A Systems Approach to Managing Nutrient Pollution in Cape Cod's Coastal Waters

by

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Abstract

Pressing problems are facing the coastal waters of the world due to the growing human activity. 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 thesis presents a systems analysis of the nutrient pollution problem in the context of 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. It proposes a system dynamics model 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 on Cape Cod by creating a shared understanding of the nutrient pollution problem across a wide range of stakeholders. Therefore, the proposed model was created with direct contributions of a diverse stakeholder team including representatives from residents, local municipalities, regional authorities, the state government, and the U.S Environmental Protection Agency. In addition to identifying the causal structure of the system through a set of qualitative diagrams, this thesis also proposes a formal simulation model and presents results of an in-depth policy analysis exploring how the degradation in Cape Cod's coastal waters could evolve under different future scenarios. Both the model-building process and the 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.

Thesis Supervisor: J. Bradley Morrison
Title: Senior Lecturer, Engineering Systems Division

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This thesis would never be possible if I did not have Sharon Nunes, a great mentor that I could always turn to whenever I needed guidance. Specifically about this research, she introduced me to the Cape Cod Commission; as a Cape Cod resident, was one of the stakeholders who shaped the model proposed in this thesis; offered continuous insightful feedback; and helped extensively edit this written report. Although words cannot express the debt of gratitude I owe to Sharon, I must say that I am thankful to have a motivating, inspirational, and friendly mentor like her.

I am also grateful to my advisor, Brad Morrison, who introduced me to a new way of thinking about the world around us through his system dynamics class. Having the opportunity of practicing system dynamics modeling in a real world problem with him in front of a client team was an invaluable experience. I am thankful for everything he has taught to me.

I must thank Paul Niedzwiecki and Leslie Richardson of the Cape Cod Commission for their continuous interest in this work since the first day I spoke with them on the phone. Also to Scott Michaud and Tom Cambareri for their insightful comments and discussions, and being always there when I needed their help.

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The model proposed in this thesis was shaped directly by an extensive stakeholder team: Andrew Gottlieb, Robert Ciolek, George Allair, Roger Parsons, Larry Ballantine, Paul Gobell, Phil Boudreau, Lindsey Counsel, Allan McClennen, Marilyn tenBrink, Ellen Weitzlwer, Nick Ashbolt, Marisa Mozzotta, Joanna Hunter, Brian Dudley, David DeLorenzo, Sharon Nunes, Scott Michaud, Leslie Richardson, and Paul Niedzwiecki. I am grateful for their contributions that made this work possible.

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Chapter 1

Introduction

1.1 Motivation

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]. The situation is not very different for the United States either. According to the recent census data [U.S. Census Bureau, 2012], 52% of the nation's total population lived in coastal watershed counties in 2010. Coastal watershed counties make less up than 20% of the US land area. However, total population of these counties increased by 45% compared to 1970 and 9% additional increase is expected by 2020. To sum up, the world population has been growing fast but it has been growing even faster in coastal areas.

In parallel with escalating human numbers and their ever-growing needs, 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 and Rosenberg, 2008]. Nearly entire east and south coasts of the United States are covered with dead zones. The Gulf of Mexico dead zone (shown in light blue in Figure 1-1) is one of the largest in the world and can

