (which requires significant action) to collapse (resulting from a complete lack of action).

Possible Futures

1. Transformation: Fisheries are restored to sustainable population numbers. Nutrient loading is reduced to meet the TMDL and water quality drastically improves. Aquaculture expands and meets seafood demands without stressing the Chesapeake Bay ecosystem.
2. Discipline: Wild fish populations improve slightly. Gradual nutrient reductions bring the Chesapeake Bay closer to restoration, but the TMDL goals are not met. Aquaculture gradually expands, but does not supply enough seafood to meet demand. Consumers still rely on fishing and imported seafood.
3. Continuation: Fishing and aquaculture continue as usual. Wild fish populations fluctuate between declining and stable condition. Nutrient pollution and occurrence of seasonal dead zones continue. Most local seafood consumption is provided by wild fisheries and imports.
4. Degradation: Decline of fisheries and water quality in the Chesapeake Bay accelerates. Some fish species go extinct, while others are severely reduced in numbers. Nutrient pollution increases and fuels worse eutrophication and dead zones. Existing aquaculture continues, but efforts to expand it fail.
5. Collapse: Fishing continues unchecked until populations collapse. The Chesapeake Bay has larger and longer-lasting dead zones as a result of increased eutrophication. Dissolved oxygen concentrations are too low to support oyster aquaculture, so that industry collapses. The fishing and aquaculture industries both collapse and no seafood is produced in the system.

The goal of using foresight is to understand the full spectrum of possibilities for the future. Mapping possible futures does not attempt to predict what will happen. Understanding the full range of possibilities allows us to develop interventions that can bring the system towards a desirable future.

Assessing Interventions

Four possible interventions are discussed that could bring the system towards a desirable future that matches the goal statement. These interventions are intended to be enacted by the Virginia Marine Resources Commission and the Virginia Department of Agriculture and Consumer Services.

1. Consumer education campaign to promote oyster aquaculture
2. Promotion of marine finfish and blue crab aquaculture in indoor recirculating facilities
3. Provision of career services to help fishermen transition into aquaculture roles
4. Promotion of pond-based aquaculture of freshwater fish.

Pros and cons of each intervention are discussed and interventions are ranked according to feasibility, impact, impact time, cost, and risk. The consumer education campaign is ranked highest, followed by provision of career services, promotion of indoor aquaculture, then promotion of pond-based freshwater aquaculture. All interventions are focused on outreach and education to suit the regulatory roles of VMRC and VDACS.

Recommendations

Recognizing that...

- Wild fish populations in the Chesapeake Bay are threatened by overfishing.
- Seafood is a healthy and popular food choice.
- Seafood production in Virginia does not meet demand.
- Many coastal communities are economically reliant on fishing.
- Nutrient pollution causes eutrophication and dead zones in the Chesapeake Bay.
- Wild fish populations will face increased environmental hazards due to climate change.

Acknowledging that...

- Fishing is an important part of coastal Virginia's cultural heritage. Fishermen have valuable knowledge that is often not incorporated into policy.
- Stakeholders, including regulators, nonprofits, and farmers, are actively making efforts to restore the Bay through nutrient reductions.
- Coastal communities are being increasingly affected by climate change impacts (sea level rise, extreme weather) and have limited resources with which to address impacts.
- There is a history of conflict between aquaculture and fishing communities.

It is recommended that...

The Virginia Marine Resources Commission and the Virginia Department of Agriculture and Consumer services implement interventions 1, 2, and 3 described in section 7:

1. Consumer education campaign to promote oyster aquaculture
2. Promotion of marine finfish and blue crab aquaculture in recirculating facilities
3. Career services to help fishermen transition into aquaculture roles.

1 Introduction

The Chesapeake Bay has historically supported a thriving fishing industry. The Bay is a productive estuarine ecosystem that at one point supported large populations of oysters, blue crabs, menhaden, demersal fish species including striped bass, Atlantic croaker, flounder, and white perch, and migratory fish like shad, herring, and sturgeon (Cronin, 1986; Buchheister et al., 2013). Oysters are a keystone species in the Chesapeake Bay ecosystem; they filter water and build reefs that provide habitat to other species. Fishing continues to be a vital part of the Bay's economy. The Bay currently produces 500 million pounds of seafood each year, and 50 different species are harvested from Bay waters (NOAA Fisheries, 2020; Virginia Seafood, 2024). Menhaden is the largest fishery by weight, while the blue crab fishery is the most economically important (NOAA Fisheries, 2020; Paolisso, 2007). Virginia is the nation's third-largest producer of marine products, outpaced only by Alaska and Louisiana. 45 counties and cities in Virginia have substantial economic dependency on the seafood industry (Virginia Seafood, 2024).

Intensive fishing began in earnest in the latter half of the 19th century. Shad, bluefish, sea trout, menhaden, and mackerel were important to the fisheries during this time. Oyster and blue crab harvesting also became a thriving industry with the introduction of the railroad and development of preservation techniques. Oystermen from New England came to the Chesapeake Bay after depleting the oyster beds up north and brought destructive deep-water dredges that were capable of harvesting massive numbers of oysters from previously inaccessible waters (Cronin, 1986; Rothschild et al., 1994). As human population grew and technology improved catch efficiency, wild stocks of both finfish and shellfish were rapidly depleted. By 1980 shad and striped bass were so scarce that Maryland prohibited their capture. Oyster stocks began to decline towards the end of the 19th century and are currently only 1% of pre-industrial abundance (Cronin, 1986). Between 1993 and 2001, commercial harvest of blue crabs declined 46% (Fogarty and Miller, 2004).

While fishery activity expanded with increasing population and demand, land-based agriculture in the Chesapeake Bay watershed also expanded, resulting in discharge of excessive quantities of nutrients (primarily nitrogen and phosphorus) and sediment to the Bay. Eutrophication from excess nutrient input led to the development of chronic “dead zones” in the Bay, low-oxygen areas that are unsuitable for fish habitat (Kemp et al., 2005; Buchheister et al., 2013). Disease and invasive species have also put pressure on wild fish populations (Schulte, 2017; Schloesser et al., 2011). As a result of the combined effects of all of these stressors, continuing to rely on wild fisheries to support seafood demand is untenable.

Aquaculture provides an opportunity to maintain or increase seafood production in the Chesapeake Bay area without stressing wild fisheries. Worldwide, aquaculture produces over 57% of aquatic animal products used for human consumption. While yields of fish from wild fisheries have been stagnant for the last few decades, aquaculture yields have increased at an accelerating rate (FAO, 2024). The United States is a large consumer of seafood, but only produces a fraction of demand domestically. 80-90% of seafood consumed in the United States is imported, and over half of that import is produced by aquaculture (National Marine Fisheries Service, 2014). Aquaculture has multiple benefits for food production. It is one of the most resource-efficient ways to produce animal protein because fish are more efficient at converting feed into meat than terrestrial animals (Swann, 1992; Knapp and Rubino, 2016). Some types of aquaculture like shellfish farming can have net positive impacts on surrounding ecosystem by filtering water and sequestering nutrients and carbon (Kellog et al., 2018). Aquaculture can also have economic benefits. Growing the industry provides jobs, maintains the supply of seafood in markets, and can allow fishing communities to maintain working waterfronts.

There are also potential drawbacks to aquaculture. It is a young industry, so technological and political frameworks are still being developed. It can be a challenge for new farmers to obtain the permits and public approval needed to be successful (Knapp and Rubino, 2016). Environmental issues like habitat destruction, over-fishing of small pelagic fish used for fish feed, and effluent discharge can be caused by aquaculture if farmers do not have environmental sustainability in mind (Naylor et al., 2000; Creswell, 2000). Finally, public perception will determine whether increased aquaculture production is economically successful. Aquaculture competes with other industries for land and water resources when it is conducted both inland and in coastal areas. Coastal aquaculture contends with opposition from the fishing industry, coastal landowners, and water recreators who view it as a hindrance to their way of life. Marine aquaculture in the United States makes up only 15% of US aquaculture production, so it has a long way to go before it becomes a widely accepted industry (Knapp and Rubino, 2016). Success also depends on consumers. Are they willing to buy farm-raised seafood?

Figure 1: Map of the study area – coastal Virginia, the lower Chesapeake Bay, and Chesapeake Bay tributaries within the state of Virginia

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This case study assesses the potential for aquaculture to augment or replace wild seafood production in coastal Virginia and the southern Chesapeake Bay (Figure 1). The benefits and drawbacks of different forms of aquaculture to the economy and ecosystems are considered. Relevant stakeholders were involved in a participatory modeling process to identify different perspectives and develop a shared goal for the future of seafood production in Virginia. The next five sections (Decision Space, Wicked Problem, Conceptual Model, System Fragilities, and Current and Future Hazards and Threats) examine characteristics of the system, the problem of supplying seafood in the face of declining wild stock, and the people and organizations involved in the problem. The final four sections explore possible futures and interventions, then propose recommendations for addressing the problem in coastal Virginia. Interventions selected for recommendation are those most likely to bring the system closer to the goal statement. Recommendations are made to the Virginia Marine Resources Commission and the Virginia Department of Agriculture and Consumer Services.

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2 Decision Space

2.1. Stakeholders

To understand the complexities of seafood production in the Chesapeake Bay, we need to start by understanding the people involved and the social system within which they operate. While this problem is relevant to the entire Chesapeake Bay area, this case study will only focus on Virginia. Fishermen were the original suppliers of seafood in the bay. The history of the fishing industry spans generations, often passed down from father to son. Fishing is part of the cultural fabric of the Chesapeake Bay area. Fish and shellfish farmers are a more recent player in the seafood industry, with the exception of some oyster leases that date back to 1899 (Grant, 2022). Farmers' desire to expand aquaculture production in Virginia is often at odds with fishermen who view them as competition (Knapp and Rubino, 2016). Actions of both fishermen and fish farmers are driven by consumer demand. They also must operate within the regulatory rules prescribed by state and federal agencies. Environmental organizations and academic researchers have intellectual interests in the production of seafood in the Bay as it relates to environmental protection. Finally, coastal residents have opinions about living and recreating near aquaculture. They can influence aquaculture success by participating in public hearings to approve or deny permits.

The following section explores the perspectives of each stakeholder in detail. Stakeholders are mapped in Figure 2 according to their degree of interest in seafood production and their authority and resources to address the issue. A role-playing exercise was conducted in class to understand the perspectives of each stakeholder. Insights from the exercise are summarized in Table 1 and are incorporated into this section. Stakeholder perspectives culminate in a list of common goals amongst all stakeholders and a goal statement for the future of fisheries and aquaculture in the Chesapeake Bay.

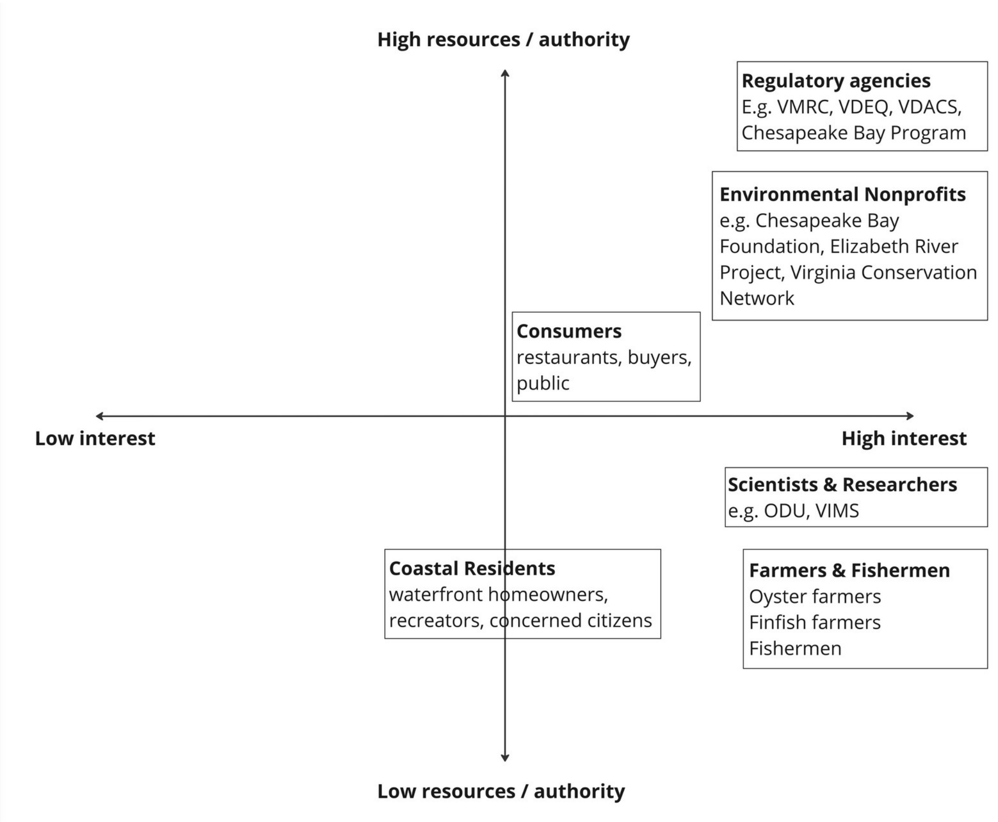

Figure 2: Stakeholder decision space. Stakeholders are mapped according to their degree of resources/authority and their degree of interest in the wicked problem.

Table 1: Results of stakeholder role-playing exercise, including stakeholder viewpoints and desired futures.

Stakeholder	Viewpoint	Desired Future
Fisherman	Opposed to aquaculture, views them as competition. Concerned about declining fish stocks and the feasibility of their livelihood in the long term.	Continuing to fish the Chesapeake Bay while maintaining a profitable business and passing down their craft to the next generation.
Oyster Farmer	Supportive of aquaculture. Cares about efficiency and making a profit. Proud of providing food for their community.	Increasing production of oysters and selling more oysters to the community.
Consumer	Cares about price of seafood and how convenient it is to buy. May be supportive of aquaculture if it can provide cheaper product.	Having a regular supply of cheap, high quality seafood.
Regulatory Agency	Concerned about aquaculture's impact on the environment and other land uses. Wants to know where it will be performed, whether it will disrupt natural landscapes, and whether oyster cages will limit what people can use waterways for.	Balancing fishing, aquaculture, and other uses of waterways in a manner that provides food for the community while protecting the natural environment.

