Towards a shared understanding of nutrient pollution in Cape Cod's coastal waters

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Abstract *– Increasing population and economic development around coastal areas have left many embayments throughout the world severely impaired. Excessive nutrient enrichment in water bodies, also known as nutrient pollution, is one of the leading impairments in coastal waters. Algal blooms, dead zones, and fish kills are spreading because of the nutrient pollution. This paper presents a systems analysis of the nutrient pollution problem in Cape Cod, Massachusetts, where the continuous degradation in coastal waters is considered as one of the greatest threats to the region's environmental and economic future. A system dynamics model was created with a diverse stakeholder team to uncover the underlying system structure that has created the degradation in Cape Cod's coastal waters since 1960s. An important goal of this work was to support the development of a regional water quality management plan by creating a shared understanding of the nutrient pollution problem across a wide range of stakeholders including residents, local municipalities, regional authorities, the state government, and the U.S EPA. The proposed model and simulation experiments reveal several critical insights, including nonlinearity of the system behavior, delay in the system's response to interventions, and the importance of timely actions.*

Background

Coastal waters of the world are vital to human life. They provide goods and services ranging from a variety of foods to recreational opportunities. They also contribute to economy through tourism, transportation and fisheries. However, coastal waters are under significant pressure of growing human activity. Increasing population and economic development around coastal areas have left many embayments throughout the world severely impaired. Ecological communities in these water bodies have been acutely damaged. Economic and social benefits provided by coastal waters are under growing risk. Yet very little has been done so far to reverse the impairment trend in coastal waters.

The world's population has almost tripled since 1950 (UN Population Division, 2011). Over 50% of the planet's population already lives within 120 miles of a coastline. Future projections indicate that 75% of the global population will live in coastal areas by 2025 (Hinrichsen, 1999). 52% of the US population lives in coastal watershed counties (U.S. Census Bureau, 2012), which make up less than 20% of the US land area. Total population of these watershed counties increased by 45% compared to 1970, and 9% additional increase is expected by 2020. In parallel with escalating human numbers and their ever-growing needs, the water quality in many rich coastal ecosystems has progressively declined. *Dead zones* - waters with little or no dissolved oxygen to support aquatic life, hazardous algal blooms, loss of habitat, and fish kills are spreading. In 2008, there were 405 dead zones worldwide, up from 49 in the 1960s (Diaz, 2008). Nearly entire east and south coasts of the United States are covered with dead zones. The Gulf of Mexico dead zone is one of the largest in the world and can grow up to 7,000 square miles from the Mississippi River delta to the upper Texas coast. The Chesapeake Bay dead zone causes loss of 83,000 tons of fish and other ocean life each year (Biello, 2008).

Algal blooms, dead zones, and losses of fish are often symptoms of excessive nutrient enrichment (also known as nutrient pollution) in water bodies. Nutrients are discharged to groundwater or surface water by various sources such as wastewater, fertilizer runoff, or storm water runoff. When superfluous amount of nutrients like nitrogen and phosphorus arrive at coastal waters, they alter the natural dynamics of the ecosystem by stimulating massive algal blooms that reduce water clarity. As the algae die and decompose, high levels of organic matter and the decomposing organisms deplete the dissolved oxygen in the water column, which is crucial for the survival of fish, shellfish, and other ecological communities. This chain of events, known as *eutrophication*, is one of the leading impairments in coastal waters of the United States (U.S. EPA, 1998).

About the project

The project underlying this study was performed in collaboration with the Cape Cod Commission, the regional planning and economic development agency serving 15 towns of Barnstable County, Massachusetts, better known as Cape Cod, where continuous degradation in coastal waters is considered as one of the greatest threats to Cape Cod's environmental and economic future. The purpose of the project was to support the commission's efforts to develop a regional water quality management plan by creating a shared understanding of the coastal water quality degradation problem and potential solutions across a wide range of stakeholders. In order to realize this goal, a group model building (Vennix, 1996) project was conducted to uncover the underlying system structure that has created the impairment in Cape Cod's coastal waters. Throughout the project, four half-day workshops were held with the stakeholder team. The first session was primarily about defining the problem. Over 90 different variables were identified to have a bearing on coastal water quality degradation. Among these variables, a few were chosen as best descriptors of the problem and reference modes were plotted for ten decades since 1960s. During the second and the third session, the structure of the system was conceptualized from various perspectives. Based on this conceptualization, a simulation model was formulated between the third and the fourth session. Finally in the last workshop, an in-depth policy analysis was performed using the simulation model to explore how the degradation in Cape Cod's coastal waters could evolve under different future scenarios and how effectively different policy alternatives can alleviate the problem in the long term.

Problem identification

The objective of system dynamics modeling is to better understand the structure of a system that gives rise to a problematic behavior. Accomplishing this objective first requires identifying the dynamic nature of the issue of interest. Therefore, we started the group model building sessions by asking the stakeholder team to list all variables they think of as relevant to the coastal water quality impairment on Cape Cod. The team identified over 90 variables in 10 categories. After generating a long list of relevant variables, the team chose a few of them as the most important for describing the nature of the problem: *nutrient loading*, *property values*, and *public understanding of coastal water quality degradation*. For each selected variable, a reference mode was drawn to describe how the issue of concern has developed to its current state and how it is expected to evolve going forward under different future scenarios.

Nutrient loading refers to the total amount of nitrogen or phosphorus entering coastal water bodies during a given time period. Together with the nutrient removal rate from the water column, the nutrient loading describes if the *nutrient concentration*, the amount of nitrogen or phosphorus in a defined volume of water, increases or decreases during that period. Figure 1 displays an approximate plot of how the Cape-wide nutrient loading has changed since 1960 and expected to change in the future. The stakeholder team identified and sketched three future scenarios: (1) no actions are taken to resolve the nutrient pollution problem; (2) no actions are taken to resolve the problem and additional urbanization takes place on the Cape; and (3) adequate actions are taken to control excess nutrients in coastal waters.

Cape Cod's economy is largely dependent on its natural resources and beauty. Tourism and second home economy represent the vast majority of the Cape Cod's economic base (Cape Cod Chamber of Commerce, 2012). On the other hand, most social services on the Cape are supported through property tax revenues. For many towns, a significant portion of the municipal tax base today comes from the coastal properties. Continuous degradation in coastal waters creates a major threat for the region's economy and social life. The reference mode shown in Figure 2 describes a reflection of this concern – how property values are expected to change over the following decades based on whether the nutrient pollution problem is solved or not solved.

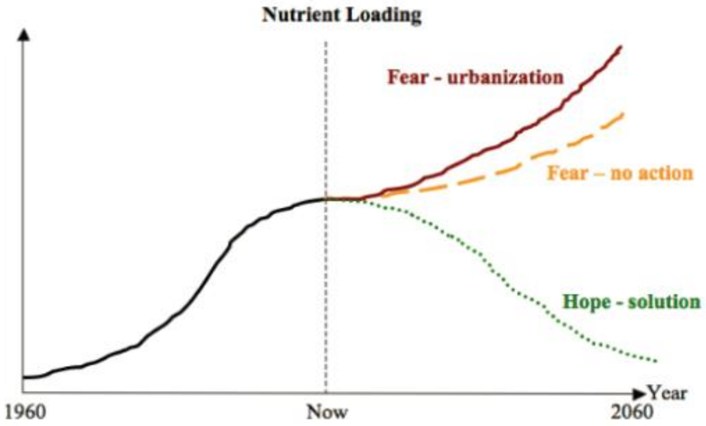

Figure 1. Nutrient Loading Reference Mode

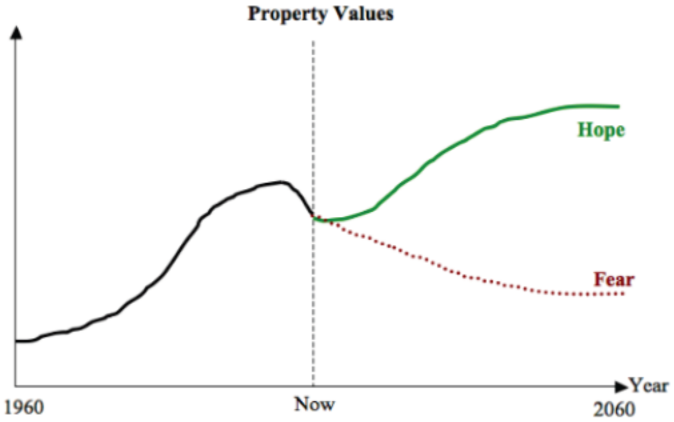

Figure 2. Property Values Reference Mode

Most ecological and economic processes contain long time delays and the nutrient pollution on Cape Cod is no exception. Creating an adequate and timely solution for long-term benefits requires public buy-in. Therefore, the stakeholder team identified the public understanding of the coastal water quality degradation as the third major variable to describe the nature of the problem. Figure 3 depicts the reference mode for this variable. In addition to presenting how the public understanding of the problem is hoped and feared to change going forward, the figure also shows the evolution of experts' and decision makers' understanding of the problem.