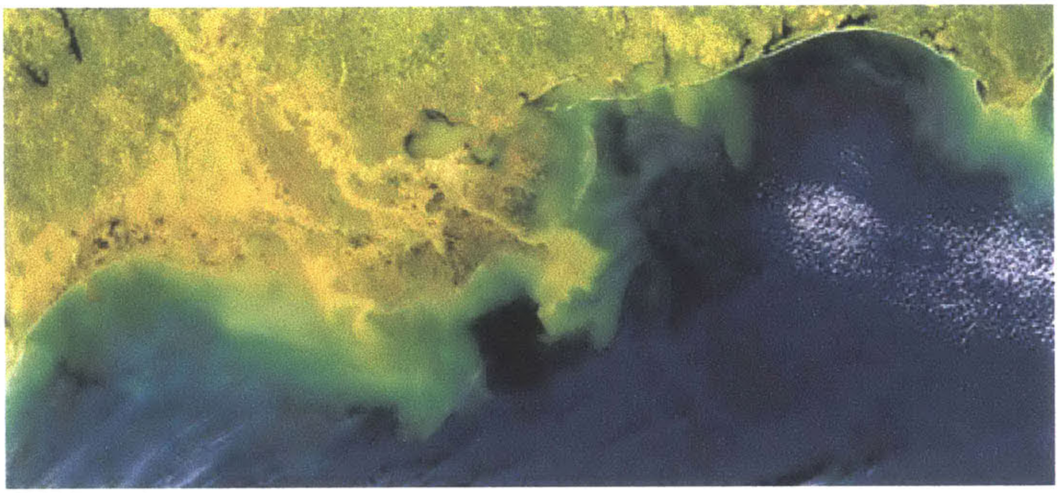

Figure 1-1: Satellite image of the Gulf of Mexico dead zone (Source: Jacques Descloitres, NASA)

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, 1998b].

In response to spreading nutrient pollution problem, the US Environmental Protection Agency created a National Nutrient Strategy [U.S. EPA, 1998a] to develop numeric nutrient criteria to help states, regions, and towns move toward adopting water quality standards for nutrients. Cape Cod, Massachusetts is one of these regions that is in the process of developing a regional water quality management plan. The primary motivation behind this study is to support the decision making process on Cape Cod by investigating how the nutrient pollution problem has been developing in the region since 1960s, how it might evolve over the next several decades under different future scenarios, and how to design effective policies to alleviate it.

Figure 1-2: Algal bloom in Chesapeake Bay (Source: Chesapeake Bay Program)

1.2 Problem Statement

Continuous degradation in coastal wates is considered as one of the greatest threats to Cape Cod's environmental and economic future. In order to respond adequately to this threat, policymakers need to better understand core dynamics leading to the degradation and its potential impacts on economy and society.

The Cape Cod aquifer is the only source of drinking water for Cape Cod and it is recharged solely by rainfall. The aquifer also supplies all of the water for the Cape's thousands of lakes and ponds, and flows to the sea. 85% of the Cape Cod homes use on-site septic systems that are not capable of filtering nutrients like nitrogen and phosphorus[Cape Cod Commission, 2012]. Discharged nutrients arrive at estuaries and embayments after traveling through the aquifer and fertilize the algal growth that blocks sunlight, obstructs natural ecosystems of fish and shellfish, and destroys recreational appeal.

Environment, economy, and society are highly interconnected systems on Cape Cod. Residential development over the last 50 years and degradation in coastal water quality shows a parallel. Even though there have not been any economic indicators of the problem so far, water quality degradation is anticipated to have significant future economic impacts for the Cape in property values, fish stocks, shellfishing, tourism, etc. On the other hand, there is an increasing focus on the Cape to transition from seasonal to year-round economy. However, different economic development patterns could have completely different environmental impacts, especially on coastal water quality. Therefore, it is essential to better understand the structure of the overall system and interactions among different components in order to build effective economic development and water quality management plans.

1.3 Thesis Statement

This thesis proposes a systems model of the coastal water quality degradation observed on Cape Cod for the purpose of identifying the core dynamics leading to the degradation. The proposed model is a theory of the underlying urban structure and internal relationships that create the impairment. The model deliberately focuses on the impact of wastewater, which is only one of numerous factors contributing to the problem. Yet this single factor is known to cause 80% of the degradation in Cape Cod's embayments [Cape Cod Commission, 2012]. Once the proposed dynamic model is accepted as adequate to describe the coastal water quality degradation, it can serve as a *management flight simulator* [Sterman, 2000] to support the decision making process. In particular, it enables decision makers to simulate various future scenarios over the next several decades and analyze potential policy interventions to address the problem in terms of effectiveness and cost.

1.4 Methods and Approaches

The project underlying this thesis 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. 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 particular, the project aimed to answer the following questions:

- What exactly is the problem Cape Cod encounters?
- How has the problematic situation developed over the last several decades?
- How could the problem evolve during the following decades under different future scenarios?
- What might be the underlying causes of the problem?
- How effectively can different policies alleviate the problem in the long term?

The method chosen to answer these questions was to build a system dynamics model of the *closed-boundary system* [Forrester, 1969] that creates the degradation in coastal water quality. The closed-boundary concept indicates that a behavior of interest in a dynamic system is never imposed from the outside but it is rather created within a closed boundary by the internal structure of the system. Moreover, the problematic behavior is often created over a long time period. Therefore, an adequate solution to the problem can only be developed after the internal structure of the system is correctly identified. Once the system structure is represented in a system dynamics model, it can be used to develop insights about past and future behavior of the system.