2.1.1. Fishermen

Perspectives of Chesapeake Bay fishermen derive from generations of working on the water. Fishermen, also known as watermen, form a tightknit community in coastal Virginia. Jessica Taylor and Patrick Daglaris (2022) interviewed a fisherman named AJ Hurst as part of the Samuel Proctor Oral History Program at University of Florida. AJ was one of Eastern Virginia's patriarchs of crabbing. He worked for 70 years in Matthews County, located on the Middle Peninsula between the York and Rappahannock Rivers, crabbing and fishing on menhaden vessels. Taylor and Daglaris write, "Between working odd jobs, learning to make pots, and tying up at other people's docks at the end of the day, he prized the camaraderie between himself and other watermen cultivated through the shared but isolated, communal but independent, work." Watermen like AJ have an intimate knowledge of the Bay cultivated through years of hands-on experience. Fishing regulation and conservation efforts can feel like an intrusion into their livelihood. Another crabber interviewed by Taylor and Daglaris expressed this by saying, "You take some old waterman that's been on the water all his life—A. J., for instance. He's forgotten more about the crab than the people at the VMRC (Virginia Marine Resources Commission) or whatever know." AJ believed that only God knows why there are fewer fish to catch nowadays. In interviews, he observed that less young people are joining the fishing industry lately. Working waterfront communities are being taken over by "bedroom communities" focused on recreation and tourism (Taylor and Daglaris, 2022).

Michale Paolisso (2002) studied the cultural model of watermen's reasoning about blue crab management and found similar sentiments. He found that the watermen's cultural model for managing the blue crab fishery contains the same elements as the scientific and resource management approaches, but in the watermen's model nature or God is the ultimate provider of crabs. Humans can reduce crab population through greed, pollution, and habitat destruction. Paolisso found that the watermen's model includes a role for regulation and science, by reducing the impacts of human greed, but they are not comfortable with the use of stock assessment approaches for estimating crab reproduction and abundance. In their view, these tools stand in the way of God's provisioning of crabs for watermen's use (Paolisso, 2002).

The perspectives of crab fishermen found here are similar to those of many small fishermen whose culture and livelihood depends on the Bay. As fish and shellfish become harder and harder to catch, aquaculture can be seen as a threat. Aquaculture products compete with their products on the market, which can drive down prices and subsequently the fishermen's revenue. Fishermen can also oppose aquaculture because they use space traditionally used for fishing and introduce a new and different culture to their communities (Knapp and Rubino, 2016). At the same time, fishermen are concerned about declining stocks threatening the longevity of their trade. Less people are joining the industry because the supply of fish isn't sufficient to maintain them. If fishing is lost entirely, the cultural knowledge and identity tied to the local fishing industry will be lost as well.

Finally, small fishermen are not the only ones operating in the Chesapeake Bay. Menhaden vessels are owned by large multinational companies. Menhaden harvest happens on a much larger scale than crabbing. Aircraft are used to spot school of fish from the air, and vacuum hoses suck thousands of fish onto ships across long voyages (Taylor and Daglaris, 2022). The corporations who own and control these vessels likely share similar concerns about aquaculture competition, but their perspectives and life experiences differ significantly from the small-scale fishermen living in coastal Virginia.

2.1.2. Fish and Shellfish Farmers

The national population of fish and shellfish farmers is incredibly diverse. The aquaculture industry includes a diverse range of species produced, rearing practices, and cultural backgrounds (Knapp and Rubino, 2016). 70% of aquaculture operations in Virgina are oyster farms (National Agricultural Statistics Service, 2019). Oyster farmers include ones who practice extensive culture (culture on the river bottom), and intensive culture (in cages or bags placed either on the bottom or suspended in the water column) (Beckensteiner et al., 2020). While other forms of aquaculture only developed in the United States in the last few decades, oyster aquaculture on private leases has been practiced in Virginia since 1899 (Grant, 2022). Other types of aquaculture in Virginia include production of hard clams and inland farming of fish like tilapia, trout, catfish, and bass (Grymes, 2022). Virginia leads the country in the production of hard clams, with most production taking place on the Eastern Shore (Virginia Farm Bureau, 2019; Virginia Institute of Marine Science, 2024b).

Fish and shellfish farmers are business owners, so their primary goal is to make a profit by selling their product. They likely care about reducing costs and improving efficiency to improve their profits. Farmers also take pride in their role in supplying food to their communities and contributing to the local economy. Shellfish aquaculture in particular is considered a “green” industry due to the ability of clams and oyster to filter nutrients and algae out of the water. Shellfish aquaculturists feel that their businesses are a win-win for the economy and the environment (Shellfish Growers of Virginia, 2024). Oyster farmers in the Chesapeake Bay come from a variety of backgrounds; some grew up working in the coastal communities they work in, while others left city jobs to pursue farming (Clarke, 2024; Mcadory, 2020). Indoor fish farmers are less integrated into the coastal community because their work occurs indoors and can often occur anywhere.

Aquaculture farmers of all types face barriers to expansion of production. Environmental groups and the media have historically portrayed aquaculture as less healthy and harmful to the environment (Amberg and Hall, 2008). Some aquaculture methods can cause environmental harm (eutrophication, overfishing of small fish for feed production). Innovation and shifting management practices over the last 30 years have allowed for the development of sustainable farming methods, but farmers who use sustainable techniques can still be affected by old prejudices (Knapp and Rubino, 2016). Aquaculture farmers also must compete with other stakeholders for space and generate public approval to be allowed to operate (Beckensteiner et al., 2020). Because aquaculture in the United States is a small and relatively new industry, it faces the burden of proving that projects will not be a problem, while older industries with strong lobbying groups (e.g. terrestrial farming) must show that the project will be a problem (Knapp and Rubino, 2016).

2.1.3. Regulators

Regulatory stakeholders include the Virginia Marine Resources Commission (VMRC), The Virginia Department of Environmental Quality (DEQ), Virginia Department of Agriculture and Consumer

Services (VDACS), Virginia Department of Wildlife Resources (VDWR), and US Army Corps of Engineers (USACE). The duties of each agency are described below.

Virginia Marine Resources Commission (VMRC)

VMRC oversees shellfish leases, aquaculture and fishing permits, and submerged land use. They have jurisdiction in navigable waters and wetlands statewide.

The Virginia Department of Environmental Quality (VDEQ)

VDEQ is responsible for controlling water pollution and regulating surface and groundwater resources. VDEQ manages the Virginia Pollutant Discharge Elimination System (VPDES) permits and water quality standards (Helfrich et al., 1993).

Virginia Department of Health, Division of Shellfish Safety (VDH, DSS)

The Virginia Department of Health Division of Shellfish Safety establishes and enforces regulations relating to sanitary practices for the handling, storing, packing, and distribution of shellfish and crabs. VDH DSS inspects and certifies shellfish sellers (also known as shellfish dealers) (Virginia Department of Health, 2021).

Virginia Department of Game and Inland Fisheries (VDGIF)

VDGIF has jurisdiction over inland freshwater fisheries. They oversee fishing and aquaculture production of freshwater fish species and import of non-native species.

Virginia Department of Agriculture and Consumer Services (VDACS)

VDACS is the lead agency for aquaculture development in the state. They do not issue permits, but they are responsible for ensuring that processing and packaging facilities are sanitary and comply with the Food and Drug Administration standards. VDACS can inspect fish processing facilities and products at any time. They also assist in aquaculture product marketing and in animal damage control at fish farms.

US Army Corps of Engineers (USACE)

USACE protects navigable waters, also known as Waters of the United States. They issue permits for activities occurring in streams and rivers including placing structures, dredging, and placement of fill material (Helfrich et al., 1993).

Each agency has a different primary mission. Some are entirely focused on environmental protection (DEQ), while others are focused on consumer protection (VDACS) or fisheries stock management (DWR). Opinions of regulators on aquaculture largely depend on the type of aquaculture being proposed and where it is being proposed. Regulators also have to respond to concerns from the public. If the public opposes issuance of an aquaculture permit, regulators are obliged to consider these comments in their decision. More details on the regulatory space are discussed in the “Rules” section below.

2.1.4. Consumers

Consumers drive the seafood industry through their purchases and preferences. Consumers include the general public, restaurant owners, and buyers for retail stores. Consumers generally prioritize price and quality when shopping for seafood, but many also care about sustainability and supporting local businesses. Consumers can be influenced by factors like production method, place of origin, and sustainability attributes on product labeling (Scheld et al., 2024). The expansion of aquaculture can increase the quantity of seafood available on the market, potentially decreasing prices for consumers. If consumers are supportive of aquaculture from an environmental and business perspective, decreased price of seafood could trigger increased demand and help to grow the industry (Lipton, 2008). Some studies have found that consumers prefer wild-caught over farm-raised seafood products (e.g. Davidson et al., 2012; Brayden et al., 2018), while others have found that consumers like both equally or even prefer farm-raised (Scheld et al., 2004).

2.1.5. Environmental Nonprofits

Environmental nonprofits are organizations whose missions are to protect and restore natural ecosystems. Some relevant environmental organizations in coastal Virginia include the Chesapeake Bay Foundation, Alliance for the Chesapeake Bay, Elizabeth River Project, James River Association, Lynnhaven River NOW, and Virginia Conservation Network. These organizations focus on the impact of human activities on ecosystems and populations of wild species. The organizations have different focus areas within the realm of environmentalism. For example, the Chesapeake Bay Foundation serves as a "watchdog" fighting for effective, science-based solutions to Chesapeake Bay pollution. Alliance for the Chesapeake Bay focuses on building relationships with people who live in the Chesapeake Bay watershed to prevent Chesapeake Bay pollution where it begins (Alliance for the Chesapeake Bay, 2024). Some organizations, like Lynnhaven River NOW and the Elizabeth River Project are focused on local-level environmental protection and restoration, so they only deal with a portion of the case study's system. Environmental nonprofits will likely take an "environment-first" perspective on aquaculture issues and be strong proponents for sustainable cultivation techniques (Chesapeake Bay Foundation, 2018). They may push for sacrificing immediate economic progress for the sake of long term gains in environmental condition.

2.1.6. Researchers

Old Dominion University and Virginia Institute of Marine Science are the leaders of research in fisheries and aquaculture in Virginia. Researchers approach aquaculture development from a scientific perspective. They study every aspect of seafood production, from fisheries stock management to breeding disease resistant oysters for aquaculture. Researchers tend to be passionate and incredibly knowledgeable about their work, but they do not necessarily have a personal stake in the success or failure of the aquaculture industry. Their degree of involvement with the community varies; some work in collaboration with other stakeholders, while others prefer to work in the isolation of academia.

2.1.7. Coastal Residents & Recreators

Coastal residents include homeowners of waterfront property and people who live in coastal communities that work or recreate in the water. Recreators can be coastal residents or people that come from other locations to do aquatic recreation activities in the Bay. Opinions of coastal residents about aquaculture are highly varied. While many may be supportive of the industry and the jobs it creates, many oppose it because they believe it interferes with other uses of public water resources. Conflict with oyster aquaculture in Virginia is common in heavily populated areas like the Lynnhaven River. This river is lined by expensive waterfront property, and many property owners believe the oyster cages are unsightly and potentially dangerous for recreational activities. Property owners also worry about oyster aquaculture decreasing property access and value (Beckensteiner et al., 2020).

2.1.8. Common Goals

While there are many differing opinions amongst stakeholders, multiple common goals were identified through the role-playing exercise (Table 1). All stakeholders generally support food production and maintaining a local seafood industry. All stakeholders are also supportive of small local businesses. Ultimately, all stakeholders desire a healthy Chesapeake Bay ecosystem that can support wild fisheries and farmed seafood.

2.2. Rules

Rules surrounding the seafood production space can be divided into three categories: ethical rules, socioeconomic rules, and regulatory rules. While regulatory rules are clearly outlined by regulatory agencies, ethical and socioeconomic rules are less tangible and are dependent on stakeholder opinions. The rules that make up the decision space are plotted in Figure 3 according to relevance to the issue and how much they influence the issue (leverage).

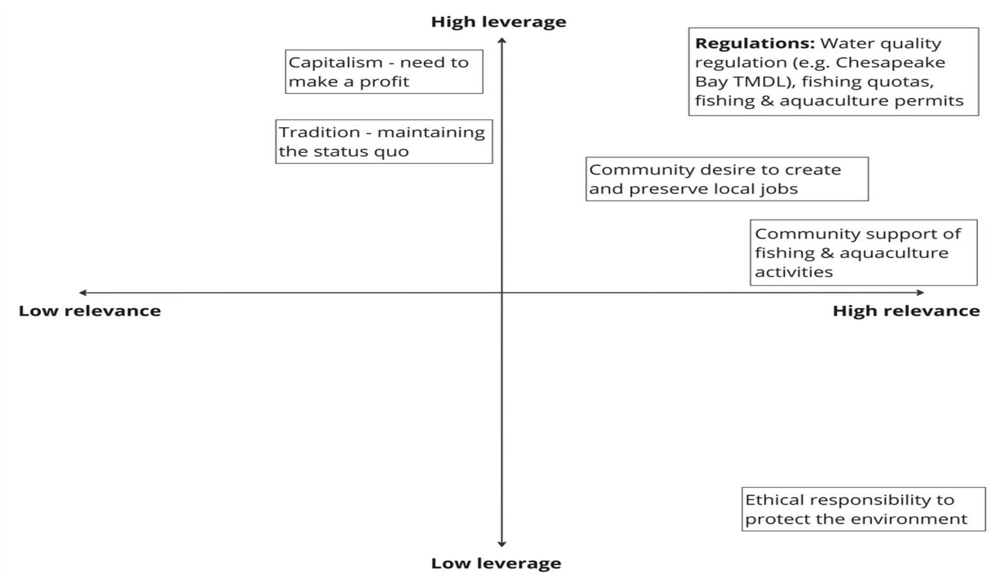

Figure 3: Rules decision space. This decision space encompasses regulations and social norms of the system that relate to the wicked problem. Rules are mapped according to leverage and relevance to the problem.

Ethical Rules

Some stakeholders believe we have an ethical responsibility to protect the environment, and this should be a priority when planning aquaculture operations. Other stakeholders put more ethical emphasis on supporting their families and communities by supplying food and income. They may also feel ethically inclined to protect the environment, but this comes second to providing for people. In figure 3, ethical responsibility is plotted in the "high relevance, low leverage" quadrant because ethics guide each person's action, but they are not necessarily tied to regulatory or monetary power.