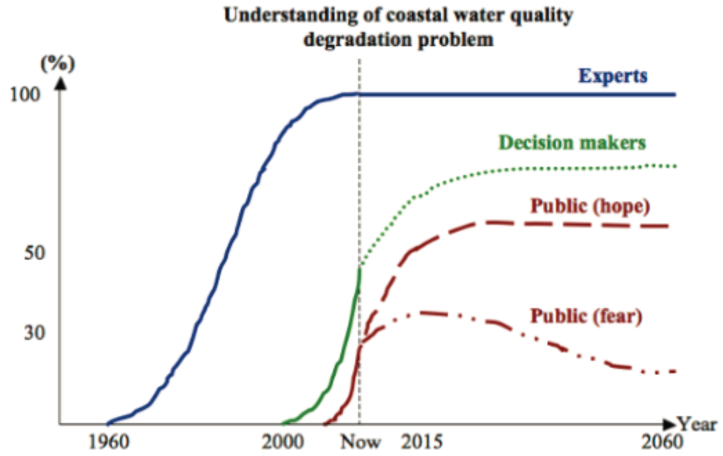

Figure 3. Problem Understanding Reference Mode

System Conceptualization

It is already known by the Cape Cod Commission and other stakeholder groups that 80% of the coastal water quality degradation on Cape Cod is caused by wastewater (Cape Cod Commission, 2012). Therefore, the stakeholder team deliberately focused on understanding the impact of wastewater on the degradation even though it is only one source of nutrients that go to embayments. It is true that fertilizers, stormwater runoff, and atmospheric deposition also contribute to the nutrient pollution problem on Cape Cod. However, they are intentionally left out of the system boundary for this study due to their relatively low contribution to the problem.

In order to conceptualize the system that creates the impairment in Cape Cod's coastal waters, several questions were posed to the stakeholder team. What does increase the nutrient concentration in coastal waters and where do nutrients accumulate in the system before reaching to embayments? How do nutrients get removed from water columns? How does the ecological system respond to excessive nutrients in water bodies? What social and economic implications of the nutrient pollution are anticipated and how could these influence the public willingness to fund a proper solution? Below, we describe the conceptual models drawn based on the stakeholder team’s responses to these questions.

Nutrient Loading and Removal Pipeline

Nutrient pollution refers to excessive accumulation of nutrients in water bodies. When nutrients are abundant in water columns, they stimulate algal growth, which in turn triggers various environmental, economic, and social implications. To manage nutrient pollution effectively, policymakers need to better understand why nutrients accumulate in water columns and how this accumulation could be prevented. Figure 4 displays a simple stock and flow structure to describe nutrient accumulation in coastal waters. *Nutrients in Water Column* is the stock of nutrients that is increased by the inflow *Nutrient Loading* and decreased by the outflow *Nutrient Removal*. *Nutrient Loading* is the total amount of nutrients that enter a water column during a given year while *Nutrient Removal* is the total amount of nutrients extracted from the water column during the same period. Whenever *Nutrient Loading* outweighs *Nutrient Removal*, nutrients accumulate in the water column and water quality deteriorates.

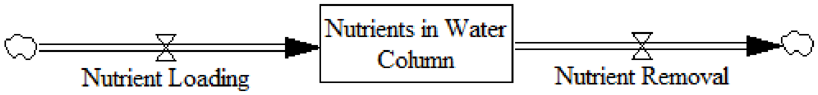

Figure 4. Stock and flow structure for nutrient accumulation in coastal waters

Managing water quality degradation requires controlling the rise of the *Nutrients in Water Column* stock. In order to accomplish this purpose, one should understand what constitutes *Nutrient Loading* and *Nutrient Removal*, and how they change over time. Figure 5 depicts the stock and flow diagram created with the stakeholder team to describe the nutrient loading to and removal from Cape Cod's embayments. As noted earlier, the model proposed in this study considers wastewater as the only source of nutrients entering to Cape Cod's coastal waters. Therefore, the system contains five different stocks where nutrients accumulate: (1) individual septic tanks known as *Title-5 septic systems*; (2) sewer treatment plants; (3) groundwater; (4) water columns; and (5) the bottom sediment. As of 2012, 90% of properties on Cape Cod depended on Title-5 septic systems for their wastewater. *Nutrients into Title-5* describes the amount of nutrients that flow into individual septic systems annually. The remaining 10% of properties were served by various sewer systems. *Nutrients into Sewer* refers to the mass of nutrients that flow into sewer treatment plants in a given year. Three outflows are possible from the stock *Nutrients in Title-5 Septic Systems*: (1) through leaching, nutrients flow into the groundwater – described by the flow Leaching from Title-5; (2) if the septic system is capable, some nutrients could be extracted from the system – described by the flow *Nutrient Removal from Title-5*; and (3) through septage transport in about every four years, nutrients flow into the sewer treatment plants – described by the flow *Title-5 Septage Transport*. Similarly, three outflows from the stock *Nutrients in Sewer Treatment Plants* exist: (1) a significant portion of nutrients are removed from the system via treatment – described by the flow *Treatment*; (2) through leaching, nutrients flow into the groundwater – described by the flow *Leaching from Sewer*; and (3) nutrients that are not removed by the treatment process flow into the groundwater as a result of treated water discharge – described by the flow *Nutrients from Treated Water Discharge*. Nutrients accumulated in the groundwater either reach the embayments, represented by the flow *Nutrient Loading from Groundwater*, or are attenuated during the groundwater travel before they reach the embayments, shown by the flow *Attenuation*.

Understanding the long-term dynamics of nutrient loadings to embayments is essential but not sufficient to cope with the coastal water quality impairment. To effectively address the degradation, policymakers should also understand the nutrient removal dynamics in water bodies as well as the relationship between nutrient loadings and nutrient removal. As illustrated in Figure 4, nutrients accumulate in the water column when the annual nutrient loadings outweigh the total amount of nutrients removed from the water column in a given year. The conceptual model in Figure 5 further elaborates on the relationship between nutrient loadings and removal. In particular, three separate outflows from *Nutrients in Water Column* stock (*Export to Ocean*, *Denitrification*, and *Sedimentation*) and an additional inflow (*Regeneration*) are identified. The model is based on the hypothesis that the annual nutrient removal rate from the water column is proportional to the total nutrients in the water (Dettmann, 2001). *Nutrients in Water Column* stock is increased by the inflow, *Nutrient Loading from Groundwater*, and decreased by three outflows: *Export to Ocean*, *Sedimentation*, and *Denitrification*. *Export to Ocean* represents the total amount of nutrients removed from a water body in a year as a result of water export from the embayment to the ocean. Dissolved nutrients in the water column are consumed by the algae. When the algae dies, it sinks to the bottom and gets decomposed by bacteria. Denitrifying bacteria converts most of the nitrogen in the algae biomass into nitrogen gas. This process, known as *denitrification*, constitutes 69-75% of the total annual nitrogen removal from the water column (Dettmann, 2001) and is represented by the flow *Denitrification* in Figure 5. Nutrients in the dead algae biomass that are not denitrified get buried in the bottom sediment. The flow *Sedimentation* describes the total annual amount of nutrients lost to the bottom sediment. Organic nutrients in sediments are later remineralized and returned into the water column. The flow *Regeneration* represents this process and increases the stock *Nutrients in Water Column*. *Sedimentation* and *Regeneration* flows create a reinforcing feedback loop between stocks *Nutrients in Water Column* and *Nutrients in Bottom Sediment*. Stated differently, when the stock *Nutrients in Water Column* raises, the flow *Sedimentation* goes up, which in turn increases the stock *Nutrients in Bottom Sediment*. As a result of the increase in *Nutrients in Bottom Sediment*, the flow *Regeneration* also goes up and further increases *Nutrients in Water Column*.