One approach to building such a model to support policy making is to acquire sufficient knowledge of the system through scientific research and stakeholder interviews, formulate and analyze the model, and present findings to policy makers. However, studies on the impact of computer models on decision making show that most of the learning about the problem of interest occurs while building the model [Vennix et al., 1998]. Stated differently, just building models and reporting what is learned is not sufficient to change the behavior of decision makers. Therefore, a different model-building approach was taken for this project. The proposed model was created with a diverse stakeholder group that had representatives from residents, local municipalities, regional authorities, the state government and the U.S Environmental Protection Agency (the complete list of team members is provided in Appendix B). This process, known as *group model-building*, perceives model building as a method to structure debate and to create a learning environment in which assumptions and strategies can be identified and tested [Vennix et al., 1998]. As a result, strategic decision making is improved by enhancing team learning, fostering consensus, and creating commitment among team members.

The key premise underlying the group model-building is that when dealing with a complex problem, all team members will have a limited view of the problem. People tend to focus on parts rather than the whole and their mental models are limited by human information processing capabilities [Vennix, 1996]. Therefore, designing effective policies to address complex problems first requires to expand the view of the problem by eliciting and integrating different mental models into a more holistic description of the problem. To achieve this goal, the group model-building employs system dynamics methodology.

Throughout this project, four half-day group model-building sessions were held with the stakeholder team. The first session was primarily about defining the problem. Over 90 different variables were identified by the team to have a bearing on coastal water quality degradation. Among these variables, a few were chosen as best descriptors of the problem and behavior of those variables 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, effectiveness and cost of various policy alternatives were analyzed using the simulation model.

It must be understood that the ultimate goal of the project was not to build a system dynamics model. Instead the goal was to create a shared understanding of the nutrient pollution problem on Cape Cod among a diverse stakeholder group. It is also worth noting that the model created by the team is not a complete model of the underlying system structure and it is not meant to be. As elegantly stated by George E. P. Box, "all models are wrong but some are useful". The proposed model is meant to be an incomplete but useful representation of the system structure that has created continuous coastal water quality impairment on Cape Cod since 1960s.

1.5 Organization of the Thesis

The rest of this thesis is organized as follows:

- Chapter 2 provides a summary of how systems thinking and modeling could help policymakers overcome major problems of the policy making process and identifies the related work in literature.
- Chapter 3 introduces the Cape Cod water quality management model - how it is defined, conceptualized, and formulated.
- Chapter 4 presents a detailed policy analysis for managing the nutrient pollutions in Cape Cod's coastal waters.
- Chapter 5 concludes the thesis by summarizing the insights developed throughout this study.
- Appendix A provides a brief overview of system dynamics modeling for readers who are not familiar with this methodology.
- Appendix B exhibits important feedback given by stakeholders during the group model-building sessions.
- Appendix C presents how important model variables behaved during different policy simulations.
- Finally, Appendix D lists important equations of the simulation model.

Readers who are not familiar with system dynamics modeling are strongly encouraged to read Appendix A before reading Chapter 3.

Chapter 2

Systems Thinking and Modeling in Public Policy Making

2.1 A Note on Systems Thinking

The behavior of a system is determined by its internal structure, not by the outside factors acting on it. The system may be activated, restricted, or impacted by external forces. However, the system's response to these forces is shaped exclusively by the structure of the system. Donella Meadows [Meadows, 2008], one of the world's foremost systems thinkers, illustrates the relationship between system structure and behavior with a simple but powerful example:

> Early on in teaching about systems, I often bring out a Slinky. In case you grew up without one, a Slinky is a toy – a long, loose spring that can be made to bounce up and down, or pour back and forth from hand to hand, or walk itself downstairs.
>
> I perch the Slinky on one upturned palm. With the fingers of the other hand, I grasp it from the top, partway down its coils. Then I pull the bottom hand away. The lower end of the Slinky drops, bounces back up again, yo-yos up and down, suspended from my fingers above.
>
> "What made the Slinky bounce up and down like that?" I ask students.
>
> "Your hand. You took away your hand," they say.
>
> So I pick up the box the Slinky came in and hold it the same way, poised on a flattened palm, held from above by the fingers of the other hand. With as much dramatic flourish as I can muster, I pull the lower hand away. Nothing happens. The box just hangs there, of course.
>
> "Now once again. What made the Slinky bounce up and down?"
>
> The answer clearly lies within the Slinky itself. The hands that manipulate it suppress or release some behavior that is latent within the structure of the spring.
>
> That is a central insight of systems theory.