Socioeconomic Rules

All seafood production operates within the structure of capitalism. The ultimate goals of all businesses are to make a profit and to grow. Ethical and regulatory rules are often put in place to serve as checks on this system, because the earth does not have resources to support unlimited growth. If a business were to prioritize environmental and ethical goals over making a profit, they would have a hard time surviving in the capitalist system.

Another social rule of sorts is the human tendency to want to do the same as others are doing (the bandwagon effect) and maintain the status quo. Change is uncomfortable because it invites risk. Status quo bias is a cognitive bias where people tend to keep doing the same things they've always been doing when change would invite a risk with an uncertain outcome (McShane, 2022). The bandwagon effect is the tendency of people to adopt certain behaviors or attitudes because they perceive that everyone else is doing it (Cherry, 2020). Status quo bias and the bandwagon effect can work together to make it very difficult for systemic change to happen. This does not mean that change is impossible, but biases must be considered when mapping a plan for change.

Regulatory Rules

Aquaculture operations must obtain permits and abide by laws and regulations. The types of permits needed depend on the type of aquaculture being performed, and where it is being performed.

Shellfish aquaculture operations (which are conducted in estuarine areas) are required to obtain an oyster ground lease from the VMRC. Additional permits are needed if the operator wants to grow shellfish in bags or cages suspended in the water column or at the surface. To harvest aquaculture products from an assigned lease, the operator needs an Aquaculture Product Owner's License and an Aquaculture Harvester Permit. If the operator wants to harvest shellfish off the bottom with a dredge or hand scrape, they need a dredge permit from the Marine Police Officer. Operators are required to report harvest through the Fisheries Management Divisions Mandatory Harvest Reporting Program. (Virginia Marine Resources Commission, 2023). If the proposed farm is located in federal navigable waters, a permit from the US Army Corps of Engineers will need to be obtained to protect navigation for commerce (National Oceanic and Atmospheric Administration, 2022). If an aquaculturist wants to sell their product directly to the public, they need to obtain a Certificate of Inspection from the Virginia Department of Health, Division of Shellfish Safety (VDH, DSS) (Virginia Department of Health, 2021).

Inland farms that produce seafood in ponds or tanks have different regulatory requirements. If they discharge wastewater to surface water (a stream, river, or bay), the operator needs to obtain a Virginia

Pollutant Discharge Elimination System permit from the Virginia Department of Environmental Quality (as part of the National Pollutant Discharge Elimination System established by the Clean Water Act) (Virginia Department of Environmental Quality, 2024). Construction of the facility may require a stormwater construction permit from VDEQ (Virginia Department of Environmental Quality, 2024b). If the operator wants to grow, transport, and sell certain types of freshwater fish (e.g., trout), they will need a Fish Breeders Permit from the Virginia Department of Game and Inland Fisheries. A VDGIF permit is also needed to import non-native species like tilapia and grass carp (Exotic Fish Importation and Culture Permit). A Hybrid Striped Bass Growers Permit is needed from VMRC if the operation wants to grow hybrid striped bass. (to prevent the escape and interbreeding of hybrid striped bass with wild striped bass) (Helfrich et al., 1993). Like shellfish operators, a Certificate of Inspection is needed from the VDH to sell their product (Virginia Department of Health, 2021).

2.3. Goal Statement

Our goal is to have an ample supply of domestically produced seafood and a healthy Chesapeake Bay ecosystem that can support sustainable fisheries and aquaculture in coastal Virginia.

3 Wicked Problem & Conceptual Model

3.1 The Wicked Problem

Wicked problems are social or cultural problems that are difficult or impossible to solve because of incomplete or contradictory knowledge, the number of people and opinions involved, the large economic burden associated with progress towards a solution, and the interconnected nature of these problems with other problems (Rittel and Weber, 1973). Seafood production in the Chesapeake Bay meets many of the requirements of a wicked problem as outlined by Rittel and Weber (1973). There is no clear right or wrong solution to addressing the problem of declining fishery stocks. Many stakeholders are involved, and as such there are a wide range of opinions on what to do about it. Some may desire for fishing to be completely replaced by aquaculture to give wild populations a chance to recover, while others would see this approach as an attack on their livelihoods and traditions. There is no rulebook that says some solutions are right while others are wrong. The problem of seafood production is also “wicked” because the characteristics of the problem are highly variable. Even within the relatively small area of coastal Virginia, there is no one solution that will work for every community. Suitable solutions will depend on local economies, ecosystem characteristics, and social perspectives. Planners must assess the needs of each community independently in collaboration with local stakeholders.

Ultimately, there is no way to produce food for human consumption without having some impact on the environment. This connects to another characteristic of wicked problems; the “no stopping rule.” Wicked problems are never truly solved. They require continuous management and adaptation. This is true of seafood production because the human population is growing, and demand for seafood (and food in general) is growing with it. Additionally, the environment is changing due to climate change, so the ecosystems that aquaculture and fishing are conducted in today will look very different in the future. Even if a solution is developed today that results in production of enough seafood to meet demand without stressing wild fisheries, the system will change and new solutions will need to be developed.

Another characteristic of wicked problems is that there is no immediate test to solutions. Despite our best modeling efforts, we cannot know for certain whether a chosen path will be successful or not. Scaling up aquaculture may produce unintended consequences. We are forced to learn what works by trial and error, and if a solution is bad, there could be serious consequences. Decision-makers who implement solutions today will be held liable for those consequences despite our limitations in being able to predict how they will pan out.

Finally, this is a wicked problem because it is a problem caused by humans, and humans are also the ones trying to fix the problem. The primary reasons that wild fish stocks are degraded are overfishing and pollution (Cronin, 1986; Schulte, 2017; Kemp et al., 2016). People have been aware that these activities are causing population declined for decades, yet we haven't figured out how to stop causing the problem. How can today's planners find a way to feed the population without further ecosystem degradation when multiple generations have tried and failed? To add to the challenge, this problem is intertwined with many other problems. Fishermen and farmers alike face unpredictability from climate change impacts, disease, supply chain issues, social unrest, and a myriad of other factors.

3.2. Understanding the System

The system considered in this case study geographically includes coastal Virginia and the portion of the Chesapeake Bay and its tributaries in or adjacent to the state of Virginia. The three main tributaries within the state of Virginia are the James River, the York River, and the Rappahannock River. Each of these rivers also has smaller tributaries (like the Elizabeth River in Norfolk) that ultimately feed into the Bay. Stakeholders and non-human elements that are involved with seafood production in this geographic area are all part of the system. Figure 4 displays a conceptual model of the system and the environment surrounding the system. The system is contained within the white inner oval, and the environment is represented by the larger blue oval. Stakeholders in the system are represented by purple boxes, physical non-human elements are represented by green boxes, and permits are represented by yellow boxes. (Permits are distinguished from non-human elements because they are social constructs instead of physical things.) Solid lines connect boxes when there are measurable flows of physical items or permits between elements of the system, and dotted lines connect boxes when only opinions or knowledge are exchanged between elements. Arrows indicate the direction of flow. Elements in the environment that influence the system are represented by text within the blue oval.

To understand system and its flows, we must first understand how seafood is produced through fishing and through aquaculture. From there, we can identify the stocks and flows associated with seafood production. The following sections provide a more in-depth description of how fishing and aquaculture are performed in Virginia, then examine flows within the system.

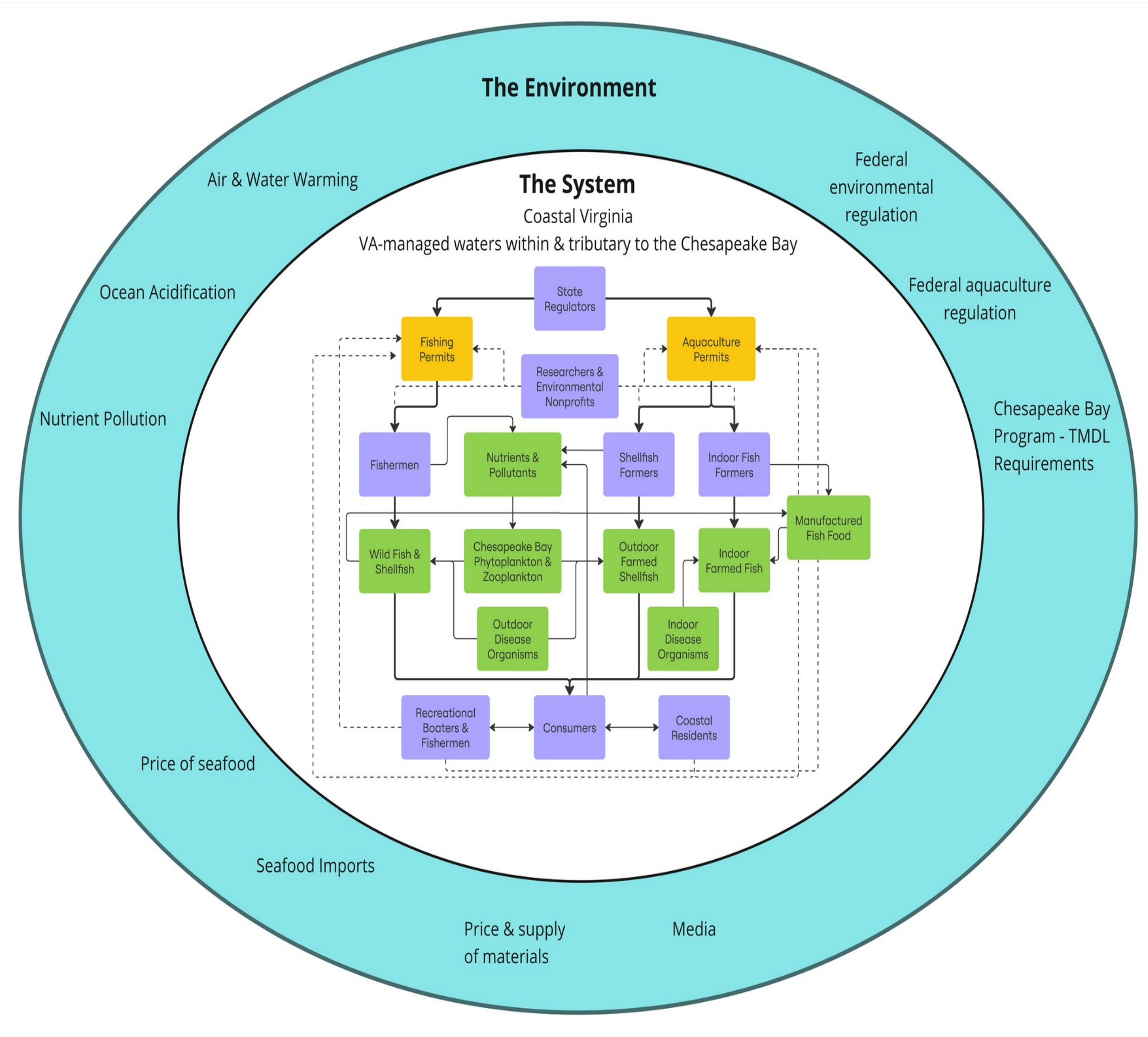

Figure 4: Conceptual model of the seafood production system in coastal Virginia and the southern Chesapeake Bay. Stakeholders are represented by purple symbols, non-human physical elements are represented by green symbols, and permits are represented by yellow symbols. The system of this case study is within the white oval, and the environment that the system exists in is represented by the blue oval. Elements of the environment that influence the system are written in the blue oval.

3.2.1. Fishing

Virginia watermen harvest 50 fish and shellfish species from the Chesapeake Bay. Among these species, in order of economic value, are oysters, blue crab, sea scallops, menhaden, clams, summer flounder, striped bass, spot, sea bass, and blue catfish. 90% of the seafood harvested in Virginia is harvested by small day boats (boats that leave port and come back within the same day) (Virginia Seafood, 2024). Part of the other 10% are large industrial vessels for fishing menhaden, primarily owned by Omega Protein, whose corporate headquarters are located in Reedville, VA. Omega Protein catches 90% of the nation's menhaden, a small pelagic fish that is processed into fish meal and fish oil

(Greenberg, 2009). There is tension between menhaden fishermen and local fishermen who target higher trophic level fish like striped bass. Menhaden are herbivorous fish that are food for many higher value carnivorous fish. Local fishermen believes that reduction of the menhaden population is causing declines in populations of the larger fish (Avery, 2022).

3.2.2. Aquaculture

There are two main types of aquaculture conducted in Virginia: outdoor shellfish aquaculture (primarily oysters and hard clams) and indoor finfish aquaculture. (There is a small amount of freshwater pond aquaculture conducted, but very limited information was found on this topic.)

Shellfish aquaculture dominates the industry. 70% of Virginia aquaculture operations are oyster farms, and Virginia is the nation's top producer of hard clams (National Agricultural Statistics Service, 2019; Virginia Seafood, 2024). Fish and shellfish can be cultivated using extensive methods or intensive methods. Extensive methods involve protecting cultivated species from predators and competitors with little to no enhancement of food supply. Intensive aquaculture involves producing fish in high density arrangements and providing most or all of the food needed by the cultivated species (Naylor et al., 2000). In extensive oyster aquaculture, oyster shell and seed are planted on the bottom of a waterway and allowed to grow with relatively little disturbance. The farmer harvests oysters using hand tongs, scrapes, rakes, dredges, or by hand. In intensive oyster aquaculture, oysters are grown in bags, racks, or cages located either on the bottom of the waterway or suspended in the water column (Beckensteiner et al., 2020). Hard clams are spawned in hatcheries, then are placed in mesh bags within bottomless cages on sandy sediments. Clams can bury in the sediment while still being retained within the bag for easy retrieval. Clams can also be planted directly on the bottom and protected from predators by nets or cages (Virginia Institute of Marine Science, 2024b; Virginia Farm Bureau, 2019). Both oysters and clams are filter feeders that derive their food from phytoplankton naturally occurring in the water. Through this process, they can remove nutrients and particulates from the water and improve water clarity. The Chesapeake Bay Program has designated oyster aquaculture as a "best management practice" due to the oysters' ability to clean the water. Watershed jurisdictions can get pollution-reduction credit for their oyster aquaculture industries (Smedinghoff, 2017). While farmers benefit from not having to feed their shellfish, the survival of their product is dependent on the environment. Changes in temperature and salinity, disease outbreaks, and harmful algal blooms can all affect the health and survival of the shellfish.