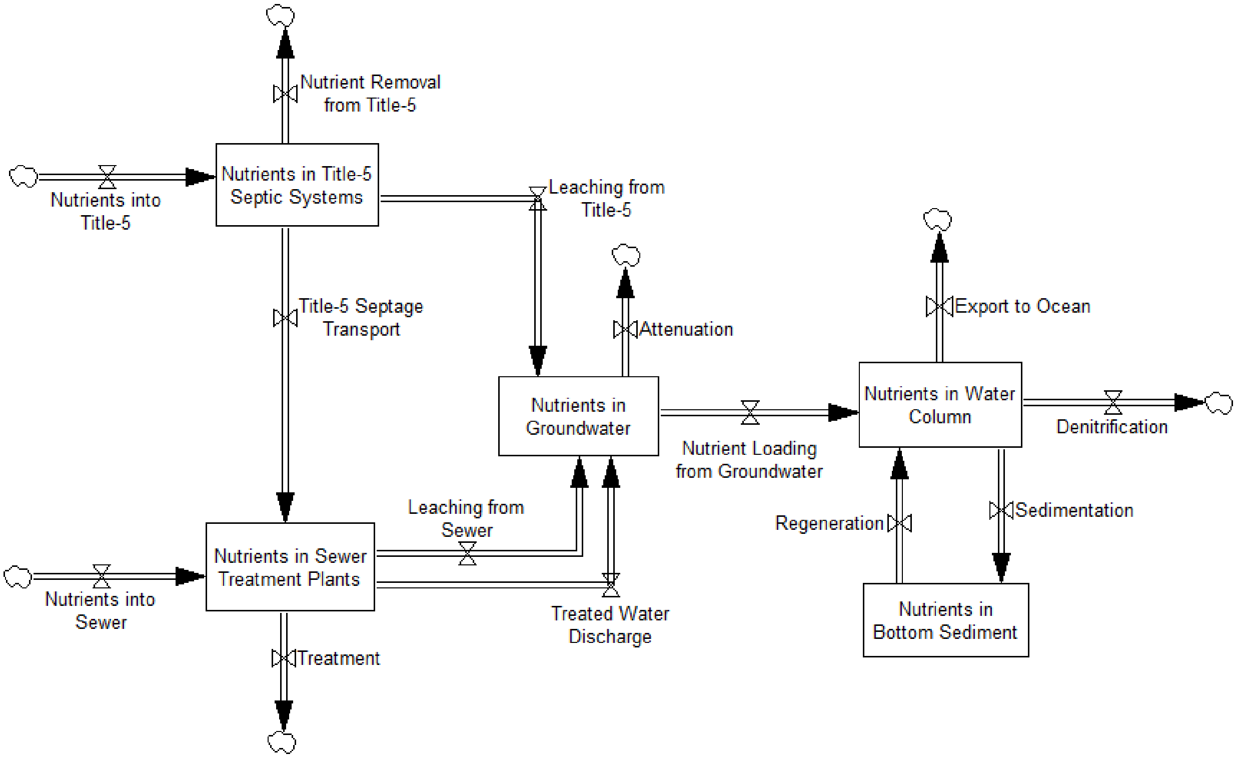

Figure 5. Nutrient Loading and Removal Pipeline

Short-Term Ecological Responses

The conceptual model in Figure 5 constitutes the core of the simulation model, described later in this paper, and focuses particularly on understanding how the nutrient concentration in coastal waters changes over a relatively long period. Driven by this long-term perspective, a coastal system's responses to variations in the nutrient concentration are shown as changes in the amount of nutrients denitrified, buried in bottom sediment, or exported to ocean annually. Although the long-term relationships between nutrient accumulation and the coastal system's responses are relatively simple (Dettmann, 2001), these dynamics are much more complex in the short-term. Figure 6 displays a simplified causal loop diagram that describes the short-term responses of aquatic systems to nutrient enrichment. Nutrients like nitrogen and phosphorus are essential food for algae, photosynthetic microorganisms that are found in most aquatic habitats. Combined with other optimum factors, such as warm temperature and lots of sunlight, excessive nutrients in water bodies stimulate the algal growth and increase the algal biomass. As the algal biomass grows, more nutrients are consumed by the algae and nutrient concentration of the water column gets reduced. In other words, the aquatic system reacts to an increase in the amount of nutrients and tries to bring it back to the stable equilibrium level by stimulating the algal growth. *Algae-Nutrient Balance* feedback loop represents this causal structure. It is a balancing feedback loop and like any other feedback loop, it works both ways. If the nutrient concentration goes below the stable equilibrium level, *Algae-Nutrient Balance* loop tries to bring it up by slowing the algal growth.

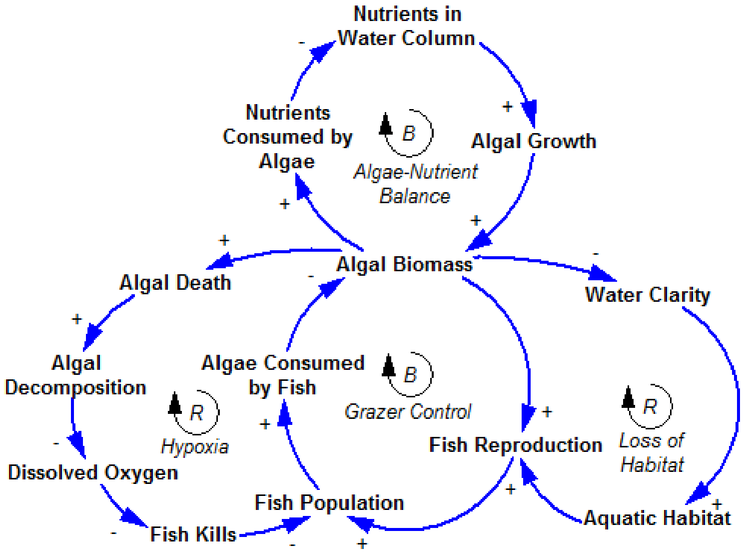

Figure 6. *Short-term Ecological Responses Causal Loop Diagram*

When the algal biomass changes (either grows or declines), the system reacts with three different feedback loops. One of them, *Grazer Control*, aims to stabilize the algal biomass level by correcting the change while the other two, *Hypoxia* and *Loss of Habitat*, reinforces the change in algal biomass. Depending on relative power of these feedback loops (i.e., which of these feedback loops dominate the system behavior), the algal biomass increases, decreases, or stays the same. *Grazer Control* is a balancing feedback loop similar to *Algae-Nutrient Balance*. Algae are eaten by fish as food. With more food available, fish reproduce more and the fish population increases. As a result of increase in the fish population, more algae are consumed by the fish and therefore the algal biomass declines.

One of the major implications of nutrient pollution is severe reduction in the dissolved oxygen content of water bodies, a process known as *hypoxia*. As algae die, they become food for bacteria that decompose the organic matter. While decomposing dead algae, bacteria use dissolved oxygen in water, which is vital for the survival of aquatic species like fish and shellfish. When the algal biomass grows, more algae die and get decomposed. In parallel with an increase in the algal decomposition, the dissolved oxygen content of water decreases, which in turn increases the probability of fish kills. As fish kills rise, the fish population goes down and less algae are consumed by fish. Consequently, the algal biomass further increases. *Hypoxia* feedback loop in Figure 6 represents the described reinforcing causal structure. Whenever this loop is dominant in the system, an increase in the algal biomass is further amplified (similarly, a decrease in the algal biomass is further reduced).

Another important ecological consequence of nutrient pollution is the habitat loss. As the algal biomass grows, it reduces the water clarity and blocks sunlight from reaching aquatic plants like eelgrass, which provides food, breeding areas, and protective nurseries for fish and shellfish. The lack of sunlight damages the aquatic habitat, which in turn reduces fish reproductivity and population. A decrease in fish population causes the amount of algae consumed by the fish to decrease as well. As less algae are consumed by the fish than what would otherwise be, the algal biomass further increases. This creates another reinforcing feedback loop, labeled as *Loss of Habitat*. Similar to *Hypoxia* feedback loop, whenever *Loss of Habitat* feedback loop dominates the system behavior, an increase in the algal biomass is self-multiplied. Although the short-term dynamics discussed above are not incorporated into the Cape Cod simulation model due to its long-term focus, policymakers should understand the complex causal structure depicted in Figure 6 in order to effectively manage the nutrient pollution problem. In particular, it is crucial to realize the reinforcing nature of *Hypoxia* and *Loss of Habitat* feedback loops.

Consensus Building Dynamics

An important characteristic of public policy problems is the need to build a widely acceptable agreement among diverse stakeholder groups with different interests about the merits of a particular solution approach (Ghaffarzadegan, 2011). Without the support of public constituency, it is hard to develop effective policies to address complex public problems that build slowly over a long time period and are often costly to solve. Coastal water quality degradation on Cape Cod is no exception. As discussed earlier in this paper, it is a counterintuitive problem that emerges from interdependencies between human and ecological systems. The problem builds for decades until its implications become prevalent. Potential solutions are costly, at least in the short-term. On the other hand, different stakeholders maintain entirely different perspectives of the problem, how it should be solved and how the cost should be distributed.

In order to generate the public support for an effective long-term solution to the water quality impairment in Cape Cod's embayments, policymakers should understand the dynamic complexity of public willingness to fund the solution. Figure 7 displays a causal loop diagram that explores the causal structure between anticipated results of the nutrient pollution and public willingness to fund an adequate solution. We explained above how an increase in the nutrient concentration causes the algal biomass to grow and the probability of fish kills to increase. Both frequent algal blooms and increasing fish kills reduce the attractiveness of coastal properties on Cape Cod, which generate a significant portion of municipal tax revenues. When property values start going down, people will react to it by looking for either a small-scale private solution (e.g., solutions that address the problem only for certain watersheds) or a large-scale public solution. Diminishing property values causes an increase in the implementation of private solutions, which eventually brings down the nutrient concentration in water columns. *Private Solution* feedback loop describes this causal structure. Similarly, *Public Solution* feedback loop explains how an increase in the nutrient concentration is later stabilized by the system via the use of a public solution. Decreasing property values not only causes an increase in the use of private solutions but also rises the public willingness to fund a large-scale public solution. When willingness to fund a public solution increases, the implementation of a public solution proceeds and reduces the nutrient concentration in water columns.

Both *Public Solution* and *Private Solution* are balancing feedback loops, which oppose whatever direction of change is imposed on the system. For instance, if the nutrient concentration is increased too much, these *stability-seeking* (Meadows, 1982) feedback loops will try to bring it down. The problem, however, is that the system is not governed by only the balancing feedback loops. The model-building team also identified five reinforcing feedback loops, four of which impact the public willingness to fund a large-scale public solution. In other words, when the willingness to fund a public solution goes down, these reinforcing feedback loops will try to bring it further down. However, like any other feedback loops, reinforcing loops also work in both directions. Therefore, if the willingness to fund a large-scale public solution increases, these reinforcing feedback loops will try to amplify it.