A Slinky is a relatively simple system, in which the relationship between structure and behavior may be easy to understand. When it comes to more complex systems – such as environment, cities, economies, or societies – this relationship may seem less obvious. Yet the core premise of systems theory remains true no matter how complex the system is. Systems, to a large extent, are responsible for their own behavior. They perform what they are structured to achieve.

Thus, in order to understand how a system works, what makes it produce a problematic behavior, and how to improve its performance, it is essential to have a good grasp of the underlying system structure. However, what is a system and what makes its structure? A system is not just a collection of independent parts. Instead, it is "an interconnected set of elements that is coherently organized in a way that achieves a purpose" [Meadows, 2008]. In other words, a system consists of three kinds of things: *elements*, *interconnections*, and a *function* or *purpose*. Elements and interconnections among them constitute the structure of a system, which in turn determines the function or behavior.

The behavior of a system is mostly driven by the interactions among its elements. In fact, an essential property of a systems is that it cannot be divided into independent parts. When an element is separated from its system, it loses its essential function. Russel Ackoff, another renowned systems thinker, explains this point in one of his system thinking lectures using the analogy of cars saying that if you take a car apart, it is no longer an automobile. More critically, the motor, which is necessary to move a car, cannot move anything – even itself – when you separate it from the car. Hence, to understand the emergent behavior of a system, interactions among elements must be excelled rather than the actions of individual elements.

In summary, systems thinking is an intuitive, holistic, and endogenous way of seeing and thinking about the problems surrounding us. It considers problems as undesirable products of underlying system structures and explores solutions again within the systems instead of focusing on external agents. It sees the world as a complex system, in which everything is connected to everything else. It is "comforting, in that solutions are in our hands, but also disturbing because we must *do things* or *see things* differently" [Meadows, 2008].

2.2 Why Public Policies Fail in the Long Term

Pressing problems are facing our world. Hunger, poverty, economic instability, environmental degradation, and ever-increasing demands of humanity on natural resources are just a few of the many problems surrounding us. Although a lot of effort has been put into resolving them, these problems still persist. No one intentionally creates those problems and no one wants them to last, but even so they are persistent. More dramatically, some of our well-intentioned efforts to resolve them have created further problems. For instance, we have constructed more and more roads to reduce the traffic congestion in our cities. Yet decades later, our roads are more congested than they have ever been.

So, why do these challenging problems persist over time? Why do our well-intentioned efforts fail to address them appropriately? And why do policies create unintended consequences? This section presents three characteristics of the public policy making that are believed to influence the failure of policies in the long term: (a) linear and reductionist mental models; (b) inability to experiment and adjust policies; and (c) non-participatory decision making processes. The subsequent section, then, explains how systems thinking and modeling can help policymakers overcome these challenges.

Policy resistance [Sterman, 2000, Meadows, 2008] is a well known phenomenon in how complex systems behave. It describes situations where interventions to improve the system behavior are delayed, diluted, or defeated by the response of the system to the intervention itself [Meadows, 1982, Sterman, 2000]. As an example, consider the U.S forest fire suppression policy [Sterman, 2000]. In order to reduce the total acres consumed in forest fires, suppression efforts are increased to put out fires of any size. Indeed, the policy has achieved reduction in the number of fires as intended. On the other hand, the suppression efforts have also increased the accumulation of dead wood and other fuels in forest floors, and led to bigger and more dangerous fires. As a result, the total forest area burned by wildfires has increased instead of decreased.

The human mind is known to have a limited capacity to deal with *dynamic complexity* arising from interactions among elements of a system [Simon, 1957, Vennix, 1996, Sterman, 2000]. In response, it favors linear thinking [Van den Belt, 2004], which ignores feedback loops and time lags. Linear thinking erroneously assumes that an action causes only one effect, and this effect happens immediately. Yet dynamic behavior of complex systems is governed by feedback loops and delays. Therefore, there is a major gap between the complexity of systems we live in and the linear, reductionist mental models of those systems that guide our decisions. Policy resistance is the result of this gap.

Limited capability of human mental models to cope with dynamic complexity makes the experimentation a necessity to improve the future performance of a system. In other words, to create long-lasting effective policies, policymakers need to test different interventions, observe how the system reacts to them, and adjust policies accordingly. However, policy resistance, long delays between actions and their consequences, and one-shot nature of most public policy problems make the experimentation very difficult and costly in real systems [Sterman, 2000, Ghaffarzadegan et al., 2011].