Indoor finfish aquaculture is less prevalent in Virginia than shellfish aquaculture, but it is conducted. Facilities produce freshwater fish including tilapia, trout, largemouth bass, and catfish. (It should be noted that all of the facilities I found information for are outside of coastal Virginia, but they are relevant because they work within the same state regulatory system and produce seafood that is sold throughout the state.) The largest fish farming facility in Virginia is Blue Ridge Aquaculture, located in Henry County. This facility farms tilapia indoors using a recirculating aquaculture system. Fish are fed with a corn and soybean based feed. Wastewater from fish tanks is processed to remove nitrogen and fish poop, re-oxygenated, and recirculated through the tank system. Waste is sent to the Martinsville wastewater treatment plant on the Smith River. Blue Ridge Aquaculture is a vertically integrated system; they produce feed, spawn fish in their nursery, and grow out fish to market size (Blue Ridge

Aquaculture, 2024). Graham Bass Fish Farm uses a similar recirculating system to grow largemouth bass, rainbow trout, and channel catfish. The farm also sells fertilizer produced from their fish waste (Graham Bass Fish Farm, 2018). Pure Salmon, an Abu Dhabi-based company, is in the process of constructing a recirculating aquaculture facility for salmon production in Tazewell County in Southwest Virginia. It is expected to open in 2028. When it is complete, the facility is expected to produce 10,000 tons of salmon annually. The facility will demand 300,000 to 400,000 gallons of water per day. Water and sewage services will need to be managed through improvements in the Tazewell County infrastructure (Cameron, 2024). On a smaller scale, some farmers raise freshwater fish in-ground farm ponds. Examples of fish raised in these systems are catfish, hybrid striped bass, and tilapia. Fish can be grown directly in shallow ponds, in cages within deep ponds, or in long concrete raceways (Virginia Tech, 2024). Extensive or intensive aquaculture methods can be used.

All recirculating aquaculture facilities and intensive pond aquaculture require fish to be fed with manufactured feeds. These feeds have historically contained large quantities of fish meal and fish oil produced from small pelagic fish like menhaden. This is especially true for carnivorous fish that cannot produce their own omega-3 fatty acids (Naylor et al., 2000). Fish meal and fish oil's inclusion in feed raised concerns about aquaculture exacerbating over-fishing of low trophic level species for the sake of farming higher value fish for sale. The NOAA-USDA Alternative Feeds Initiative is working on identifying alternative ingredients for fish feed that can meet the dietary needs of fish while maintaining the nutritional value of seafood. The quantity of fish meal and fish oil for carnivorous fish have been reduced over the last three decades, being replaced by ingredients like plant protein, oil from algae, and marine microbes (NOAA Fisheries, 2018).

Indoor fish farming operations are more controlled than outdoor shellfish aquaculture, but they do have other challenges. They must compete for land and water with other uses, and they are responsible for managing any waste they produce. Even a recirculating system will produce some waste in the water purification process.

There is a notable lack of marine finfish aquaculture in Virginia. In other parts of the world, fish are raised in net pens in coastal waters. This method would be challenging in the Chesapeake Bay due to conflicts with fishermen and navigational hazards. It would also raise concerns about nutrients from fish feeds adding to nutrient pollution and eutrophication problems in the Bay. The Institute of Marine and Environmental Technology (IMET) in Baltimore is working on developing techniques for cultivating non-native marine fish like European seabass and Mediterranean seabream in indoor recirculating aquaculture facilities. Non-native species were chosen for cultivation to avoid competing with local wild-caught fish. IMET is also working on developing ways to cultivate blue crabs in captivity (Kobell, 2018). Blue crabs are difficult to cultivate because they are cannibalistic and tend to prey on fellow crabs who have just molted (Donnelly, 2009). Research is being done to synchronize molting of blue crabs in captivity to reduce losses (Kobell, 2018).

3.2.3. Stocks and Flows

This case study's system can be understood as a series of interconnected stocks and flows. In figure 4, stocks are represented by boxes and flows are represented by solid lines.

Stocks of wild fish flow from natural ecosystems to consumers through the intervention of fishermen. The rate of flow of fish depends on the number of fishermen, fishing effort, and quotas for allowable catch. If stocks are overfished, the size of stocks and the rate of flow decreases. Flow is also influenced by consumer demand. If consumers indicate fishermen that their product is in high demand, they will apply more fishing effort and the number of fishermen will increase.

Stocks of wild fish are also influenced by the flow of nutrients and pollutants from the Chesapeake Bay watershed to the Bay and its tributaries. Stocks of nutrients and pollutants are generated in farms, sewage treatment plants, and natural sources. These stocks flow into the Chesapeake Bay through stormwater and point source discharges. Introduction of nutrients to the Bay can trigger blooms of phytoplankton, including both beneficial and harmful species. Herbivorous fish and filter feeding shellfish feed on phytoplankton, so higher stocks of plankton can lead to higher stocks of fish. However, if there is an overgrowth of phytoplankton, there is too much stock for fish to consume and access plankton die and decompose. When this happens, the decomposition process consumes oxygen from water and produces dead zones that can kill fish, thereby reducing fish stocks. Also, if harmful algae bloom as a result of nutrient input, they can produce toxins that kill fish (reducing stock). Flows of pollutants can also harm fish species and have a reducing effect on the fish stocks. The stock and flow relationship between nutrients and pollutants, plankton, and fish is non-linear due to these complexities. Finally, when fishermen remove fish from the ecosystem, they also remove nutrients and transport them back to land.

In aquaculture systems, the stocks of fish are intimately controlled. Farmers acquire stocks of fish feed, feed them to the fish (the flow), and stocks of fish increase. The production of fish feeds involves flows of stocks of small wild caught fish, corn, soybeans, algae, and microbes to manufacturing facilities, then to aquaculture farmers. Fish produced through aquaculture flow through the farmer to the consumer. The fish feed contains nutrients that are transferred into the fish and then into the consumers when they eat the fish. Consumers release nutrients through sewage, and some of those nutrients end up in the Chesapeake Bay with wastewater treatment plant discharge. (The same is true of consumers eating wild-caught fish.) Nutrients are also released in fish excretions. Aquaculture farmers are responsible for managing this waste. If they do not, and the waste is released into waterbodies, it can result in nutrient pollution and eutrophication. This leads to a potential feedback loop; eutrophication caused by nutrient pollution from aquaculture can damage wild fish populations, which decreases seafood supply from fishermen and increases demand for aquaculture.

Finally, the regulatory system within which fishing and aquaculture operate involves flow of permits and leases from regulators to fishermen and farmers. The number of permits available is influenced by physical stocks including wild fish populations, water availability (for aquaculture), nutrients, and fish feed availability.

3.2.4. Influence of the environment

The environment is everything outside of the system. Influences of the environment on the system range from regional to global mechanisms. On a regional level, nutrients and pollutants from the entire Chesapeake Bay watershed flow into the lower Chesapeake Bay adjacent to Virginia. From a policy perspective, fishing and aquaculture in the Bay is influenced by requirements of the Chesapeake Bay

Total Maximum Daily Load (TMDL) regulatory document. The TMDL is implemented by the Chesapeake Bay Program, which operates on a regional level with all of the states in the Chesapeake Bay watershed. On a national and global level, seafood production is influenced by the price of seafood (dictated by the market) and the price and availability of materials needed for fishing and aquaculture. The sale of seafood is influenced by the portrayal of seafood and seafood production practices in the media. Seafood is also imported into the system from national and international producers, which can affect demand for seafood produced within the system. Finally, the system is influenced by the impacts of climate change. Climate change causes increasing air and water temperatures and ocean acidification that can affect the survival of wild fish populations and the success of aquaculture operations. Impacts of climate change will be discussed further in the hazards section.

4 System Fragilities

The Chesapeake Bay and coastal Virginia have numerous fragilities that make the system more susceptible to hazards and threats. Here, I discuss fragilities related to fishing and aquaculture that shape the current state of the system and potential for future management efforts.

4.1. Environmental Fragilities

Life Requirements of Fish and Shellfish

Fish and shellfish have fragilities related to their life requirements. Fish and shellfish all need to eat. They need oxygen at different levels depending on the species. They need habitats to live in that provide sufficient space and protection from predators. Some species need to migrate between habitats at some point in their life. If fish and shellfish are raised by people outside of their natural habitats, people need to provide replacement habitats that meet the same needs. Fish and shellfish are also susceptible to disease.

Structure of the Chesapeake Bay

The geological and hydrological structure of the Chesapeake Bay is another fragility. The Bay is almost 300 km long with a deep (20 to 30 m) and narrow (1 to 4 km) central channel surrounded by shallow areas and a sill confining the deep channel at its seaward end. Circulation patterns in the channel are largely controlled by flow from the Susquehanna River and tidal forcing. High winter and spring flows from the Susquehanna cause summer stratification, which isolates deep channel waters. There is also a tidally driven counterflow in the lower layer of the estuary that retains particulates and dissolved materials in the Bay. The structure of the Bay is a fragility because it is inherently more susceptible to eutrophication and anoxia. The counterflow creates a long residence time for freshwater and nutrients of 90 to 180 days. The combination of stratification and a long residence time creates a system with most nutrient inputs retained within the Bay and a tendency for oxygen depletion in deep waters. The Bay also has a large watershed area relative to its estuarine water area (14.3 m-1). Nutrients produced by human activities in this large watershed area all end up in the Bay (Kemp et al., 2005). This fragility is relevant to fisheries and aquaculture because eutrophication and anoxia can negatively impact both wild and farmed species of fish and shellfish. These hazards will be discussed further in the hazards section.

Lack of Oyster Reefs – Keystone Species

The Chesapeake Bay's lack of oyster reefs is an ecosystem fragility. Oysters are a keystone species in the Bay, and without them the Bay is significantly less resilient to hazards. As was discussed in the introduction, overfishing has nearly eradicated natural oyster reefs in the Chesapeake Bay. Wild oyster stocks are 1% of pre-industrial abundance (Cronin, 1986; Kemp, 2005). As a result, oyster reefs have significantly reduced filtering capacity in the Bay, leading to increased settling of dead phytoplankton, increased bacterial respiration of phytoplankton organic matter, and anoxia (Rothschild et al., 1994). The Chesapeake Bay's 19th-century oyster population was capable of filtering the entire volume of the upper and middle Bay in 3.6 days. The current wild oyster population takes around 700 days the filter the same amount of water (Newell, 1988). The Virginia Institute of Marine Science has found that an acre of oyster reef can remove 500 lbs of nitrogen from the water each year (Sandi, 2024). To get an idea of how oyster reef destruction affects nitrogen removal, we can look at historic surveys of the Lighthouse Bar oyster reef in the Choptank River (tributary to the Chesapeake Bay). In 1913, the Lighthouse Bar oyster reef was 292.3 hectares. By 1990, it had decreased to only 139.3 hectares (48% of it's original size) (Rothschild et al., 1994). If 500 lb of nitrogen is removed per acre of reef (and 1 hectare = 2.47 acres), the 1913 reef was able to remove 722 lbs of nitrogen per year. The 1990 reef could only remove 344 lbs of nitrogen per year, meaning 378 lbs of nitrogen remained in the water column where it could fuel eutrophication.

In addition to affecting water quality, the lack of oyster reefs also negatively affects other species. Oyster reefs create habitat for diverse populations of invertebrates and fish. Juvenile crabs have a 3 to 4 times better chance of surviving predators on oyster reefs than they do on sandy bottoms (. While the overfishing that caused oyster reef destruction is a hazard, the current lack of reef area in the Chesapeake Bay is a serious fragility that affects the Bay's fisheries and susceptibility to nutrient pollution (NOAA Fisheries, 2020).

4.2. Infrastructure Fragility

The fourth fragility is related to the human component of fishing and aquaculture. Due to the aquatic nature of fishing and shellfish farming in Virginia, facilities and infrastructure that supports these activities are located in coastal areas. Fishing vessels are supported by ports, processing facilities, and distribution lines. Oysters and clams are grown in coastal and estuarine areas that are accessed by coastal roadways. Generally, people who work in fishing and aquaculture also live in coastal communities. The dependence of fishing and aquaculture on coastal infrastructure is a fragility because coastal areas in Virginia are threatened by sea level rise and the impacts of extreme storms. Many coastal communities in Virginia are economically dependent on seafood production. The dependence of seafood production on coastal infrastructure makes both the physical infrastructure and the prosperity of coastal communities vulnerable.

4.3. Economic Fragility

The success of aquaculture operations is dependent on economics. Farmers have to pay for permits and leases, labor, and materials like feed and cages. The market price of seafood also fluctuates depending on availability and consumers' willingness to pay. If the margin between revenue and cost is too small, the business will fail. The need for aquaculture operations to be profitable in order to continue supplying food to the community is a fragility. Aquaculture farms exist within a capitalist system that is controlled by a variable free market (Fidelity International, 2024). That means that economic, rather than environmental, pressures can sometimes be the limiting factor in seafood production.

5 Current and Future Hazards and Threats

Hazards to seafood production in the Chesapeake Bay include internal (within the system) and external (outside the system) hazards. Table 2 describes worst, medium, and best case scenarios for each of the system hazards and relates them to the relevant fragilities.

5.1. Internal Hazards

5.1.1. Overharvesting

Overharvesting is the number one hazard that has caused decline of wild fish populations. For decades, people have removed more fish from the Chesapeake Bay and its tributaries than wild populations are able to replace. While oysters and fish have also been faced with other hazards like disease and eutrophication, overharvesting is the overwhelming driver of species decline (Cronin, 1986; Kemp et al., 2005). In fact, when oyster diseases were first identified in the 1950s, the state responded by allowing fishermen to take even more oysters than usual so they could harvest them before they died from disease. This exacerbated the already rapid decline of wild oyster populations (Schulte, 2017). Overharvesting was able to occur at such a rapid rate due to technological advancements that allowed for higher yields with less effort. For example, oysters were originally harvested by hand or with tongs that target a small area at a time. Dredges started being permitted for oyster harvest in the mid-19th century. These devices scrape along the bottom of the river, collecting large numbers of oysters and destroying the reef ecosystem in the process (Cronin, 1986). Menhaden fishing uses planes to spot schools of fish that are captured with purse seine nets. These massive nets can harvest entire schools of fish at once, and anything else that gets caught up in them (Cronin, 1986).