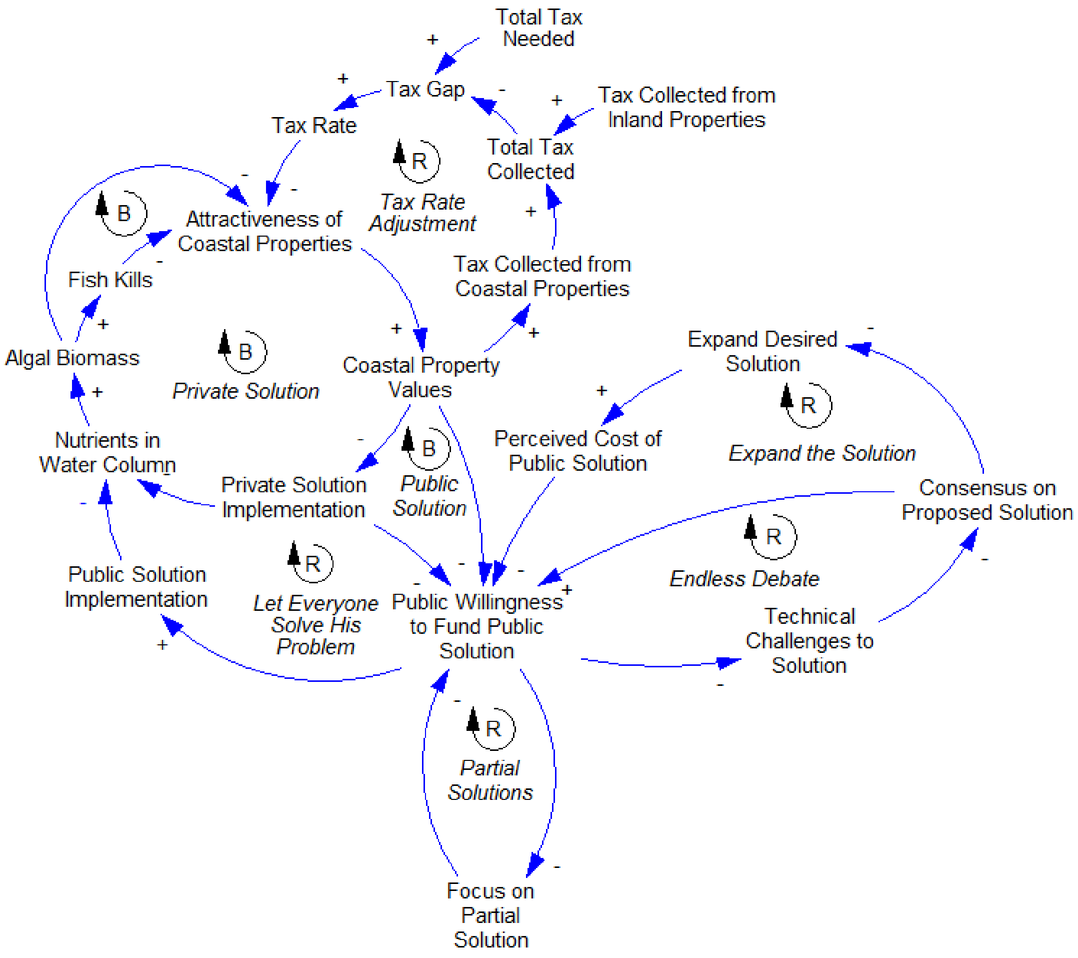

Figure 7. Willingness to Fund Public Solution Causal Loop Diagram

Large-scale solutions to complex public problems often come with short-term costs and they are hoped to produce major benefits in the long run. Perceived cost of such solutions negatively affects the public willingness to fund them. As the public willingness to fund a large-scale public solution declines, three possible reactions by the system are expected. First, the public solution implementation also declines and this causes an increase in the nutrient concentration of coastal waters. Increasing nutrient concentration boosts algal biomass and fish kills, which eventually reduce the attractiveness of coastal properties. As waterfront properties become less attractive, coastal property values start declining. Diminishing coastal property values increases the implementation of private solutions, which further reduce the willingness to fund a public solution (*Let Everyone Solve His Problem* reinforcing feedback loop). Second, the focus starts shifting to partial public solutions to reduce the perceived cost. However, focusing more on partial solutions may further reduce the willingness to fund a public solution as the proposed partial solutions will be highly criticized due to their partial nature (*Partial Solutions* reinforcing feedback loop). Third, technical challenges to the proposed large-scale public solution start increasing. The more technical challenges result in the less consensus on the proposed solution, which further reduces the willingness to fund a public solution (*Endless Debate* reinforcing feedback loop). Moreover, as the consensus on the proposed solution declines, there will be more attempts to expand the scope of the solution. If the desired solution scope increases, the perceived cost also rises and further brings down the willingness to fund a public solution (*Expand the Solution* reinforcing feedback loop).

In addition to four feedback loops that affect the willingness to fund a large-scale public solution, the system also contains another reinforcing feedback loop, which acts on coastal property values. As already explained, increasing nutrient concentration in coastal waters eventually reduces the attractiveness of waterfront properties and diminishes coastal property values. When coastal property values decline, the tax collected from coastal properties also goes down. Assuming that there is no change in the total tax needed and the tax collected from inland properties, the decline in tax collected from coastal properties increases the gap between the total tax needed and the total tax collected. As the tax gap grows, the property tax rate increases. Increasing tax rate reduces the attractiveness of waterfront properties and, as a result, coastal property values go further down. *Tax Rate Adjustment* reinforcing feedback loop describes this causal structure.

To sum up, an adequate long-term solution to the coastal water quality degradation on Cape Cod could only be possible with the support of public constituency. Therefore, it is essential for policymakers to be aware of the underlying system structure that governs the public willingness to fund a large-scale public solution. In particular, it is crucial to understand how powerful the reinforcing feedback loops described above could be in both generating and destroying the public support for an adequate solution proposal when they dominate the system behavior. If they are dominant while the public support declines, they could function as vicious cycles. On the other hand, if they dominate the system behavior when the public support for an effective long-term solution increases, they could turn to virtuous cycles.

Model Formulation

After conceptualizing the system structure that creates the coastal water quality impairment on Cape Cod, the model-building team crafted a simulation model to explore the dynamic behavior of the system as well as to experiment with different policy interventions to address the problematic behavior. Below we describe a high-level structure of the Cape Cod water quality management model. The model, divided into three main modules, aims to explore long-term dynamics of the coastal water quality degradation and analyze long-term effectiveness of various solution alternatives to keep the nutrient concentration in water columns under control. Therefore, the simulation model was built around the nutrient loading and removal conceptual model presented above. Short-term ecological responses and consensus building dynamics were intentionally left out of the simulation model.

Nutrient Loading and Removal Module

The nutrient loading and removal module constitutes the foundation of the simulation model. It examines the accumulation of nutrients in water columns over decades. Once the dynamics of nutrient enrichment in coastal waters is well understood, testing different interventions becomes possible. Figure 8 displays a simplified version of the nutrient loading and removal module where important variables and causal relationships are also shown in addition to stocks and flows (remaining variables and causal links are omitted for illustrative purposes). Table 1 specifies the parameter estimation for exogenous variables in the nutrient loading and removal module.