Finally, creating effective long-term policies often requires building consensus among a wide range of stakeholder groups [Vennix, 1996, Van den Belt, 2004]. However in practice, stakeholders are usually not in the center of the policy making process. They are at most consulted by the experts conducting studies, such as model building, to support the policy making. But even those studies often do not involve relevant stakeholder groups directly. Consequently, stakeholders neither agree with outcomes of these studies nor support the resulting policy. Inability to build consensus increases the likelihood of conflicts during the implementation [Van den Belt, 2004]. With more conflicts among stakeholders, policies are less likely to be successful in the long run.

2.3 A Recipe for Successful Long Term Policies

To create policies that will successfully address messy problems in the long term, policymakers need tools and methods to overcome inherent difficulties of the public policy making process. They need methods to expand the boundaries of limited human mental models and to identify the implications of feedbacks created by the policies. They need tools to simulate the long term behavior of the system and to conduct free experiments of different intervention alternatives. Finally, they need processes to increase the participation of stakeholders in the decision making and to build consensus among them about merits of particular policies.

Fortunately, such tools and methods already exist and they are increasingly used to design successful policies both in companies and public policy settings. This thesis is based upon two of them: *system dynamics* and *group model-building*. System dynamics is a method to systematically elicit and share mental models, to integrate these mental models into a more holistic view of the problem, and to explore the dynamics of this holistic view through simulations [Vennix, 1996]. It is worth noting that eliciting and mapping mental models, while necessary, is not sufficient to deal with dynamic complexity, feedback structure, time delays, accumulations, and nonlinearities of complex systems [Sterman, 2000]. Hence, simulation is essential to test dynamic hypotheses. Moreover, such simulation models can be used by policymakers to experiment with different interventions and adjust the policies accordingly.

Complex public policy problems often impact diverse stakeholder groups who hold widely different perspectives of the problem. To achieve stability during the implementation, these stakeholders must be represented in the policy making process. However, when dealing with a dynamically complex problem, different individuals, by definition, will have a limited view of the problem due to their limited mental models compared to the complexity of the problem at hand. Therefore, there is a need to create a shared understanding of the problem as well fostering consensus on the issue and ensuring commitment with the final policy decision. Group model-building [Vennix, 1996] is a method of creating system dynamics models with a diverse stakeholder team to increase understanding of a complex problem among stakeholders, to build consensus after sufficient deliberation, and finally to create acceptance of the resulting policy decision. *Mediated modeling* [Van den Belt, 2004] is another method that is very similar to group model-building and aims to create effective public policies again using system dynamics and stakeholder participation. Mediated modeling is used particularly in the environmental policy making.

2.4 Related Work

Building system dynamics models to study important problems in public settings has a long tradition dating back to some early classics of the field, *Urban Dynamics* [Forrester, 1969], *World Dynamics* [Forrester, 1971], and *The Limits to Growth* [Meadows et al., 1972, Meadows et al., 2004]. Since then system dynamics methodology has been used to analyze public policies in a variety of areas including environment [Van den Belt, 2004, Guo et al., 2001], climate change [Sterman and Sweeney, 2002, Sterman, 2008, Fiddaman, 1997, Fiddaman, 2002], public health [Homer et al., 2004, Richardson, 2007, Cavana and Clifford, 2006], energy [Naill, 1992, Ford, 2005], sustainability [Saeed, 1991, Sterman, 2012], and others.

In water and wastewater management, system dynamics models are used extensively to evaluate regional, national or global water resources management policies [Winz et al., 2009, Abbott and Stanley, 1999, Simonovic and Fahmy, 1999, Simonovic, 2002, Simonovic and Rajasekaram, 2004, Guo et al., 2001, Xu et al., 2002, Connor et al., 2004, Sehlke and Jacobson, 2005, Neto et al., 2006]. Several studies in drinking water quality management [Hines and Knight, 1971, Albuquerque, 2004] and water and wastewater network management [Rehan et al., 2011] are also noteworthy. However, applications of system dynamic to the nutrient pollution management has been limited so far [Vezjak et al., 1998, Mirchi and Watkins, 2012, U.S. EPA, 2013].