Scientists have been warning regulators and fishermen for over a century that fish are being harvested at unsustainable rates. Despite this, regulations have not been successful at reducing fishing rates. Harvesting as much as possible is economically profitable in the short-term as long as consumer demand exists. Regulations have often taken a short-sighted approach to regulating harvest; prioritizing maintaining the industry over long term population health. The response to oyster disease in the 1950s is a prime example of this. Rather than shutting down harvest to put less pressure on the oyster population in the face of another stressor, regulators prioritized maintaining the industry by harvesting as many healthy oysters as possible. The worst case overfishing scenario will occur if fishing continues without any harvest limits until populations completely collapse. The graph in figure 5 displays an example of fish population collapse. Global capture of sturgeon declined rapidly in the 1980s due to overfishing (McGregor Reid et al., 2013). Chesapeake Bay fish populations are at risk of following the same trajectory. The best case scenario will occur if harvest is reduced to sustainable levels that allow population regeneration (Table 2).

Table 2: Hazards, fragilities, and hazard scenarios of the system. Hazard scenarios were developed based on relevant data and models.

Hazards		Fragilities	Worst Case Scenario	Middle Case Scenario	Best Case Scenario
	Overharvesting	Fish and shellfish need sufficient population density to reproduce. Fish are susceptible to predation, including by humans.	Wild fish and shellfish are harvested without effective limits until all populations pass the tipping point and experience total population collapse. The fishing industry ceases to exist. The Chesapeake Bay doesn't have enough spawning stock to rebuild wild fish populations. With no more fish in the water, the Bay experiences total ecosystem collapse. Algae blooms worsen and larger aquatic organisms that feed on fish disappear.	Harvest of wild fish continues as it is now. Populations fluctuate between being threatened and regaining numbers as regulators attempt to set quotas that allow for the industry to continue operating without eradicating wild species.	Harvest is reduced to sustainable levels that allow regeneration of wild populations. (These levels are dependent on species.) Aquaculture supplements wild seafood so consumption of seafood does not have to decrease.
	Disease	Fish and shellfish are susceptible to disease.	MSX and Dermo increase in severity in the Chesapeake Bay, partially as a result of rapidly increased water temperature and long drought periods. The wild oyster population is completely decimated and oyster aquaculture is no longer feasible.	MSX and Dermo are a consistent but manageable threat in the Bay. Slowly increasing global temperatures increase water temperature in the Bay and increase the frequency of drought periods (and corresponding periods of high salinity). Aquaculture and reef restoration continue at a similar rate to today. Die-offs due to disease occur periodically.	Climate stabilizes because humanity has transitioned to renewable energy sources. MSX and Dermo still exist in the Bay, but farmers are able to continue aquaculture using adaptive measures (farming at lower salinities, using selectively bred oyster stock, etc.). Wild oyster stocks are enhanced by reef restoration and reduced harvesting, and they evolve to be disease resistant.
	Nutrient Pollution	The structure of the Chesapeake Bay leads to a long water residence time. The lack of oyster reefs reduces water circulation. Fish require oxygen and are susceptible to anoxia caused by eutrophication.	Nutrient pollution increases in the Chesapeake Bay watershed to 550 million lbs of N and 50 million lbs of P per year (maximum discharge observed over the last 20 years). Eutrophication and anoxia worsen and fisheries reach the third stage of eutrophication-driven population decline (Caddy, 1993, 2000). Fishing is no longer possible in the Chesapeake Bay and dissolved oxygen concentrations in many locations are too low for oyster aquaculture.	Total nitrogen and phosphorus loads to the Chesapeake Bay match the 1985-2020 averages (204 million lbs of N / yr, 12.07 millions lbs of P / yr). Eutrophication and dead zones maintain the current frequency, with bottom-water anoxia occurring every summer.	Total nitrogen and phosphorus loads to the Chesapeake Bay meet the TMDL limit. They are consistently less than 185.9 million lbs of N and 12.5 million lbs of P. The Chesapeake Bay is given the chance to recover. Eutrophication and dead zones become less common.
Climate Change	Sea Level Rise	Communities and businesses are dependent on coastal infrastructure. Infrastructure is not built to be able to move, so it is susceptible to flood damage.	The AMOC shuts down, and sea level rises 3 m by 2100 (1 m above projected values) (Mulhern, 2020). Many coastal communities are no longer inhabitable. Most wetlands are lost.	Sea level rises at a rate of 8 mm/yr. By 2050, sea level will rise 20.8 cm and nuisance flooding will occur in Norfolk for 54 days per year (Ezer and Atkinson, 2015). By 2100 sea level will rise 61 cm. Residents have to retreat from shoreline properties and a large portion of wetlands are lost.	Sea level rises at a rate of 4 mm/yr. By 2050, sea level will rise 10.5 cm and nuisance flooding will occur in Norfolk for 21 days per year (Ezer and Atkinson, 2015). By 2100, sea level will rise 30.5 cm. Some residents have to retreat from shoreline properties or adapt infrastructure to be able to withstand flooding. Wetlands are allowed to migrate in some areas so wetland area remains the same.
Climate Change	Water Temperature Increase	Fish and shellfish have temperature ranges that they can survive in. They cannot adapt quickly enough to match the rate of global warming.	The Chesapeake Bay warms 6° C. Warm water tolerant species take over, and many cold-temperate species are lost. Aquaculture farmers have to raise warm-water tolerant species or do indoor farming.	The Chesapeake Bay warms 3° C. The population shifts towards warm-tolerant species, with cold-temperate species only surviving in waters that are deep enough to be cold, but not too deep to be anoxic.	Human society stops using fossil fuels and global temperatures remain at current levels. Chesapeake Bay fish populations adapt to current temperatures and pH.
Climate Change	Ocean Acidification	Oysters require a basic pH environment to calcify their shells and reproduce.	pH in the Chesapeake Bay falls below 7.2. Oyster reproduction is disrupted and the wild population collapses (Boulais et al., 2017). Oyster aquaculture is no longer profitable because oysters cannot grow and reproduce successfully. The oyster industry ends in the Chesapeake Bay.	pH decreases to 7.6 and carbonate ion concentration decreases by 45% by 2100 (as projected by the IPCC A2 storyline). Oyster growth declines significantly and oyster aquaculture becomes rare in the Chesapeake Bay.	Ocean pH remains at 8.1 and carbonate ion concentrations remain at present day values. Oyster aquaculture and reef restoration expand, and both wild and farmed populations increase in numbers. Water quality improves as a result.

Figure 5: Decline of global sturgeon capture due to overfishing (McGregor Reid et al., 2013)

5.1.2. Disease

Two diseases, MSX and Dermo were first identified in Chesapeake Bay oysters in the 1950s (Kemp, 2005). Both diseases cause oyster mortality but are harmless to humans. The combined impact of MSX and Dermo has caused hundreds of millions of dollars in losses over the last 40 years in mid-Atlantic states (Ewart and Ford, 1993). Since oyster aquaculture occurs in estuarine environments, these diseases threaten both wild and farmed populations of oysters.

MSX is caused by the protozoan parasite Haplosporidium nelsoni. (It was named MSX because it was originally observed as a Multinucleated Sphere with unknown affinity (X).) It infects oysters through the gills (indicating that the infective stage is water-borne) and can kill them within two to three weeks. H. nelsoni produces spores in late June through early July and in the autumn. It is believed that the spores are infective to an intermediate host (currently unknown) that transfers infection to oysters. Chesapeake Bay oysters become infected from mid-May through October (Virginia Institute of Marine Science, 2024c). Infection with H. nelsoni is more common at high salinities (about 15 ppt) and is rare at salinities below 10 ppt (Barnegat Shellfish, LLC, 2022). Temperature also plays a role in regulating MSX. Infections are acquired at temperatures about 20° C. At this temperature resistant oysters can overcome the parasite, while susceptible oysters are killed. Between 5-20° C, the parasite proliferates in infected oysters faster than they can control it. Both the parasite and oyster are inactive below 5° C (Virginia Institute of Marine Science, 2024c).

Dermo is caused by the protozoan parasite Perkinsus marinus. (It was originally thought to be caused by a fungus that was named Dermocystidium marinum. This has since been corrected, but the name stuck.) Dermo is highly infectious and can be transmitted directly from oyster to oyster. Infections typically occur between July and October (Virginia Institute of Marine Science, 2024). Dermo causes degradation of oyster tissue and can take up to three years to kill an oyster. After two to three years of exposure to Dermo, a 40-90% decrease in growth is usually observed in infected oysters prior to mortality (Barnegat Shellfish, LLC, 2022). A new strain of Dermo developed around 1986 that was significantly more virulent and capable of killing oysters within months of infection. The infectiousness of Dermo increases at higher temperature and salinity (Virginia Institute of Marine Science, 2021). Infections intensify about 20° C and salinity above 12-15 ppt (Virginia Institute of Marine Science, 2024). Since both MSX and Dermo are more lethal at high salinity, their impact is tied to climate. Higher temperatures and drought can increase the salinity of the Bay.

Diseases that threaten farmed finfish depend on the environment they are grown in. Diseases common in recirculating aquaculture facilities are commonly parasites with direct life cycles and bacterial and viral diseases. They can spread quickly in these systems because fish are grown in high densities and water is recirculated through the system by definition. Examples of RAS parasites include Icthyophthirius multifiliis ("ich"), Cryptocaryon irritans ("salt water ich"), and Amyloodinium (marine velvet disease). Bacterial and viral diseases can propagate because microbial flora is less diverse than in natural systems. Examples are mycobacteriosis and streptococcosis. Warm water temperatures, low dissolved oxygen, low pH, high soluble zinc, high fulvic acid, and high humic acid can all promote mycobacterial growth. All of these conditions can be present in RAS systems (Yanong et al., 2021).

Freshwater ponds used for aquaculture are high in organic material due to accumulation of feed, fish, and fish waste. As a result, they are susceptible to parasites that favor high organic environments like sessile ciliates (Heteropolaria/Epistylis, Apiosoma, Ambiphyra), trichodinids (Trichodina, Tripartiella), and Tetrahymena. Fish in freshwater ponds are also susceptible to infection by metazoan parasites with indirect life cycles (meaning the parasites have different final and intermediate hosts) because the ponds support multiple species (birds, snails, etc.). Bacterial diseases like Edwardsiella ictalurid and Streptococcus and viral diseases can also occur in ponds, and are very difficult to control once they break out due to logistical challenges of pond disinfection (Yanong et al., 2021).

Table 2 outlines hazard scenarios for oyster diseases in the Chesapeake Bay. None of the hazard scenarios for disease involve complete eradication. Disease will be present in the ecosystem no matter what, but the severity of its impact on fisheries and aquaculture will depend on climate change and management activities. In the worst case scenario, climate change will cause rapidly increasing water temperature and long drought periods. This will create warm, high salinity conditions that let MSX and Dermo thrive. In the best case scenario, climate stabilizes and farmers develop adaptive management techniques that mitigate disease impacts.

5.1.3. Nutrient Pollution

Nutrient pollution is both an internal and external hazard in the system. The whole Chesapeake Bay watershed is connected to the lower Bay that is adjacent to coastal Virginia. Nutrients primarily come from agriculture. They can also come from septic systems and wastewater treatment plants (human sewage), nitrous oxide deposition, and natural environments. The primary nutrients of concern are nitrogen and phosphorus (Chesapeake Bay Program, 2024b). The Chesapeake Bay is a nitrogen-limited system, so nitrogen inputs are the primary culprit for triggering algal blooms and eutrophication.

Nutrient pollution in the Chesapeake Bay fluctuates based on management activity and rainfall. The mean annual total nitrogen load from 1985 to 2020 is 204 million pounds, and the mean annual total phosphorus load is 12.07 million pounds (Faunce, 2023). Significant spikes in loading occur in years with above average rainfall (Figure 6) (Chesapeake Bay Program, 2024b). The Chesapeake Bay Total Maximum Daily Load sets an annual total nitrogen load limit at 185.9 million lbs and an annual total phosphorus load limit at 12.5 million lbs. Loads must drop below this number to maintain a healthy ecosystem (United States Environmental Protection Agency, 2010).

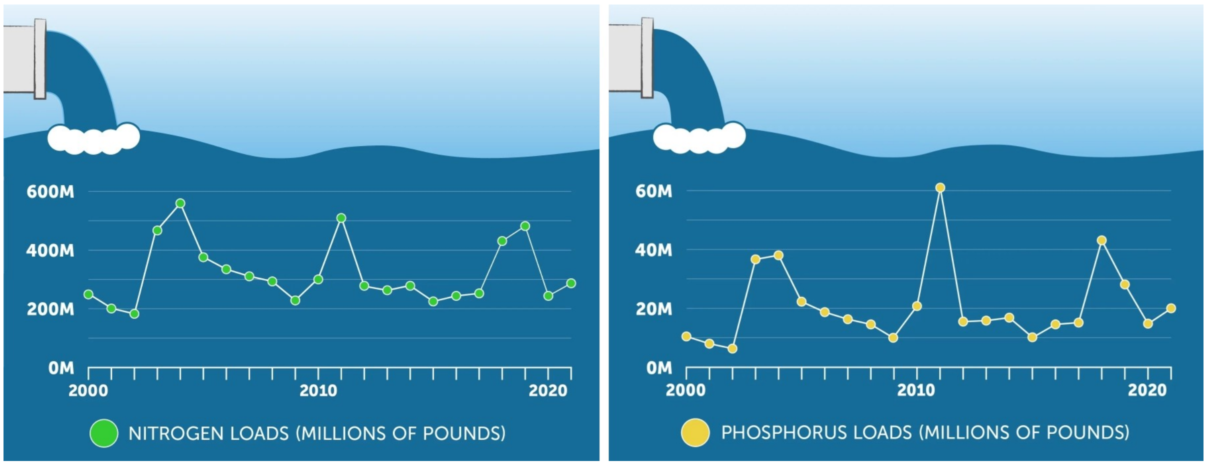

Figure 6: Total N and P loading to the Chesapeake Bay (Figure credit: Chesapeake Bay Program, 2024b. Data provided by the US Geological Survey.)