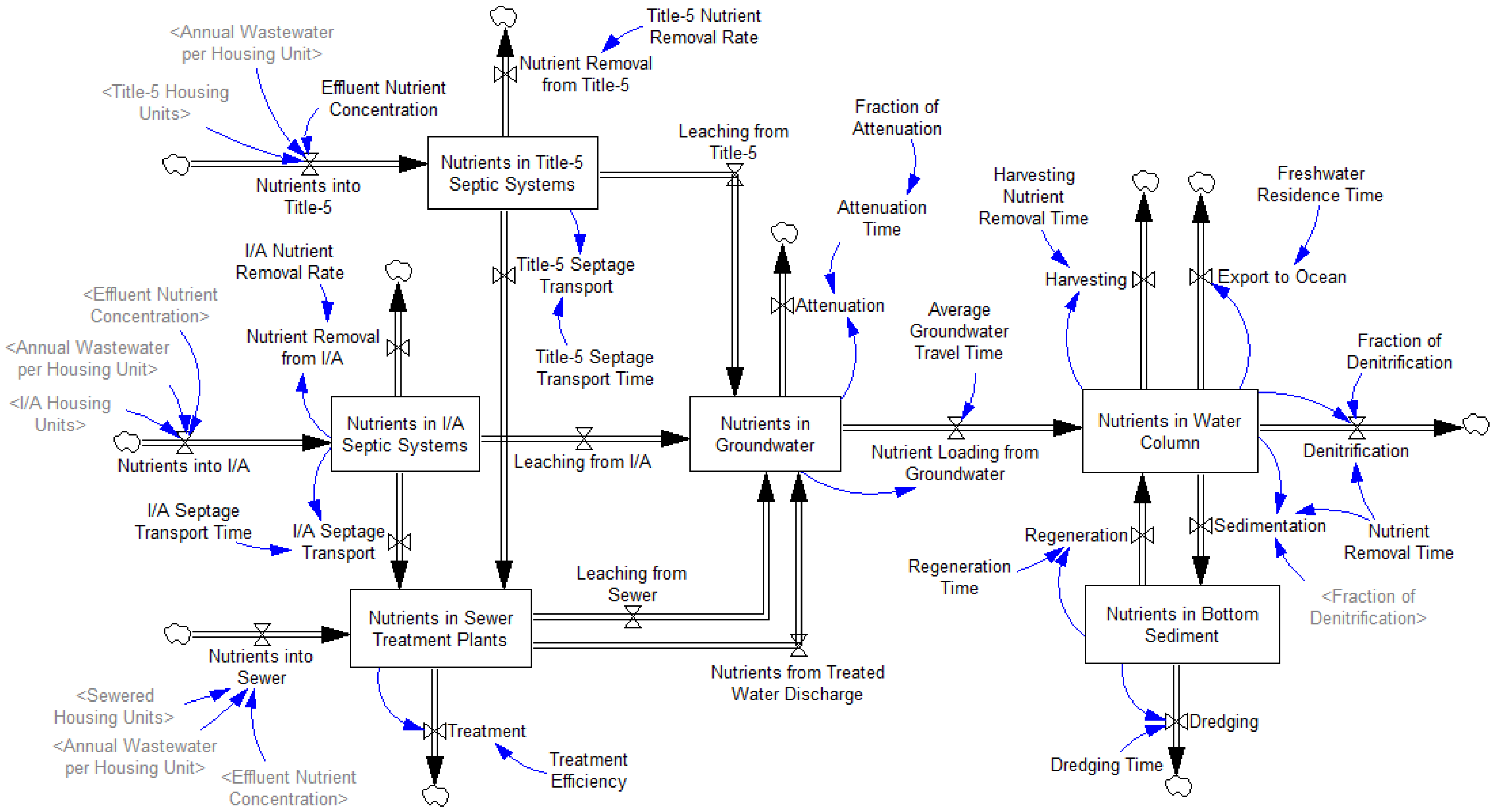

Figure 8. Nutrient Loading and Removal Module

Table 1. Exogenous Variables in Nutrient Loading and Removal Module

Variable	Description	Value
Average Household Water Use	Wastewater generation per household per day is calculated as a fraction of indoor water use	234 gallon per household per day
Fraction of Wastewater	Wastewater generated per gallon of indoor water use	0.9
Effluent Nutrient Concentration	Fraction of nutrients in a liter of wastewater	26 mg/L
Title-5 Nutrient Removal Rate	Fraction of nutrients removed by a Title-5 septic system	0
Title-5 Septage Transport Time	How often septage in a Title-5 septic system is transported to wastewater treatment facilities	4 years
I/A Nutrient Removal Rate	Fraction of nutrients removed by an I/A septic system	0.5
Treatment Efficiency	Fraction of nutrients removed from effluent by wastewater treatment facilities	0.85
Fraction of Attenuation	Fraction of nutrients removed during groundwater travel to embayments	0.265
Groundwater Travel Time	Average time that groundwater travels between point sources and embayments	10 years
Freshwater Residence Time	Average transit time through the embayment for inflowing freshwater	3 weeks
Nutrient Removal Time	How long it takes to remove all nutrients in the water column if there was not any more inflow of nutrients	3.3 months
Fraction of Denitrification	Fraction of nutrients removed in the water column by the denitrification process	0.7
Regeneration Time	How long it takes to regenerate all nutrients in the bottom sediment to the water column	1 year

Compared to its conceptual version in Figure 5, the nutrient loading and removal module contains a few additional stocks and flows. In addition to the commonly used Title-5 septic tanks, properties that are not served by the sewer system could also use more innovative septic tanks, called *innovative alternative (I/A) septic systems*, which are able to filter a significant portion of nutrients in wastewater as opposed to Title-5 septic systems. Therefore, a new stock, called *Nutrients in I/A Septic Systems*, is added to represent nutrient accumulation in I/A septic tanks. Similar to *Nutrients in Title-5 Septic Systems*, three outflows are possible from this new stock: nutrients removed by the I/A systems (*Nutrient Removal from I/A*), nutrients leaching to groundwater (*Leaching from I/A*), and nutrients transferred to a sewer treatment plant through septage transport every few years (*I/A Septage Transport*). Although there are not many properties on the Cape with I/A septic systems at the moment, the *Nutrients in I/A Septic Systems* stock and corresponding flows are included in the simulation model because one of the solution alternatives considered by the Cape Cod Commission is to encourage a wider use of I/A septic systems.

Similarly, two new flows are added to be able to experiment with two distinct solution alternatives that aim to increase the removal of nutrients from water columns as opposed to reducing the nutrient loading. One of these alternatives is to harvest oysters in water bodies. As oysters are consumers of dissolved nutrients in the water column, they are expected to reduce nutrient concentration of water columns. The outflow *Harvesting* from the stock *Nutrients in Water Column* represents the impact of oyster harvesting on nutrient accumulation in coastal waters. The other solution alternative is to physically remove the bottom sediment where nutrients also accumulate and get regenerated to the water column later. The outflow *Dredging* from the stock *Nutrients in Bottom Sediment* is added to the simulation model to test this solution idea.

Policy Interventions Module

In the proposed model, the degradation in water quality corresponds to an increase in the level of *Nutrients in Water Column* stock. In other words, if *Nutrients in Water Column* stock increases from one year to another, additional nutrients accumulate in the water column and the water quality deteriorates. An increase in a stock during a period of time can only be interpreted as follows: inflows to the stock surpass its outflows during the same period. Therefore, to reverse coastal water quality degradation, policymakers have two broad categories of alternatives: (a) reduce annual nutrient loadings so that the amount of nutrients reaching embayments within a year is less than what can effectively be removed during the same period; or (b) increase the amount of nutrients removed from water bodies in a year so that more nutrients are extracted from the water column compared to annual loadings. Two solution alternatives to enhance annual nutrient removal are oyster harvesting and physical removal of bottom sediment (dredging). Figure 8 displays how these options are modeled within the nutrient loading and removal module. This section, on the other hand, presents how the nutrient loading and removal module is extended to experiment with policy interventions aiming to reduce nutrient loadings.

As mentioned earlier, 80% of the nutrient pollution problem in Cape Cod's embayments is attributed to wastewater. Therefore, to reduce nutrient loadings, it is vital to decrease the amount of nutrients released from wastewater to groundwater. About 90% of properties on Cape Cod rely on on-site wastewater disposal governed by Title-5 of the Massachusetts Environmental Code (MA DEP, 2007) and the remaining 10% are served by a few larger off-site sewer treatment facilities managed by towns. On the other hand, while wastewater treatment facilities and sewers usually filter out most of nutrients in wastewater, the vast majority of on-site septic systems on Cape Cod are not capable of removing nutrients in wastewater because Title-5 does not require nutrient removal for on-site septic systems. Therefore, there are two major solution alternatives to reduce nutrient loadings: (1) increasing the percentage of properties served by sewer systems, and (2) replacing a significant portion of traditional on-site septic systems with more innovative ones that can filter nutrients out of wastewater.

Figure 9 displays a simplified version of the stock and flow diagram created to experiment with policy interventions aiming to reduce nutrient loadings to coastal waters (some variables and causal links are omitted for illustrative purposes). Residential properties with different wastewater systems are shown as three separate stocks. *Title-5 Housing Units* stock represents properties with traditional on-site septic systems while *I/A Housing Units* stock corresponds to properties using innovative/alternative on-site septic systems that are capable of removing nutrients. Similarly, *Sewered Housing Units* stock represents properties served by sewer systems. In order to reduce the amount of nutrients flowing into *Nutrients in Title-5 Septic Systems* stock in Figure 8, *Title-5 Housing Units* must be decreased assuming that *Annual Wastewater per Housing Unit* and *Effluent Nutrient Concentration* are constant. As shown in Figure 9, the level of *Title-5 Housing Units* stock can be reduced in three different ways: by reducing the inflow *New Title-5 Housing Units*, by increasing the outflow *Sewer Installation Rate*, or by increasing the other outflow *I/A Conversion Rate*. When relevant policies are put into effect in simulation, corresponding flows in the model are enabled or adjusted as needed. Also, both Title-5 to I/A conversion and sewer installation are bound by a maximum capacity determined by the availability of the workforce and funding. Estimations of exogenous parameters in the policy interventions module are given in the following chapter as different intervention scenarios are described.

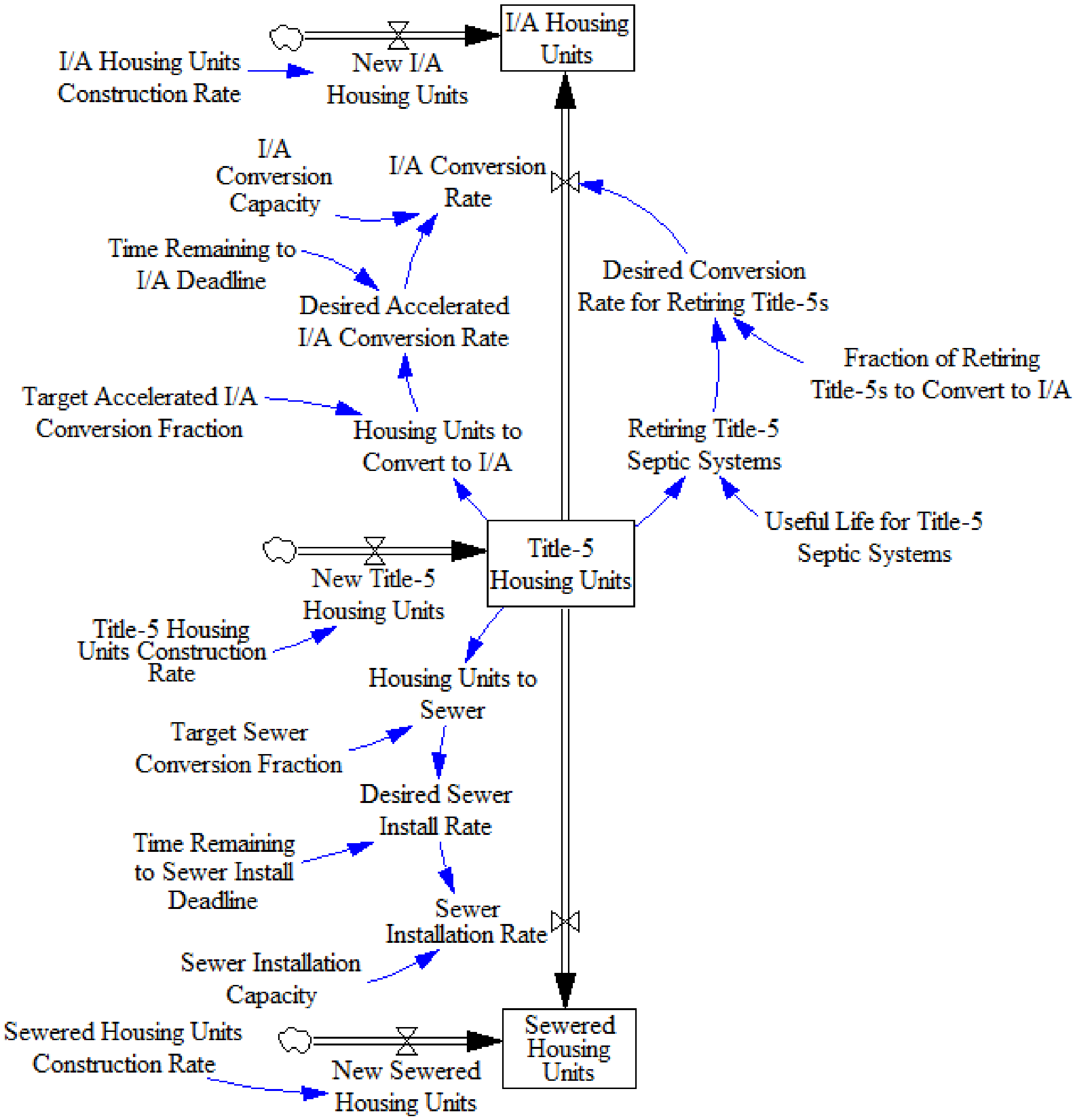

Figure 9. Policy Interventions Module

Cost Analysis Module

Most solution alternatives to reverse the degradation trend in Cape Cod's coastal waters are anticipated to be very costly when implemented in a large scale. Therefore, cost effectiveness is an important criterion to evaluate different options. In order to satisfy this need, the simulation model is supported with a specific module to analyze how much cost accrues over time as different policy interventions are put into effect. The cost analysis module, explained in detail in (Delibas, 2013), is built based on the findings of the Barnstable County Wastewater Cost Task Force (Cape Cod Commission, 2013) and designed particularly to examine cost effectiveness of two major policy intervention types: replacing traditional on-site septic system with innovative/alternative versions and installing a centralized sewer system.