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Chapter 3

Cape Cod Nutrient Pollution Management Model

3.1 Problem Identification

The objective of system dynamics modeling is to better understand the structure of a system that gives rise to a problematic behavior. Therefore, the model-building process starts with identifying the problem that will be studied throughout the project from a systems point of view. However, the approach taken to identify the issue of interest is not to write down a detailed problem statement. Instead, the concern is captured by (a) identifying a small set of variables that can effectively describe the problematic behavior; and (b) sketching approximate behavior of these variables over time in a set of graphs, called *reference modes* [Sterman, 2000]. Reference modes are central to the model-building process. They specify the pattern of the problematic behavior that the model should be able to replicate.

Identifying several variables that best characterize the problem often requires generating a long list of variables that have a bearing on the issue of interest and selecting the most important ones. For this project, group model-building sessions were started 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 different categories. After generating a long list of relevant variables, the team chose three of them as most important for describing the nature of the problem: (1) nutrient loading; (2) property values; and (3) public understanding of coastal water quality degradation. For each selected variable, a reference mode was drawn by the team 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. The complete list of variables and additional reference modes are provided in Appendix B.

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

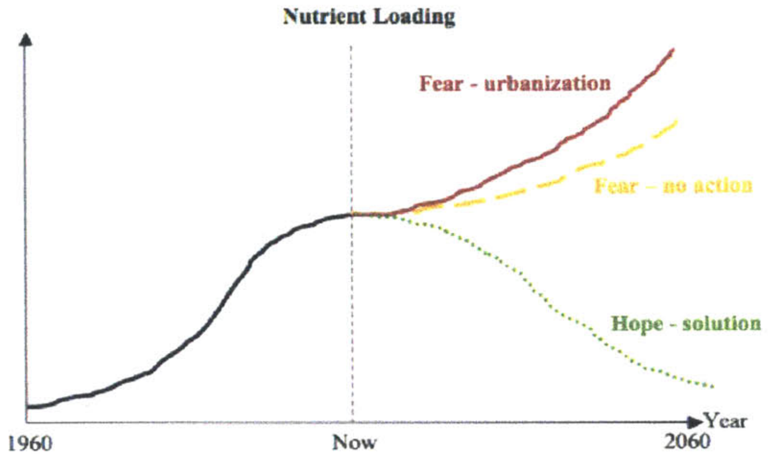

Figure 3-1: Nutrient Loading Reference Mode

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 3-1 displays an approximate plot of how the Cape-wide nutrient loading has changed since 1960 and how it is 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 3-2 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 ("hope") or not solved ("fear").

A typical characteristic of complex systems is that the cause of a problem may lie far back in time from its symptoms [Sterman, 2000]. On the other hand, research shows that people, in general, underestimate time delays [Sterman, 1989, Sterman, 2000, Sterman, 2012, Buehler et al., 2002, Faro et al., 2010]. Underestimating time delays causes people to believe that the appropriate short-term response to a potential long-term risk is to wait until harmful effects become evident rather than taking timely actions, which are usually costly in the short term. However for complex systems, wait-and-see policies often do not work well [Sterman, 2012]. By the time potential harms become real, the system might reach an irreparable state.

Figure 3-2: Property Values Reference Mode

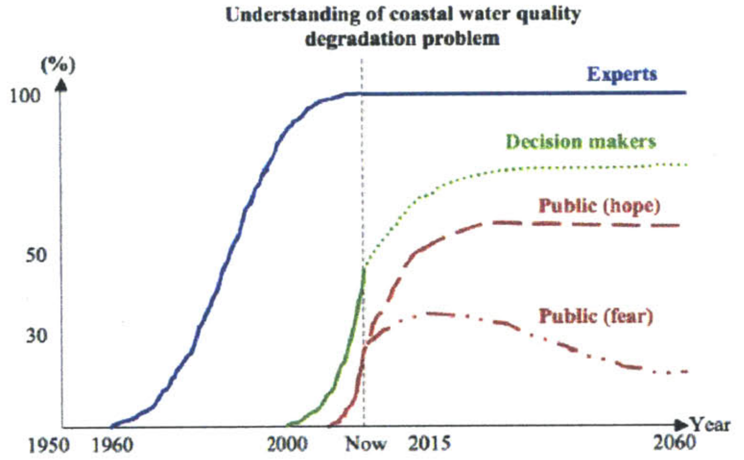

Figure 3-3: Problem Understanding Reference Mode

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 3-3 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 experts' and decision makers' understanding of the problem since 1960s.