According to Caddy (1993, 2000), eutrophication affects fish communities in a sequence of three stages. First, the added supply of algae promotes enhanced production of demersal (bottom-dwelling) and pelagic (water column) fish species. Second, the ecosystem experiences a decline of demersal fish but continued increase in pelagic fish due to benthic habitat loss. Third, the ecosystem experiences a decline in total fish production due to deteriorating water and habitat quality (Caddy, 1993, 2000). This sequence has been observed in the Chesapeake Bay. Fisheries landings are now dominated by menhaden, a pelagic species. Long-term increase in menhaden production has likely been stimulated by nutrient loading. The ratio of landings of pelagic to demersal fish has increased from 1.9 in the 1960s to 2.66 in the 1990s. Commercial landings of demersal fish species has declined from 34.4% to 27.3% over the same time period, correlating with increase in menhaden landings (38% in the 1960s to 67% in the 1990s). Landings of demersal blue crab and oysters have also declined. There is limited evidence that the Bay may now be entering the third phase (harmful algal bloom-induced fish kills, hypoxic events, fish lesions) (Kemp et al., 2005).

While fish communities have been following the pattern of eutrophication impact, declines in landings of some species and increases in others are also very tied to shifts in fishing patterns and markets. Landings are largely dependent on fishing effort and efficiency. The combined effect of multiple hazards (like overfishing and eutrophication) must be taken into account when assessing impacts.

The worst case hazard scenario presented in Table 2 will occur if average annual nutrient loading is 550 million lbs of N and 50 million lbs of P, the maximum loading observed in the last 20 years (Figure 6). Severe eutrophication and anoxia will be a constant feature of the bay, and fisheries will reach the third stage of eutrophication-driven population decline. The best case scenario will occur if nutrient loads are reduced to meet the TMDL limit (185.9 million lbs of N, 12.5 million lbs of P). In this scenario, pelagic phytoplankton production will decrease and dead zones will become less common.

5.2 External Hazards

5.2.1. Climate Change

Climate change is a hazard to aquaculture in Virginia due to changes in sea level, air and water temperature, ocean pH, and precipitation patterns that occur as a result of rising global temperatures. Air temperatures in the Chesapeake Bay watershed have increased between 0.2 and 1.4° C over the last century and the average water temperature in the Bay has increased by 1° C. By the end of the 21st century, the Chesapeake Bay region will experience a 50 – 160% increase in CO_2 concentrations, 0.7 – 1.6 m increase in sea level rise, and 2-6° C increase in water temperature (Najjar et al., 2010).

Sea Level Rise

Global sea level rise is being driven by climate change due to warm water expansion and ice sheet melting. The rate of sea level rise on Virginia's coast is one of the highest in the United States at 4-6 mm per year. (The global mean sea level rise rate is 1.7 mm per year.) This rate is accelerating. The rate of sea level rise is especially high in coastal Virginia due to a combination of low coastal elevation, land subsidence (caused by Glacial Isostatic Adjustment and groundwater extraction), and weakening of the Atlantic Meridional Overturning Circulation (AMOC). Coastal Virginia is experiencing an increase in minor tidal flooding, and increased risks from major storm events (Ezer and Atkinson, 2015).

Sea level rise poses a threat to fisheries and aquaculture because it will trigger flooding of coastal communities and loss of structured habitats. Structured habitats like wetlands and marshes serve as habitat for fish and shellfish populations. Coastal flooding damages infrastructure that is needed to produce, transport, and sell aquaculture products. It can also lead to increased pollution of estuarine waters. Macías-Tapia et al. (2021) demonstrated that a single tidal flooding event in the Lafayette River, a sub tributary of the Chesapeake Bay, could deliver more nitrogen and phosphorus than was allocated for the entire year by the TMDL (Macías-Tapia et al., 2021).

Figure 7 maps projected sea level in 2100 around the Lafayette River (a sub-tributary of the Chesapeake Bay in Norfolk, VA) for each of the three hazard scenarios presented in Table 2 (NOAA, 2024). The best case scenario (Figure 7, left panel) will occur if sea level rises at a conservative rate of 4 mm/yr. By 2100, sea level will rise 30.5 cm. The middle case scenario (Figure 7, middle panel) will occur if sea level rises at 8 mm/yr. By 2100, sea level will rise 61 cm (Ezer and Atkinson, 2015). The worst case scenario will occur if the AMOC shuts down (Figure 7, right panel). This will likely lead to 3 m of sea level rise by 2100 (Mulhern, 2020). None of the scenarios involve sea level staying the same, because climate change is guaranteed to continue no matter what happens in the system. Figure 7 shows that the best and middle case scenarios would flood some coastal areas around the Lafayette River, but most of the river's watershed would still be habitable. The worst case scenario would cause severe inundation of the city of Norfolk around the Lafayette River and the city would be uninhabitable.

Figure 7: Projected sea level rise in Norfolk, Virginia around the Lafayette River. The left panel corresponds to the best case hazard scenario (30.5 cm), the middle panel corresponds to the middle case scenario (61 cm), and the right panel corresponds to the worst case scenario (3 m). Images generated using the NOAA Sea Level Rise Mapper (NOAA, 2024).

Increased Water Temperature

Increased water temperature has a complex impact on aquaculture and fisheries. Fish species response to rising temperatures will be dependent on the temperature ranges they are adapted to. Warm-water species like southern flounder, cobia, and Spanish mackerel will thrive under warmer water conditions, while cold-temperate species like yellow perch, striped bass, and soft clam will struggle. Increased winter temperatures may benefit some species by extending the growing season and decreasing mortality of overwintering juveniles (e.g. blue crab). However, increased winter temperatures could also increase survival of pathogens. Dermo and MSX both flourish under higher temperatures, which would damage oyster populations. Warmer water has lower dissolved oxygen solubility, so warmer waters could more easily become hypoxic or anoxic. Warmer water conditions can also accelerate nutrient recycling, which would increase eutrophication, potentially exacerbation low oxygen conditions.

Increased water temperature will also impact critical habitats for fish. Many habitat-forming native plants are already at the upper edge of their temperature range. For example, eelgrass becomes stressed at water temperatures above 30° C (Chesapeake Bay Program, 2024). A massive die-off of eelgrass occurred in the Chesapeake Bay in 2005 as a result of an extended heatwave with temperatures above the tolerable range (Najjar et al., 2010). Eelgrass is at the southern extent of its range in the Chesapeake Bay, and it cannot move north because it needs to live in high salinity water found at the mouth of the Bay. Eelgrass is critical habitat for fish and crabs (NOAA, 2020).

Ocean Acidification

Increased concentration of atmospheric CO_2 increases CO_2 concentration in ocean water, which decreases the pH (more acidic). Decreased pH decreases the carbonate ion (CO_3^{2-}) concentration in the water, making it harder for organisms with calcium carbonate shells like oyster to build shells. pH is expected to decrease by 0.5 and carbonate concentration is expected to decrease by 45% by 2100 (Najjar et al., 2010). Miller et al. (2009) found that oysters calcified more slowly under CO_2 concentrations of 560-800 ppm (expected range of future atmospheric CO_2 concentrations) than in ambient conditions (Miller et al., 2009). Boulais et al. (2017) found that oyster reproduction is disrupted at pH below 7.2 (Boulais et al., 2017).

Increased Occurrence of Extreme Weather Events (floods, droughts) & Salinity Changes

Climate change has a complex impact on precipitation events. In the Chesapeake Bay, precipitation intensity is expected to increase as a result of the combined effect of increased annual precipitation and increased number of dry days. Drought is expected to increase, with a 24-79% increase in occurrence of short-term (1 – 3 month) droughts by 2100 and a larger increase in occurrence of medium and long-term droughts. The increased occurrence of extreme weather (stronger storms and more frequent droughts) can be a hazard to fisheries and aquaculture, but the effects are complex and hard to predict. Increase storm intensity can increase erosion in the watershed and lead to increased sediment loading to the Bay, which can lead to declines in submerged aquatic vegetation habitat due to low light availability.

As result of changes in precipitation, flow of the Susquehanna River is expected to increase from January to May. Susquehanna River flow during this period is a significant predictor of summertime circulation and biogeochemistry in the Bay. Increased freshwater flow from January to May is expected to decrease salinity of the Bay in winter and spring and provide an influx of nutrients that stimulate phytoplankton production. Decrease salinity in the surface layer can increase stratification and exacerbate summer hypoxia in deep waters. A 10% increase in Susquehanna River flow is expected to cause a 10% increase in the volume of anoxic water, a 6% increase in the volume of severely hypoxic water, and a 3% increase in the volume of mildly hypoxic water in the Chesapeake Bay. Increased areas of anoxia and hypoxia in deep waters will cause further decline of demersal fish species in the Bay. (Najjar et al., 2010). Blue crabs, an economically important demersal species, need dissolved oxygen concentrations of 3 mg/L. In spring 2024, high precipitation and streamflow caused abnormally low salinity, and hypoxic conditions began in April (earlier than usually). Part of the mainstem of the Bay that includes a blue crab sanctuary was below 3 mg/L oxygen (National Oceanic and Atmospheric Administration, 2024).

Changes in salinity will also cause changes in the distribution and abundance of fish, predators, and prey. Species that are more tolerant of lower salinity may outcompete other species. For example, blue catfish, and invasive species, can tolerate salinity below 14 PSU, lower than many native fish species. Lower salinities will allow them to thrive while feeding on native species. Oysters can tolerate salinities between 5 and 35 PSU, but they grow best and reproduce more in water with salinity between 10-28 PSU.

5.2.2. Market Volatility

Aquaculture is a business, and the success of that business depends on profit. Market volatility can be a hazard to aquaculture because it affects the cost of supplies and the price of the final product. A volatile market has large and unpredictable changes in prices. Volatility can be caused by political and economic factors, major weather events, global health crises, and individual business decisions (Fidelity International, 2024). Climate change will cause an increase in the frequency of extreme weather disasters and may trigger global conflicts over water, food supply, and migration. These hazards can increase market volatility, thereby impacting aquaculture businesses in Virginia.

6 Foresight and Possible Futures

6.1. Understanding Foresight

The goal statement established by stakeholders is, “to have an ample supply of domestically produced seafood and a healthy Chesapeake Bay ecosystem that can support sustainable fisheries and aquaculture in coastal Virginia.” The likelihood of reaching this goal is dependent on actions taken now to work towards a desirable future. This section uses the tools of foresight and future science to understand the spectrum of possible futures.

Foresight is the process of systematic, purpose-driven deliberations on the future between interested stakeholders with the goal to identify actions needed for better future outcomes. Foresight involves three core elements: anticipation, participation, and action. Anticipation involves using systematic monitoring to track the state of the system. Participation is direct involvement of all stakeholders in the visioning process, with the understanding that knowledge about the system is widely distributed. Action involves using insights gained from anticipation and participation to anticipate plausible future events and take action to guide the system’s trajectory toward a desirable future (Parliamentary Office of Science and Technology, 2009). Foresight is different from traditional planning processes because it explicitly considers multiple possible futures without putting emphasis on determining which one is most likely to happen. Traditional planning depends on predictions that state what the future will be within a certain margin of error. The future of the system will look very different from the past because climate change is pushing the planet into a state never before experienced by humans. Therefore, it is impossible for us to predict what the future will look like. The best we can do is understand all possible future scenarios and develop adaptable interventions that can be applied no matter the trajectory.

Figure 8 maps the spectrum of possible futures for seafood production in coastal Virginia and the Chesapeake Bay. Five possible future scenarios are described, informed by the hazard scenarios in Table 1. The scenarios represent a range of system states (from transformation to collapse) that correlate with the amount of action taken to address the wicked problem. How decision-makers respond to the hazards and fragilities identified in sections 4 and 5 of this report will dictate which trajectory the future takes. It’s important to note that the future is unlikely to match any of these scenarios exactly. It will most likely have characteristics of multiple scenarios combined, with other characteristics caused by unexpected events. The practice of mapping future scenarios allows us to open our minds to the range of possibilities so we can make informed decisions about interventions.

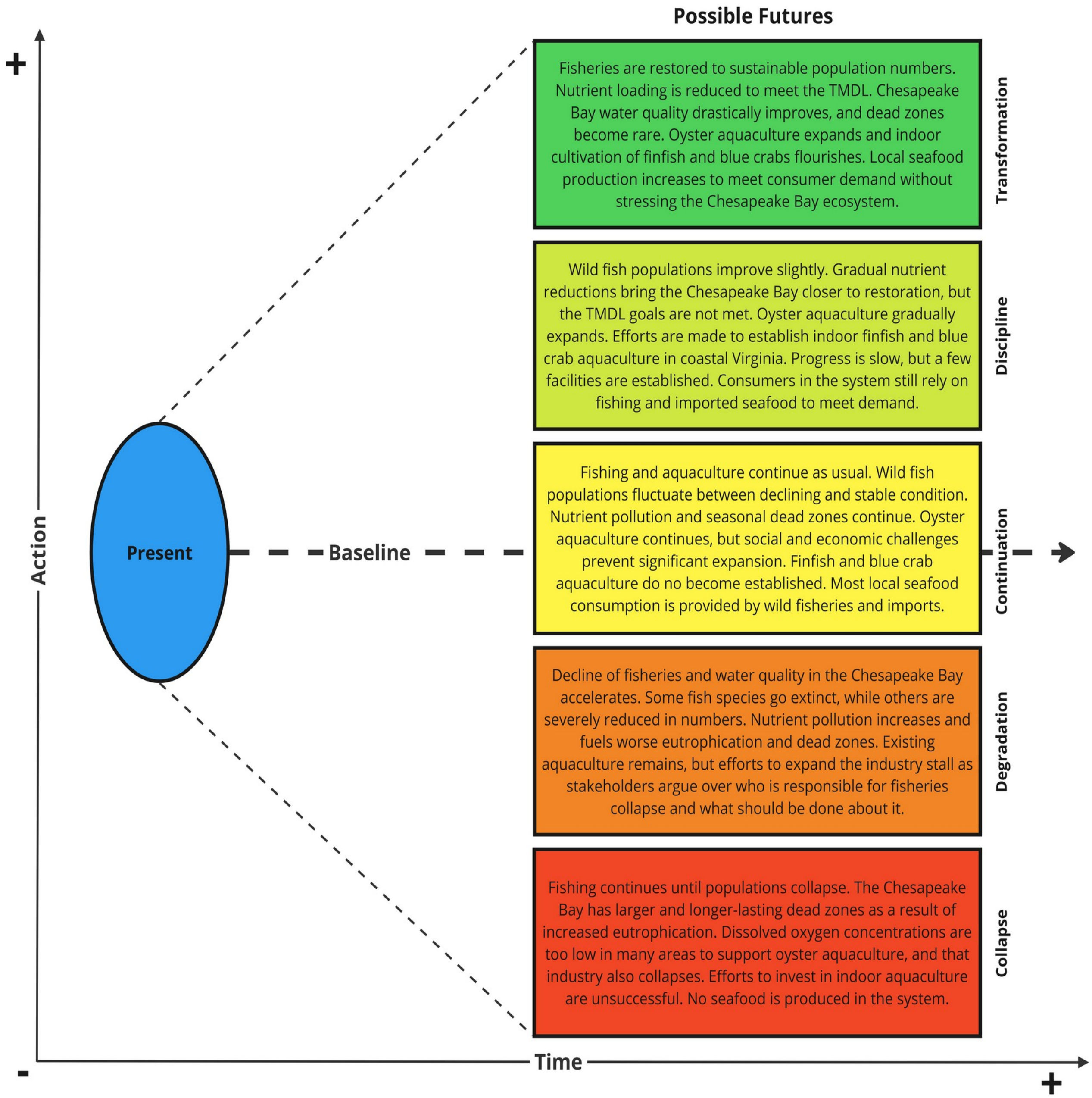

Figure 8: The spectrum of possible futures. Future scenarios represent a range of actions levels (low to high) corresponding with a range of future conditions (collapse to transformation).