Table 2. Cape-Wide Simulation Assumptions

Variable	Description	Value
Base Fraction of Title-5 Housing Units	Fraction of housing units that are served by Title-5 septic systems. Assumed to be constant between 1960 and 2040.	0.9
Base Fraction of I/A Housing Units	Fraction of housing units that are served by I/A septic systems. Assumed to be constant between 1960 and 2040.	0
Base Fraction of Sewered Housing Units	Fraction of housing units that are served by sewer system. Assumed to be constant between 1960 and 2040.	0.1
I/A Conversion Capacity	Maximum number of Title-5 septic system can be converted to I/A within a year.	5,000 housing units per year
Sewer Installation Capacity	Maximum number housing units that can be connected to the sewer within a year.	1,500 housing units per year

Simulations and Policy Analysis

Using the simulation model, an in-depth policy analysis is performed to explore how the degradation in Cape Cod's coastal waters could evolve under different future scenarios and how effectively different policy interventions can alleviate the problem in the long term. For the simulation experiments, all embayments and estuaries of Cape Cod are considered as an aggregate. In this case, the Cape-wide coastal water quality is interpreted as the average nutrient concentration of Cape Cod's all embayments and estuaries. Such an aggregative approach is preferred by this study to stay focused on understanding long-term dynamics of coastal water quality impairment, which are believed to be common across most Cape Cod watersheds.

The Cape-wide simulations analyze how the coastal water quality would be impacted by 30% growth in population and housing units between 2011 and 2040. The growth is assumed to be exogenous in this model. In other words, any degradation in coastal water quality, actions to reverse it, or values of any other model variables are assumed to have no impact on the new development between 2011 and 2040. Figure 10 displays the estimated growth pattern in housing units across the Cape between 1960 and 2110. Several remarks are worth noting: (a) the growth pattern between 1960 and 2010 is adopted to approximately match the census data with linear growth assumption between 1960-1970, 1971-1990, and 1991-2010; (b) 30% total growth is estimated between 2011-2040; (c) no growth is assumed after 2040 to keep the analysis focused on the impacts of additional development on coastal water quality degradation. Parameter estimations for exogenous model variables, shown in Table 1, are applicable for the Cape-wide simulations. Additional exogenous parameters are assigned numerical values as shown in Table 2.

Baseline Scenario

The baseline scenario is defined to answer the following question: how does the average water quality of Cape Cod embayments change over time in response to 30% additional growth over the next 30 years if no actions are taken to stop or reverse the impairment? Therefore, in the baseline scenario, 90% of new housing units constructed between 2011 and 2040 are assumed to use standard Title-5 on-site septic systems while the remaining 10% are supposed to be served by sewer systems. Figure 11 displays how the Cape-wide nutrient accumulation in coastal waters is expected to grow if no actions are taken to control the excessive nutrient enrichment. The behavior observed is similar to the growth pattern in housing units. However, two important observations must be noted. First, the nutrient accumulation in water columns keeps growing at a slowing pace approximately until 2070s even though the number of housing units levels off in 2040. More importantly, despite the fact that housing units increase by 30% compared to 2010, the amount of nutrients in water columns grows up to 44% with respect to the same year.

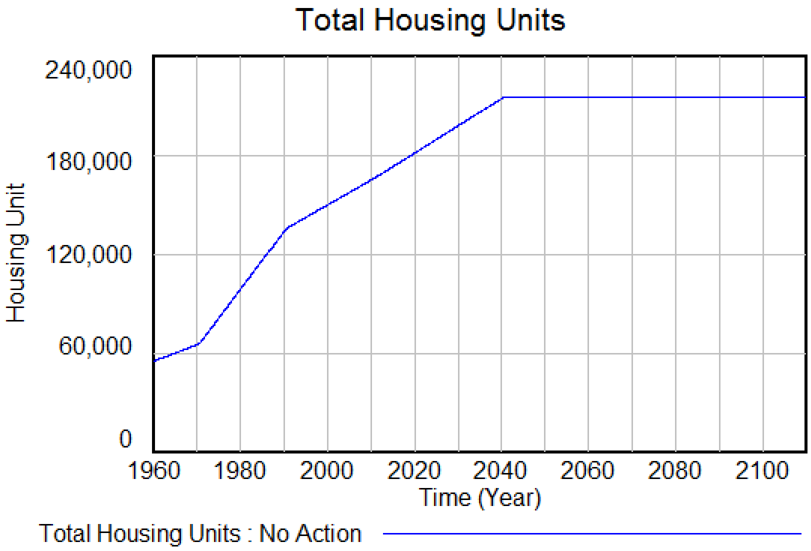

Figure 10. Cape-Wide Growth in Housing Units

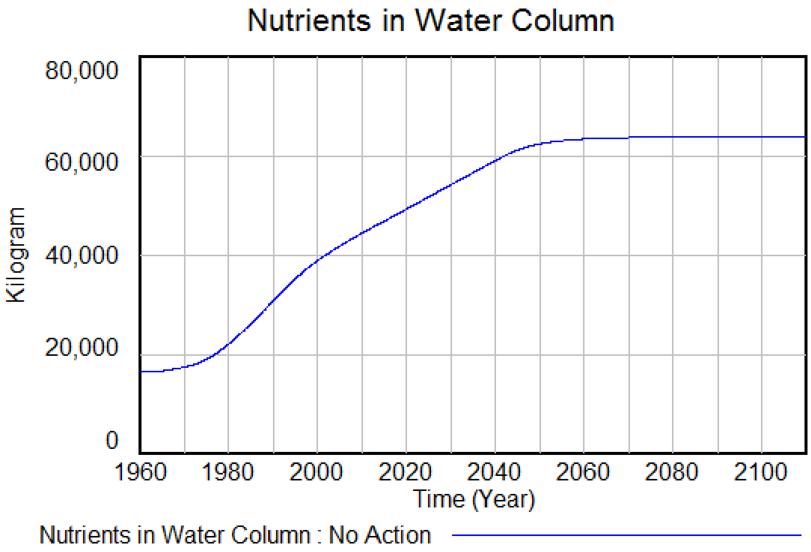

Figure 11. Cape-Wide Baseline Scenario: Nutrients in Water Column

It is vital to understand why the nutrient accumulation in water columns grows significantly more compared to how much wastewater is generated by households. Table 3 provides a summary of the growth in major model variables with respect to their 2010 levels. As seen, the amplification effect is observed in *Nutrients in Groundwater* stock. Although its inflows (namely, *Leaching from Title-5*, *Leaching from Sewer* and *Nutrients from Treated Water Discharge*) increase around 33%, the stock itself grows by 44%. When the dynamic behavior of *Nutrients in Groundwater* stock along with its inflows and outflows (see Figure 12 and Figure 13) is examined more carefully, one can observe the following: (i) the total inflows to *Nutrients in Groundwater* is always more than the total outflows during the timeframe that more housing units are constructed; (ii) after the growth-in-housing-units stops in year 2040, the total outflows from *Nutrients in Groundwater* eventually catches the total inflows but this takes almost 30 more years; (iii) finally, even if no more housing units were built after year 2010, *Nutrients in Groundwater* would still grow cumulatively by 10% until the system reaches equilibrium around year 2040.