3.2 System Conceptualization

After describing the problematic behavior through several graphs over time, the next step in the model-building process is to conceptualize the system structure that gives rise to this behavior. An important task in system conceptualization for system dynamics model-building is to define the system boundary, which determines what is considered to belong to the modeled system and what is not [Vennix et al., 1998]. If omitting an element does not cause misinterpreting the problematic behavior then this element can be left out of the system boundary [Forrester, 1968].

Regarding the coastal water quality impairment on Cape Cod, it is already known by the Cape Cod Commission and other stakeholder groups that 80% of the degradation 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.

After the system boundary is defined, conceptualization of the system starts. System conceptualization aims to (a) determine accumulations in the system and what changes them; and (b) identify feedback loops of circular causality. Two types of diagrams are employed to accomplish these purposes: *causal loop diagrams* and *stock-and-flow diagrams*. Causal loop diagramming is a powerful tool in system dynamics toolset to express the causal structure of a system and to identify feedback loops. On the other hand, *stock-and-flow diagrams* are used to describe where in the system, accumulations take place and what increases or decreases these accumulations. Appendix A provides more details on both diagram types.

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? The following subsections describe the conceptual models drawn with the team based on their responses to these questions.

3.2.1 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.

Accumulations are represented by *stocks* in system dynamics modeling. Stocks characterize the state of the system and provide it with memory. They also create delays that often cause disequilibrium in the system behavior [Sterman, 2000]. Figure 3-4 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.

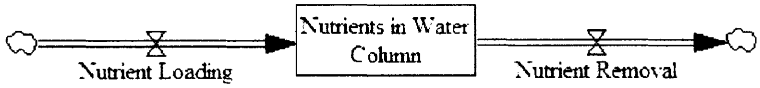

Figure 3-4: Stock and flow structure for nutrient accumulation in coastal waters

Managing water quality degradation requires controlling the rise of *Nutrients in Water Column* stock. To accomplish this purpose, one should understand what constitutes *Nutrient Loading* and *Nutrient Removal*, and how they change over time. Figure 3-5 depicts the stock and flow diagram, also known as *pipeline*, 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 thesis 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 depend 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,

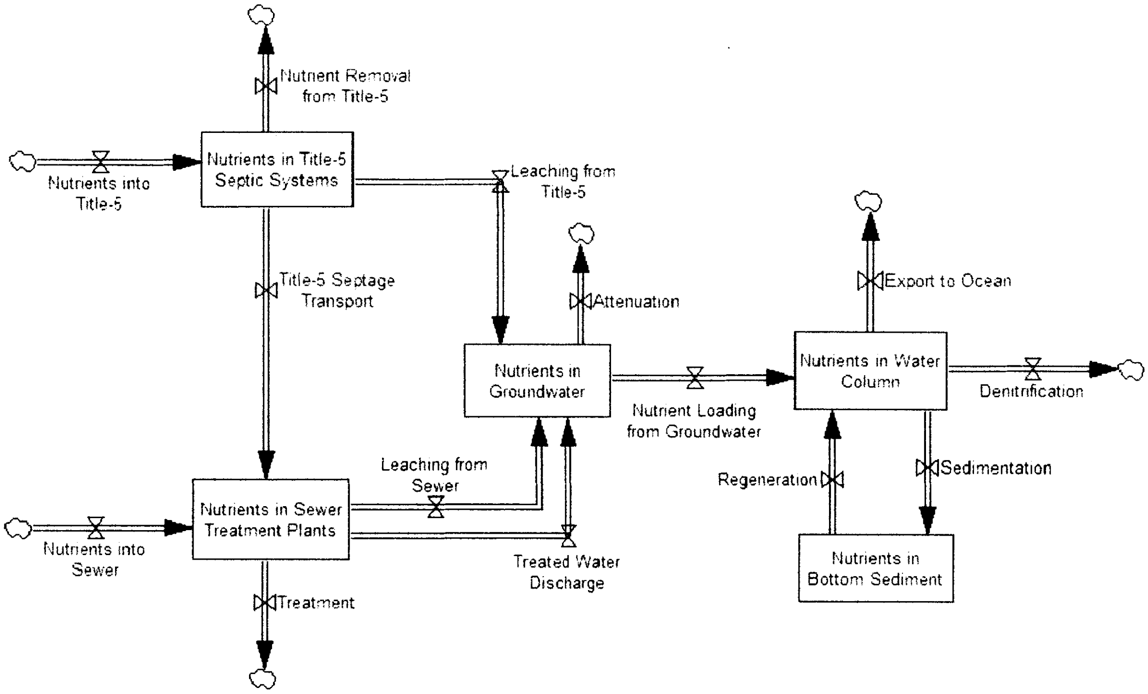

Figure 3-5: Nutrient Loading and Removal Pipeline

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 3-4, 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 3-5 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]. Referring to numerous other research, Dettmann states that the long-term relationships between nutrients in water column and responses of estuaries and marine mesocosms