6.2. Possible Futures

The range of possible futures is described below. There are some hazards that cannot be addressed within the system and will therefore have an impact no matter what interventions are taken. These hazards are the external ones: hazards connected to climate change (sea level rise, water temperature increase, ocean acidification) and market volatility. Effects of these hazards are not explicitly described in the future scenarios in Figure 8 because the effects are not dependent on actions taken within the system. Examples of these effects include:

- increased flooding in coastal areas due to sea level rise,
- warmer water temperatures stressing cold-temperate adapted native species,
- increased prevalence of Dermo and MSX due to warmer waters,
- decreased oyster growth due to ocean acidification, and
- changes in costs of supplies and the market rate of seafood affecting business profits.

6.2.1. Transformation

Transformation equates to a paradigm shift in how the system operates. In this scenario, significant action is taken to protect against hazards and reduce fragilities. Threatened fisheries are restored to sustainable population numbers similar to those seen before industrialization. Nutrient loads are reduced in the Chesapeake Bay to levels that meet the goals of the TMDL. Chesapeake Bay water quality drastically improves, and critical habitats like sea grasses and oyster reefs are restored. With eutrophication under control, dead zones become rare. Oyster aquaculture expands, and its presence contributes to water quality improvements and economic success. Fishing is only conducted at sustainable levels, and many fishermen have transitioned to working in aquaculture. Finfish and blue crabs are cultivated in indoor recirculating aquaculture systems, allowing for increased local seafood production to meet consumer demand without stressing the Chesapeake Bay ecosystem. The transformation scenario corresponds to the best case hazard scenarios for overfishing, disease, and nutrient pollution (Table 2). The transformation scenario will only be able to happen if climate change impacts match the best and middle case hazard scenarios. Severe sea level rise corresponding to the worst case hazard scenario would decimate coastal communities, and likely the fishing and oyster aquaculture industries along with them.

6.2.2. Discipline

The discipline scenario is one where action is taken to address the wicked problem, but actions are smaller than in the transformation scenario and do not lead to a paradigm shift. In this scenario, threatened fish species see some improvement. Species that are on the decline stabilize, but they do not grow to match historic highs. Gradual nutrient reductions are achieved in the Chesapeake Bay watershed. The Bay is brought closer to the goals of the TMDL, but they are not met. Oyster aquaculture gradually expands in the Bay. Indoor finfish and blue crab aquaculture finds a foothold in coastal Virginia. Aquaculture does not expand to the point where it becomes the primary source of seafood in coastal Virginia. Many fishermen are resistant to switching to aquaculture and continue pushing for their right to harvest from the Bay. The discipline scenario corresponds with conditions between the best and middle case hazard scenarios for overfishing, nutrient pollution, and disease (Table 2). Similar to the transformation scenario, this scenario cannot occur under the worst case climate change hazard scenarios.

6.2.3. Continuation

The continuation scenario represents the future that will happen in the "business as usual" scenario. In this option, current efforts to address the wicked problem continue at the same rate. This scenario represents the baseline condition in the spectrum of possible futures. In this scenario, fishing and aquaculture continue at current rates. Wild fish populations fluctuate between declining and stable condition as regulators attempt to set quotas that prevent population collapse while maintaining the fishing industry. Nutrient loading continues to exceed TMDL goals, and the Chesapeake Bay continues to experience seasonal dead zones. Oyster aquaculture continues to operate at similar rates. Finfish and blue crab aquaculture are practically non-existent in coastal Virginia. Most local seafood consumption is still provided by wild fisheries and imports. This scenario corresponds to the middle case hazard scenario for all hazards (Table 2).

6.2.4. Degradation

In the degradation scenario, hazards cause significant declines in the system. Fish population numbers drop, and some species are lost completely. Nutrient pollution increases due to unsuccessful attempts at reductions and increased precipitation intensity caused by climate change. This leads to longer and more intense dead zones and further declines in critical habitats for wild fish. Existing aquaculture remains but attempts to expand aquaculture stall as stakeholders argue over who is responsible for fisheries collapse and what should be done about it. Oyster farmers observe declines in growth due to worsening water quality. The degradation scenario would occur under conditions between the middle and worst case hazard scenarios for overfishing, nutrient pollution, and disease (Table 2). Climate change impacts between the middle and worst case hazard scenario would cause further degradation of the system (e.g., flooding of coastal fishing and aquaculture infrastructure due to sea level rise and slower oyster growth due to acidification and temperature stress).

6.2.5. Collapse

The collapse scenario is the worst case scenario. In this scenario, gross inaction leads to complete collapse of the Chesapeake Bay fisheries and ecosystem. Native fish species go extinct, and without fish to eat the plankton, eutrophication increases significantly. The Bay experiences constant dead zones throughout the entire year. Dissolved oxygen concentrations are too low in many areas to support oyster aquaculture, so that industry also collapses. Efforts are made after the fisheries collapse to invest in indoor finfish and blue crab aquaculture to replace food supply from fishing, but technological and economic barriers prevent rapid expansion. 100% of seafood consumed in coastal Virginia comes from outside of the system. Communities experience significant economic hardship as a result of the loss of fishing and aquaculture. The collapse scenario corresponds to the worst case hazard scenarios for overfishing and nutrient pollution (Table 2). If the worst case scenario for climate change impacts also occurred, coastal communities would also collapse due to sea level rise inundation.

All of the futures described are possible. We cannot tell which futures are probable with the resources in the scope of this case study. Therefore, we have to develop interventions under the assumption that we cannot exclude any of the possible futures as too preposterous to consider. We can, however, decide which futures are desirable. Desirable futures are ones that most closely resemble the goal statement. The “transformation” future matches the goal statement but would take a massive amount of action to achieve. The “discipline” future brings the system closer to the goal statement. It makes positive progress and gives the system potential to eventually reach the goal given further action and adaptation. The transformation and discipline futures are both desirable. The other three futures (continuation, degradation, and collapse) are all undesirable. The degradation and collapse futures will result in worsening conditions that move the system further away from the goal. The continuation “status quo” future makes no progress towards reaching the goal. The Chesapeake Bay ecosystem is already degraded, so maintaining that degraded state is not desirable. Interventions discussed in section 7 will aim to bring the system towards either the transformation or discipline futures.

7 Assessing Interventions

In this section, four potential interventions are discussed that could guide the system towards a desirable future (Table 3). All four interventions aim to expand aquaculture in the Chesapeake Bay because the desired future outlined by the goal statement includes both restoration of the Chesapeake Bay ecosystem and production of enough local seafood to meet demand. Aquaculture is the only way seafood production in coastal Virginia can expand without further stressing wild populations. Research has demonstrated that there are significant social and economic barriers to aquaculture (Beckensteiner et al., 2020; Knapp and Rubino, 2016). In coastal Virginia, social and economic issues are currently more of a barrier to aquaculture expansion than environmental or space concerns. Environmental concerns are considered in each intervention alongside social and economic concerns. No interventions are proposed that would lead the future towards a non-desirable future.

Potential interventions include three types of aquaculture: outdoor oyster aquaculture, indoor aquaculture in recirculating facilities, and pond-based freshwater aquaculture. Aquaculture types that have a high likelihood of environmental harm or public opposition are not included. Net pen aquaculture is not discussed for this reason. This style of aquaculture involves farming finfish like salmon in pens or cages in open water. Fish are fed with feed, and water is exchanged freely between the pens and the environment (SeaChoice, 2024). This type of aquaculture has a high risk of causing nutrient pollution because fish feed and fish waste is added to the ecosystem. It is therefore not appropriate in a system that is already impacted by nutrient pollution.

7.1. Consumer education campaign to promote oyster aquaculture

The first proposed intervention is a consumer education campaign about oyster aquaculture. This intervention would involve a twofold education and communication approach. Beckensteiner et al. (2020) demonstrated that social and economic issues are the primary barriers to expanding oyster aquaculture in Virginia. Although the number of oyster leases has increased over the last couple decades, only one third of the leases is actively being used. Beckensteiner et al. suggest that “Not in my backyard” (NIMBY) attitudes towards oyster aquaculture are preventing expansion. Coastal residents and recreators are afraid that increasing the presence of aquaculture will take aquatic area out of the public use space (Beckensteiner et al., 2020). Others may be concerned that aquaculture will decrease waterfront property value. According to Stump (2019), the effect of oyster aquaculture on property values depends on the type of aquaculture being performed. Active aquaculture overall was found to have a positive effect on property values, but cage aquaculture had a negative effect on aquaculture (Stump, 2019). This effort would address community concerns and misunderstandings about oyster aquaculture with two actions.

Table 3: Possible interventions to address the wicked problem. Pros and cons of the interventions are described and interventions are ranked. See Table 3 for a detailed breakdown of the ranking.

Interventions	Description	Pros	Cons	Rank
Consumer education and communication campaign regarding oyster aquaculture	Research has shown oyster leases are underutilized. Social and economic barriers are likely limiting oyster cultivation, not space. This intervention would involve a series of participatory workshops with coastal residents and consumers about oyster aquaculture. The goal would be to expand oyster aquaculture while minimizing conflict with neighbors, and to improve consumer literacy regarding environmental and economic benefits of oyster aquaculture.	Gives all stakeholders an opportunity to be heard in a non-confrontational setting. Improves community and consumer knowledge about oyster aquaculture. Has the potential to increase acceptance and sales of locally farmed oysters.	No guaranteed outcome. Expansion of aquaculture depends on the receptiveness of the community and consumers.	1
Promote marine finfish and blue crab aquaculture development in recirculating tank facilities	Alternatives to wild finfish and blue crabs are necessary due to population declines. This intervention would involve a program to streamline permitting and reduce costs for development of aquaculture in recirculating tank facilities. The program should emphasize responsible siting of facilities and sustainable water, feed, and energy use.	Diversifies aquaculture and introduces sustainable alternatives to threatened species. Creates new aquaculture jobs and increases local seafood production. Facilities designed to be resilient to climate change.	More seafood on the market may decrease price and reduce profit for existing producers. Facilities need energy, water, and fish feed. Oversight and monitoring are needed to ensure facilities are operated sustainably. Risk of large corporations dominating the new market.	3
Career services to help fishermen transition into aquaculture roles	Many coastal communities are still economically dependent on fishing. This program would provide training and knowledge to fishermen interested in transitioning to aquaculture roles. The program can also involve participatory sessions to understand fishermen's viewpoints and knowledge of the Bay and incorporate them into future policy.	Decreases community reliance on fishing while preserving cultural knowledge. Generates local workforce to staff new aquaculture businesses. Improves local economic stability.	Success is dependent on the willingness of fishermen to change careers. Older generations may not be interested in changing. May trigger conflict within the fishing community as new aquaculture businesses are viewed as a threat to existing fishing operations.	2
Promote pond-based aquaculture of freshwater fish	Encourage farmers who grow vegetables or raise livestock to use some of their land to create farm ponds for growing freshwater fish species. Emphasize sustainable extensive aquaculture methods that minimize the need for feed inputs.	Ponds do not require constant energy input like recirculating facilities. Would increase fish production without stressing marine and coastal environments. Would help farmers diversify their products and increase resilience to change.	Potential for nutrient pollution if not managed well. Ponds are susceptible to environmental stressors. Expansion of pond aquaculture on farms may lead to establishment of ponds on non-agricultural land. Supply of freshwater fish may not be able to replace demand for marine species.	4

1. Educational materials about oyster aquaculture are developed by VMRC and VDACS. These materials should be posted on the department websites, shared on social media, and shared with oyster farmers who can use it in their marketing material. Materials should include information about the history of oysters in the Bay and their benefits to the environment and the local economy. Materials can also include information about how to eat oysters; how to shuck them, recipes to use them in, and how to know when they are safe to eat raw.
2. A series of participatory workshops are conducted with coastal residents, recreators, and consumers about oyster aquaculture. The purpose of the workshops would be to understand the community's perspective on oyster aquaculture while providing education and correcting misunderstandings. Expanding aquaculture would use aquatic space that is currently used for boating, fishing, and aesthetic purposes. Oftentimes, public hearings for aquaculture permits are the only opportunity the community has to share their opinions on aquaculture in their neighborhoods. At this point, the farmer has already invested a significant amount of time and money in the permit process, so protests from community members can sow conflict. This conflict can be avoided if the community is involved in the planning process early on, before any individual business has invested. It's possible that community members would support some types of aquaculture but not others or would support it in some areas but not others. For example, on-bottom aquaculture where oysters are planted directly on the riverbed or bottom-cages may be more popular than floating cages because they can't be seen from the surface, and they don't restrict boat passage.

Workshops could also involve free oyster tasting and shucking demonstrations by local aquaculture farmers. These activities would provide incentive for community participation and may attract consumers who are curious about oysters but don't know how to eat them. Some financial investment would be required to compensate farmers for their oysters. This investment would pay off in the long run if workshops contribute to oyster aquaculture expansion.

Pros of this intervention include:

- All stakeholders have a chance to be heard in a non-confrontational setting.
- Community and consumer knowledge about oysters and oyster aquaculture would improve.
- Can increase acceptance of oyster aquaculture and sales of locally farmer oysters.

Cons of this intervention include:

- There is no guarantee that workshops would increase acceptance of aquaculture or oyster sales. Success would depend on workshop attendance and community opinions.
- Some money would need to be invested by VMRC and VDACS to conduct the workshops and pay for oyster tasting.