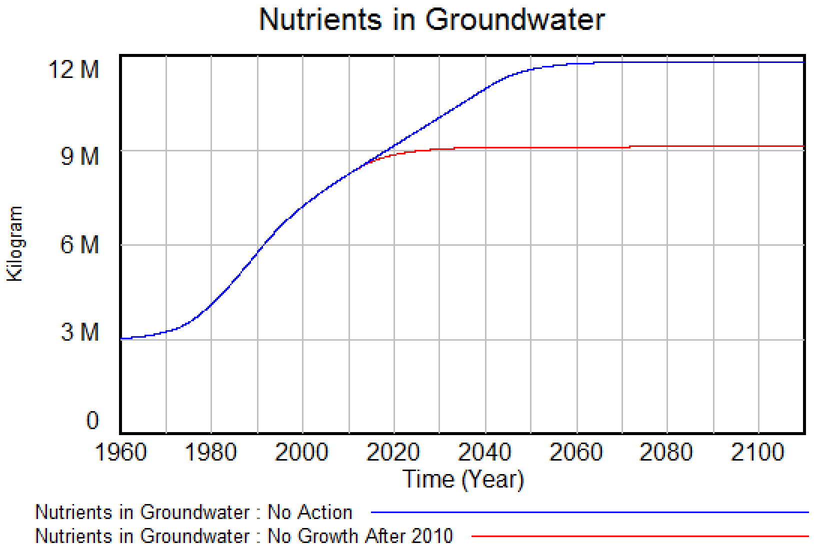

Figure 12. Cape-Wide Baseline Scenario: Nutrients in Groundwater

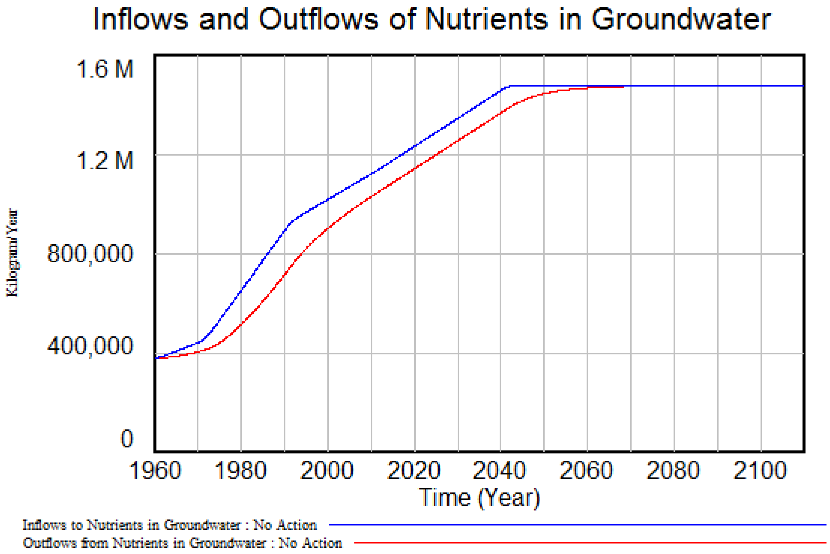

Figure 13. Cape-Wide Baseline Scenario: Inflows and Outflows of Nutrients in Groundwater

Table 3. Growth in Major Variables Compared to 2010

Variable	Growth
Nutrients in Title-5 Septic Systems	32%
Nutrients in Sewer Treatment Plants	33%
Nutrients in Groundwater	44%
Nutrients in Water Column	44%
Nutrients in Bottom Sediment	45%
Nutrients into Title-5	31%
Nutrients into Sewer	31%
Leaching from Title-5	32%
Leaching from Sewer	33%
Treated Water Discharge	33%
Attenuation	44%
Nutrient Loading	44%

Policy Intervention Scenarios

There are two major categories of alternatives to decrease nutrient accumulation in coastal waters: (a) reducing nutrient loadings to water columns; and (b) increasing nutrient removal in water bodies. Therefore, two separate sets of Cape-wide policy interventions are evaluated to improve the baseline behavior of the system. Four of these interventions aim to reduce the amount of nutrients released from wastewater to groundwater and eventually reaching embayments while the other four hope to increase how much nutrients are removed in coastal waters. Below are the nutrient loading reduction scenarios evaluated by the stakeholder team:

- **40% Sewer, 10% I/A, 50% Title-5**. Within a 50-year implementation period starting from 2020, additional sewer systems are constructed to serve 40% of Cape Cod properties that currently use on-site Title-5 septic systems. In addition, 10% of Title-5 septic systems are phased out and converted into innovative/alternative systems during the same period. Finally as of 2020, 40% of the new constructions take place in sewered areas and 10% are required to use innovative/alternative systems while the remaining 50% still use traditional Title-5 septic systems.

- **30% Sewer, 50% I/A, 20% Title-5**. Between 2020 and 2070, the Cape-wide sewer system coverage is extended to serve 30% of properties that are currently using Title-5 septic systems. During the same period, additional 50% Title-5 septic systems are converted to innovative/alternative systems. Also starting from 2020, the distribution of different wastewater systems among the new development is assumed as follows: 30% sewered, 50% with innovative/alternative system, and 20% with traditional Title-5 septic systems.

- **I/A for New Development**. Starting from 2020, all new construction projects are required to use innovative/alternative on-site septic systems instead of traditional Title-5 systems.

- **Replace Retiring Title-5 with I/A**. In addition to requiring all new construction to use innovative/alternative on-site septic systems as of 2020, also gradually phase-out existing traditional Title-5 septic systems and replace them with innovative/alternative systems when they complete their useful lifetime and need to be reconstructed.

Figure 14 displays how the nutrient accumulation in water columns changes compared to the baseline scenario when these policies are implemented exclusively (only one policy is implemented in each simulation). Table 4 summarizes the performance of each intervention scenario. The following observations are worth noting:

- For most Cape Cod embayments, nutrient concentrations around year 2000 are considered healthy and taken as targets. Although both *40% Sewer, 10% I/A, 50% Title-5* and *30% Sewer, 50% I/A, 20% Title-5* policies achieve the 2000 levels, the former lags 12 years behind the latter.

- *Replace Retiring Title-5 with I/A* scenario is highly effective in terms of performance. With this policy, the average nutrient concentration in Cape Cod's coastal waters returns to the 2000 level in 35 years after the implementation starts. However, this policy is the least cost effective due to very high operation and maintenance cost of innovative/alternative septic systems.

- *I/A for New Development* intervention is not able to achieve much. It can only reduce the peak nutrient accumulation in water columns by 15% compared to the baseline but the average nutrient concentration at the equilibrium is still 49% above the 2000 level and 30% above the 2010 level.

In addition to decreasing nutrient loadings to embayments, one could also try various interventions to increase nutrient removal in coastal waters to reduce the accumulation. For Cape Cod's embayments, two variations of oyster harvesting and dredging the bottom sediment are evaluated through simulations. Figure 15 depicts how the system responds to nutrient removal enhancement interventions while Table 4 provides a numerical analysis. Below are these intervention scenarios:

- **10% Sediment Dredging**. Starting from 2020, 10% of bottom sediment is dredged out every year.

- **20% Sediment Dredging**. Starting from 2020, 20% of bottom sediment is dredged out annually.

- **Moderate Oyster Harvesting**. As of 2020, embayments are harvested with oysters enough to remove all nutrients in 10 months if there were no new nutrient inflow to coastal waters.

- **Extreme Oyster Harvesting**. Starting from 2020, embayments are harvested with oysters enough to remove all nutrients in 5 months if there were no new nutrient inflow to coastal waters.

Neither dredging out the bottom sediment nor harvesting oysters in embayments result in considerable improvements compared to the baseline behavior. In fact, impacts of dredging is almost ignorable. Removing 10% of the bottom sediment physically every year reduces the peak nutrient concentration only by 1% compared to the no action scenario. It is important to understand why the benefits of dredging are so little. Dredging helps lower the nutrient accumulation in bottom sediment, which determines how much nutrients are regenerated and released to the water column. However, regeneration from the bottom sediment only accounts for 0.5% of total nutrient loadings. Therefore, 10% reduction in the regeneration is not able to keep up with growing nutrient loadings from groundwater discharge. Similarly, oyster harvesting cannot balance the increasing nutrient loadings even though it can reduce the peak nutrient concentration 10-20% depending on the scale of harvesting. In summary, nutrient removal enhancements are not as effective as nutrient loading reduction policies in coping with the nutrient pollution on Cape Cod.

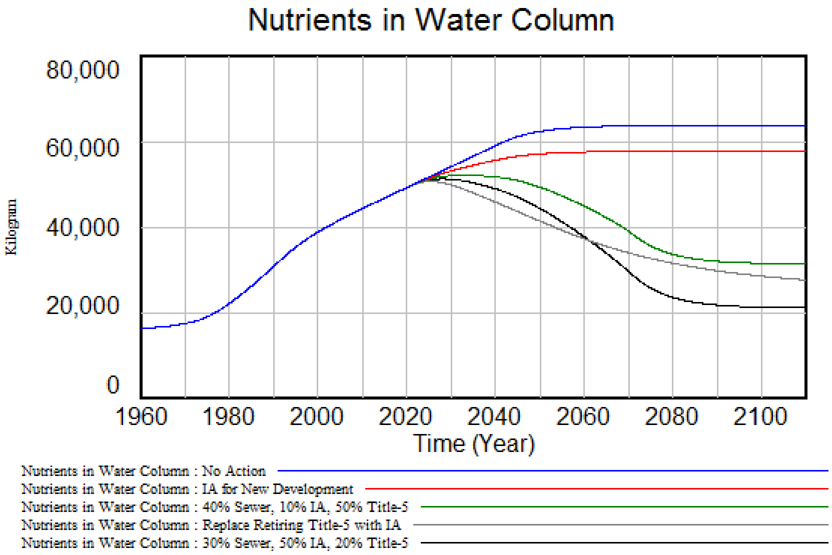

Figure 14. Cape-Wide Nutrient Loading Reduction Scenarios

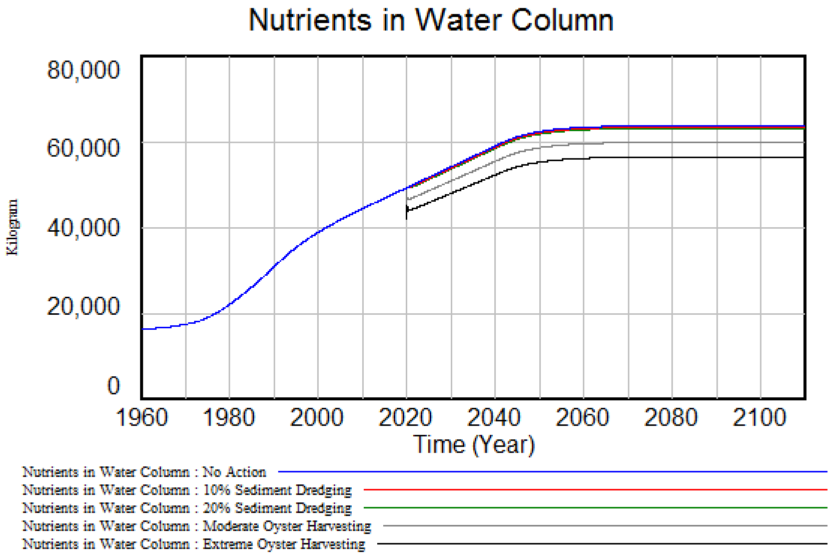

Figure 15. Cape-Wide Nutrient Removal Enhancement Scenarios

Implications of Wait-and-See Policies

Complex system problems often build slowly over a long time before their effects become prevalent. In response, people may tend to deal with these problems gradually or suggest not to take any costly actions until the problem becomes real (Sterman, 2002). For instance, instead of taking necessary steps to reverse the impairment trend in coastal water quality in a timely manner, they may propose to wait and see if the degradation and its impacts are worse than expected, and only then implement policies to mitigate the problem. However, knowing that policy interventions take significantly long time until achieving the target nutrient concentration, it is crucial to further analyze implications of such wait-and-see policies. Figure 16 presents how the nutrient accumulation in water columns change over time when the same policy is implemented with a 30-year delay (see Table 4 for the numerical comparison). Nutrient concentration in