7.2. Promotion of marine finfish and blue crab aquaculture in recirculating facilities

The second proposed intervention is promotion of marine finfish and blue crab aquaculture development in indoor recirculating tank facilities. This intervention would focus on development of an alternative to wild caught finfish and blue crabs. Researchers at IMET have successfully developed systems to cultivate marine finfish and blue crabs indoors, but they have not yet been implemented in Virginia (Institute of Marine and Environmental Technology, 2024). VMRC and VDACS can promote this type of aquaculture in Virginia by streamlining the permitting process for establishment of these facilities and discounting permit fees for new businesses in the first years of operation. Permitting confusion and cost have been identified as a barrier to aquaculture expansion (Knapp and Rubino, 2016). This intervention should involve:

1. Establishing a "one-stop" website for permitting indoor aquaculture. The website should clearly outline the step-by-step process for establishing an indoor aquaculture business in Virginia, with links to the appropriate applications. Staff at the VMRC or VDACS should be identified who can answer questions from potential farmers. I recommend collaborating with IMET to develop educational materials for the website.
2. Discounting permit fees for new businesses for the first 3 to 5 years of business. This will help new businesses get off the ground and will reduce overhead costs until the businesses become profitable.

   Pros of this intervention include:

   - Expansion of aquaculture in recirculating systems would diversify seafood production in coastal Virginia and provide sustainable alternatives to threatened species.
   - New aquaculture businesses would create jobs.

- There is potential for an increase in local seafood production since indoor systems are not limited by environmental conditions.
- Facilities can be responsibly sited and designed to be resilient to climate change. They can be built in areas that will not be inundated by sea level rise even in the worst case hazard scenarios. This ensures continuous seafood production even if coastal infrastructure is damaged.
- Recirculating systems minimize water use when compared to non-recirculating systems.

Cons of this intervention include:

- A surge of seafood supply may decrease the market price and reduce profits for wild fishermen who are already economically struggling.
- Indoor facilities require energy and water supply to operate. Energy supply would need to be constant because recirculating systems run 24/7. Sustainable energy sourcing should be emphasized in the permitting process, but renewable energy may not be available in every locality.
- Facilities would produce wastewater and solid waste. Responsible disposal of this waste needs to be part of management plans submitted during permitting.
- Fish grown in indoor facilities need to be fed with fish feed. Sustainable fish feed exists, but it is sometimes not as nutritious as feed that uses wild-caught fish. The permitting process should require potential farmers to report what species they will be growing and how they will be fed, so a sustainable feeding plan can be developed before operations begin.
- Consistent oversight and monitoring would be required to make sure operations are operating sustainably. Without this, they could change energy use, water use, waste disposal method, or feed type from what was initially proposed.

7.3. Career services to help fishermen transition into aquaculture roles

Pushback from fishermen to aquaculture is partially due to economic dependency of their businesses and their communities on fishing. This intervention would address this challenge by providing career services to help fishermen transition into aquaculture. Before trainings are offered, VMRC and VDACS should hold participatory workshops with fishermen and other fishing industry stakeholders to understand their perspectives on fishing and aquaculture. Fishermen are unlikely to participate in aquaculture training if they feel like they are being pushed out of their traditional livelihoods. Fishermen's perspectives need to be heard, respected, and incorporated into policy. If outcomes from workshops show positive response from some participants to transitioning to aquaculture, career training services should be provided. VMRC and VDACS can connect with research groups like IMET and other aquaculturists to conduct trainings. Collaborating with people currently in the industry is recommended so trainees can get first-hand insight into the challenges and benefits of the business. Trainings can also explicitly include advice for building businesses that are resilient to impacts of hazards like disease, sea level rise, and ocean acidification. This intervention would be especially effective if it is combined with one of the first two interventions.

Pros of this intervention include:

- Decreasing community reliance on fishing and improving economic stability
- Preserving fishermen’s cultural knowledge about the Chesapeake Bay.
- Improving relations between aquaculture farmers, regulators, and fishermen.
- Generating a local workforce to staff new aquaculture businesses.
- Training aquaculture practitioners to plan their businesses to be resilient to climate change.

Cons of this intervention include:

- No guarantee of success. Success is dependent on the willingness of fishermen to change careers. Older people and people whose families have been fishing for generations might not have an interest in change.
- Workshops and trainings may trigger conflict within the fishing community if new aquaculture businesses are seen as threat to fishing operations.

7.4. Promotion of pond-based aquaculture of freshwater fish

The final intervention option aims to expand aquaculture production of freshwater fish rather than marine species. Under this option, VMRC and VDACS promote pond-based aquaculture on existing farmland. Farmers who grow vegetables or raise livestock would be encouraged to use some of their land to create farm ponds for growing freshwater fish species. Extensive aquaculture methods that require little input of feed would be encouraged. This intervention is proposed on existing farmland because farmland is already a source of nutrient input to the Chesapeake Bay watershed. Adding finfish aquaculture to these areas would likely not add additional load of nutrients if growing area or pasture area are converted into fish ponds.

Pros of this intervention include:

- Farmers can diversify their food production options, making them more resilient to economic and environmental changes.
- Adding ponds can increase biodiversity on farms.
- Fish waste from pond aquaculture can be used as fertilizer for crop production.
- Increasing fish production without relying on marine and coastal environments that are susceptible to sea level rise.
- Ponds do not require constant energy input like indoor facilities.

Cons of this intervention include:

- Potential for nutrient pollution of ponds are not responsibly managed.
- Ponds are susceptible to environmental stressors.
- Promoting pond-based aquaculture could lead to establishment of fish ponds on non-agricultural land. This could result in a net increase in nutrient loading to the Chesapeake Bay.
- Freshwater fish may not be able to fill the same niche in the market as marine fish species. Increasing pond-based aquaculture may not replace demand for marine species.
- May take jobs away from the coastal area because pond-based aquaculture can be done anywhere.

7.5. Comparing and ranking the four interventions

To rank the four interventions discussed, I rated them based on the following parameters:

- Feasibility (f) – How likely are VMRC and VDACS to be able to perform the intervention?
- Impact (I) – How much impact will the intervention have on addressing the wicked problem?
- Time to see impact (t) – How much time will it take to see an impact?
- Cost (c) – How expensive will the intervention be?
- Risk (r) – How much risk is involved (environmental, social, and economic)?

A value from 1 to 5 was assigned to each intervention for each of the parameters, with 1 being low (e.g. low feasibility, low risk, low cost) and 5 being high. A rating (R) was generated based on these numbers using the formula R=(f*I)/(t*c*r). The parameter values and rankings are displayed in table 4. The rating is listed in column 2 of the table, followed by the five assessment parameters included in the equation. Rankings from 1 to 4 were then assigned to the four interventions based on their ratings, with the highest rating being ranked number 1 and the lowest rating being ranked number 4. Rankings are displayed in table 3 alongside intervention descriptions.

Table 4: Ranking of interventions. Interventions were rated based on five parameters: feasibility(f), impact (I), impact time (t), cost (c), and risk (r). The rating (R) was calculated based on the equation R=f*I/(t*c*r). Rankings between 1 and 4 were assigned (Table 2) based on the rating (with the highest rating corresponding with rank 1 and lowest rating corresponding with rank 4).

Interventions	Rating	f	I	t	c	r
Oyster aquaculture education campaign	5	5	4	2	2	1
Promotion of indoor aquaculture	1.0417	5	5	4	3	2
Career services for aquaculture transition	1.6667	5	4	4	3	1
Promotion of pond-based freshwater aquaculture	0.8333	5	3	3	2	3

All four interventions were ranked “5” for feasibility (f) because they are designed to be within the scope of VMRC and VDAC’s work. Impact (I) was ranked between 3 and 5 for the four interventions. Pond-based aquaculture promotion was ranked the lowest because even though it could lead to increased fish production, it would not have a direct impact on marine fish production (“sea”-food) or coastal fishing communities. Indoor marine aquaculture promotion was rated highest for impact because it has the potential to produce the most food out of all of the options. Time to see impact (t) was highest for promotion of indoor aquaculture and career services for aquaculture transition because both of these options involve significant shifts in the industry. New businesses would need to be established, and it would take time to train business owners and employees. The oyster aquaculture education campaign has the lowest time to see impact because oyster aquaculture is already an established industry. An increase in community acceptance and sales to consumers would likely trigger rapid expansion. Costs (c) are expected to be similar for all four interventions but may be slightly higher for promotion of indoor aquaculture and career services. The indoor aquaculture intervention explicitly includes discounting permit fees for the first few years of business, so this could involve a loss in revenue for VMRC and VDAC. Career services would require a long series of workshops and trainings that would take more staff time than the other interventions. Finally, pond-based aquaculture was ranked as the highest risk (r) with a value of 3, and the oyster aquaculture promotion and career services interventions were tied for the lowest risk with a value of 1. Pond-based aquaculture is the highest risk because it has the highest chance of leading to further nutrient pollution if not properly managed. Oyster aquaculture promotion and career services are both outreach-focused efforts that emphasize expansion of existing industry, so they carry relatively little risk (other than the risk of stakeholders not wanting to participate). Promotion of indoor aquaculture carries some risk because facilities need to be responsibly managed to have little environmental impact. However, if proper attention and oversight are given in the permitting process, a significant amount of seafood could be produced with low impact when compared to the impact of current fishing practices.

8 Discussion and Conclusions

The challenge presented by this wicked problem is to produce seafood in coastal Virginia without degrading the Chesapeake Bay ecosystem. The challenge turned out to be one primarily affected by social and economic barriers rather than environmental ones. Sustainable aquaculture is feasible, but expanding aquaculture depends on its acceptance by the community and economic conditions. This case study did a good job of describing the seafood production system in coastal Virginia and coming up with interventions that can move the system on a path towards expanding aquaculture and reducing reliance on wild fisheries. Perspectives of all relevant stakeholders were considered based on information available online and through peer-reviewed research. A good baseline understanding of the flows involved in fishing and aquaculture was obtained through research on the history of the system and current fishing and aquaculture practices. These flows were mapped in a conceptual model. System fragilities and internal and external hazards were considered, and peer-reviewed research was referenced to generate hazard scenarios. Effort was made to include the true worst-case scenario (total ecosystem collapse). Hazard scenarios and foresight were used to generate potential future scenarios, and interventions were developed that could bring the system towards a desirable future.

While this case study was effective at developing a baseline understanding of the system, it was limited by the scope of this class and available resources. I was not able to have direct conversations with stakeholders, so I had to base my understanding of their perspectives on research other people have done. The stakeholder role-playing exercise was conducted at a time when I and the other participants had a very limited understanding of the decision space. This case study would benefit from conversations with real stakeholders and participatory modeling workshops with those stakeholders. Development of hazard scenarios was also limited by time and resources. It would be beneficial to do detailed modeling of coastal Virginia in relation to all of the hazards to get a better idea of how the system would respond to different scenarios. Hazard scenarios were based on the best information I could find in the time available. In some cases this information was very specific to coastal Virginia (e.g. Ezer and Atkinson, 2015), but in others the information available was more general, applying to the whole East Coast or the nation.

Interventions discussed in this case study have a high likelihood of bringing the system towards a desirable future. Community workshops and career services address social barriers to aquaculture expansion by increasing acceptance of the industry. Indoor aquaculture expansion provides an opportunity to diversify seafood produced by aquaculture while designing facilities that are resilient to climate change hazards. Since this case study is being prepared for VMRC and VDACS, the proposed interventions are primarily focused on outreach and community engagement. VMRC and VDACS are not aquaculture producers themselves, so the best way they can address the wicked problem is by fostering an environment where aquaculture can thrive. The downside of this is that there is no guarantee that their efforts will succeed. Success is dependent on willingness of the community to adopt new practices and welcome a new industry. As state regulatory agencies, VMRC and VDACS are also limited in their ability to mitigate external hazards like climate change and market volatility. Climate resilience must be considered when implementing any of the proposed interventions. Aquaculture businesses can be designed to accommodate sea level rise, rising water temperatures, and ocean acidification through responsible site selection, infrastructure construction, and economic planning. If VMRC and VDACS make a conscious effort to foster open, honest communication and give all stakeholders a meaningful role in the planning process, they have a very good chance of addressing the wicked problem. Sustainable aquaculture has thrived in other locations, and it can thrive here.

9 Recommendations

Recognizing that...

- Wild fish populations in the Chesapeake Bay are threatened by overfishing.
- Seafood is a healthy and popular food choice.
- Seafood production in Virginia does not meet demand.
- Many coastal communities are economically reliant on fishing.
- Nutrient pollution causes eutrophication and dead zones in the Chesapeake Bay.
- Wild fish populations will face increased environmental hazards due to climate change.

Acknowledging that...

- Fishing is an important part of coastal Virginia’s cultural heritage. Fishermen have valuable knowledge that is often not incorporated into policy.
- Stakeholders, including regulators, nonprofits, and farmers, are actively making efforts to restore the Bay through nutrient reductions.
- Coastal communities are being increasingly affected by climate change impacts (sea level rise, extreme weather) and have limited resources with which to address impacts.
- There is a history of conflict between aquaculture and fishing communities.

It is recommended that...

The Virginia Marine Resources Commission and the Virginia Department of Agriculture and Consumer services implement interventions 1, 2, and 3 described in section 7:

1. Consumer education campaign to promote oyster aquaculture

2. Promotion of marine finfish and blue crab aquaculture in recirculating facilities
3. Career services to help fishermen transition into aquaculture roles.

These three interventions are recommended in tandem because they address three separate needs in the aquaculture industry, and when they are performed together, they can support each other's success. Intervention 1 addresses the primary barrier to oyster aquaculture expansion, social acceptance. Oyster aquaculture is already an important part of seafood production in coastal Virginia and expanding it would benefit both the economy and water quality in the Bay. Intervention 2 would support expansion of aquaculture in coastal Virginia to include other species (besides shellfish) that are more widely consumed and are currently sourced entirely from wild populations. Intervention 3 would support interventions 1 and 2 by improving communication between the fishing and aquaculture communities and encouraging a career shift for people in the fishing industry who will soon struggle to find sustainable work.

Intervention 4 is not recommended. It was ranked lowest out of the four options and does not directly benefit coastal communities that have historically been dependent on Chesapeake Bay resources. It is also not recommended because it has the potential to lead to further nutrient pollution in the Bay, which would exacerbate existing hazards.

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