Cape Cod's coastal waters grows up to 34% compared to the 2000 level when *40% Sewer, 10% I/A, 50% Title-5* policy is implemented starting from year 2020. On the other hand, if the same policy is implemented as of 2050, the nutrient accumulation in water bodies hikes up to 61% compared to the 2000 level. Similarly, the 2000 level of average nutrient concentration is reached 33 years later when the implementation starts in 2050 instead of 2020. To sum up, the wait-and-see policies may cause Cape Cod to face significantly higher degradation in its coastal waters, which lasts much longer.

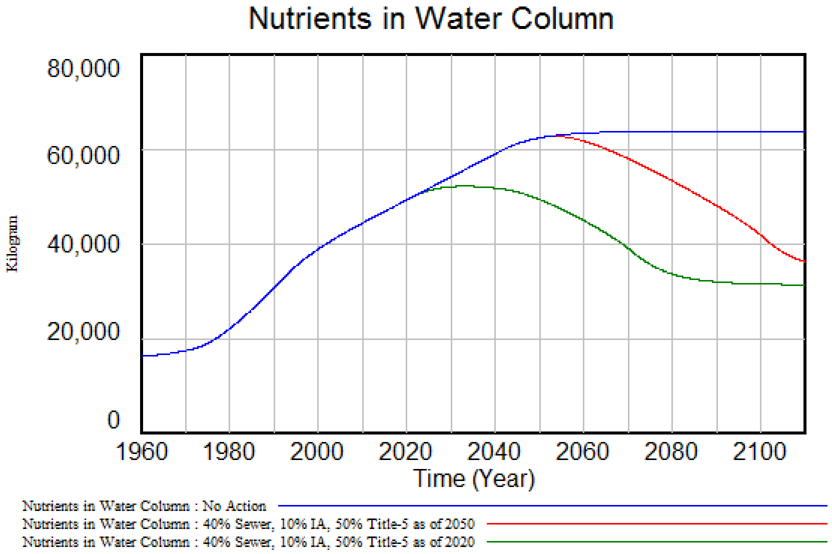

Figure 16. Impacts of Postponing the Solution

Table 4. Summary of Cape-Wide Policy Interventions

Scenario	Peak vs. 2000 Level	Returns to 2000 Level	Peak vs. 2010 Level	Returns to 2010 Level	Cumulative Capital Cost by 2110	Cumulative O&M Cost by 2110
No Action	64% higher	Never	44% higher	Never	$2.58 B	$3.50 B
I/A for New Develop.	49% higher	Never	30% higher	Never	$3.04 B	$10.53 B
40% Sewer, 10% I/A, 50% Title-5 (as of 2020)	34% higher	In 2070	17% higher	In 2061	$6.88 B	$12.56 B
40% Sewer, 10% I/A, 50% Title-5 (as of 2050)	61% higher	In 2103	41% higher	In 2096	$6.61 B	$7.56 B
Replace Retiring Title-5 with I/A	30% higher	In 2055	14% higher	In 2043	$5.37 B	$39.54 B
30% Sewer, 50% I/A, 20% Title-5	32% higher	In 2058	15% higher	In 2050	$7.32 B	$27.41 B
10% Sediment Dredging	63% higher	Never	44% higher	Never	N/A	N/A
20% Sediment Dredging	62% higher	Never	43% higher	Never	N/A	N/A
Moderate Oyster Harvesting	54% higher	Never	35% higher	Never	N/A	N/A
Extreme Oyster Harvesting	45% higher	Never	27% higher	Never	N/A	N/A

Conclusions

Coastal waters of the world are facing significant problems as a result of growing human activity. Excessive nutrient enrichment, also known as nutrient pollution, is one of those problems. It is a complex systems problem, which develops slowly over time for decades before its economic and social implications become prevalent. The long time delay between causes and effects leads many people to have widely dissimilar perspectives of the nutrient pollution problem and its potential impacts. Moreover, it makes the experimentation almost impossible for policymakers to test different interventions and adjust the final policy accordingly.

The primary goal of this work was to support the development of a regional water quality management plan on Cape Cod, Massachusetts by creating a shared understanding of the nutrient pollution problem across a wide range of stakeholders. In order to achieve this goal a system dynamics model-building project was conducted with a diverse stakeholder team – including representatives from residents, local municipalities, regional authorities, the state government, and the U.S Environmental Protection Agency – to uncover the underlying system structure that creates the degradation in Cape Cod's embayments and estuaries. Using the dynamic simulation model, a detailed policy analysis is performed to explore how the degradation in Cape Cod's coastal waters may evolve under different future scenarios and how effectively various policy alternatives can alleviate the problem. Both the group model-building process and the results of the simulation experiments revealed several critical insights about the coastal water quality degradation on Cape Cod and its potential solutions. The key lessons learned throughout this study can be summarized as follows:

- The relationship between the population growth and the degradation in coastal water quality is not linear. 30% increase in total housing units results in 44% additional nutrient accumulation in water columns.

- Nutrients keep accumulating in groundwater for 30 more years after the wastewater generation levels off. Nutrient loadings to embayments also increase during this period as the amount of nutrients reach at embayments is proportional to how much nutrients are carried by groundwater.

- Even if no more housing units are built on the Cape as of today, the average nutrient concentration still increases by 10% before the system reaches the equilibrium in 30 years.

- Wait-and-see policies may cause Cape Cod to face significantly higher degradation in its coastal waters, which lasts much longer. Therefore, taking timely actions is essential.

- In order to reduce the nutrient concentration back to a healthy level, major reduction in nutrient loadings to embayments is needed. Efforts to increase nutrient removal in embayments, such as oyster harvesting or dredging the bottom sediment, are not able to balance the growing nutrient loadings by themselves.

- An adequate long-term solution to the coastal water quality degradation on Cape Cod could only be possible with the support of the public constituency. Therefore, it is essential for policymakers to be aware of the underlying system structure that governs the public willingness to fund a large-scale public solution. Endless debates and partial solutions may only make the problem worse in the long term.

Bibliography

Biello, D. (2008). Oceanic Dead Zones Continue to Spread. *Scientific American*, 15.

Cape Cod Chamber of Commerce. (2012). *Cape Cod Economic Development*. Retrieved from http://www.ecapechamber.com/cape-cod-chamber-economic-development.asp

Cape Cod Commission. (2012). *Cape Cod Regional Wastewater Management Plan*. Retrieved from http://www.capecodcommission.org/index.php?id=332

Cape Cod Commission. (2013). *Understanding the Cost Factors of Wastewater Treatment and Disposal*. Retrieved from http://www.capecodcommission.org/resources/RWMP/RWMP_costs_comparative.pdf

Delibas, A. (2013). *A Systems Approach to Managing Nutrient Pollution in Cape Cod's Coastal Waters.* Masters Thesis, Massachusetts Institute of Technology.

Dettmann, E. H. (2001). Effect of water residence time on annual export and denitrification of nitrogen in estuaries: A model analysis. *Estuaries and Coasts*, 24(4):481-490.

Diaz, R. a. (2008). Spreading Dead Zones and Consequences for Marine Ecosystems. *Science*, 321(5891):926-929.

Ghaffarzadegan, N. a. (2011). How small system dynamics models can help the public policy process. *System Dynamics Review*, 27(1):22-44.

Hinrichsen, D. (1999). *Coastal Waters of the World: Trends, Threats, and Strategies.* Island Press.

MA DEP. (2007). *Massachusetts State Environmental Code, Title 5*. Retrieved from http://www.mass.gov/dep/service/regulations/310cmr15.pdf

Meadows, D. H. (1982). Whole earth models and systems. *Co-Evolution Quarterly*, 98-108.

Sterman, J. D. (2002). Cloudy skies: assessing public understanding of global warming. *System Dynamics Review*, 18(2):207-240.

U.S. Census Bureau. (2012). *Statistical Abstract of the United States: 2012*. Retrieved from http://www.census.gov/compendia/statab

U.S. EPA. (1998). *National water quality inventory: 1996 Report to Congress. Report No. EPA841-R-97-008.* U.S. Environmental Protection Agency, Office of Water.

UN Population Division. (2011). *World Population Prospects: The 2010 Revision, CD-ROM Edition.* United Nations Publications.

Vennix, J. (1996). *Group Model Building: Facilitating Team Learning Using System Dynamics.* Wiley.