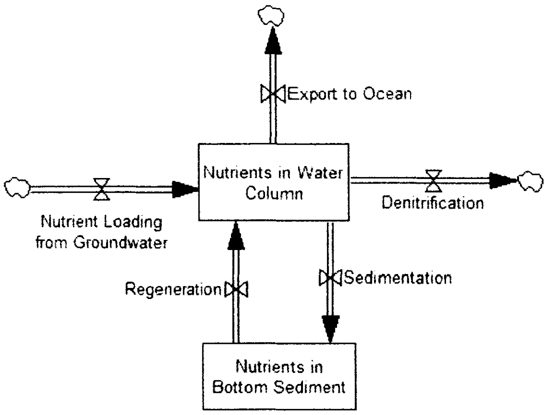

Figure 3-6: Nutrient Removal Pipeline

are much simpler compared to complex short-term (e.g., daily, weekly, or seasonal) dynamics. As the main objective of this research is to support long-term policymaking on Cape Cod to cope with the coastal water quality degradation, primary emphasis is given to the long term nutrient removal dynamics in water bodies. However, the following subsection presents a qualitative analysis of short-term ecological responses to nutrient accumulation in water columns.

Nutrient removal portion of the model depicted in Figure 3-5 is redrawn in Figure 3-6 for illustrative purposes. *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 3-5.

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*.

3.2.2 Short-Term Ecological Responses

The conceptual model in Figure 3-5 constitutes the core of the simulation model introduced later in this thesis and focuses particularly on understanding how 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.

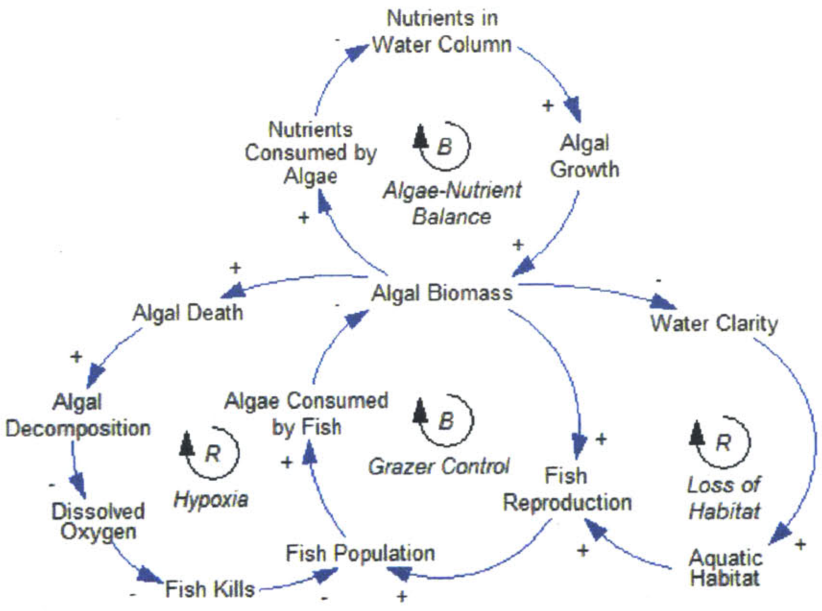

Figure 3-7: Short-term Ecological Responses Causal Loop Diagram

Figure 3-7 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 gets larger, 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.

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 3-7 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 3-7 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.

3.2.3 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 et al., 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 thesis, 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 required public support for an effective long-term solution to water quality impairment in Cape Cod's embayments, policymakers should understand the dynamic complexity of public willingness to fund the solution – how it changes over time based on different social responses to the problem. Figure 3-8 displays a causal loop diagram that explores the causal structure between anticipated results of nutrient pollution and public willingness to fund an adequate public solution.

Section 3.2.2 explained 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, 2008] 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.

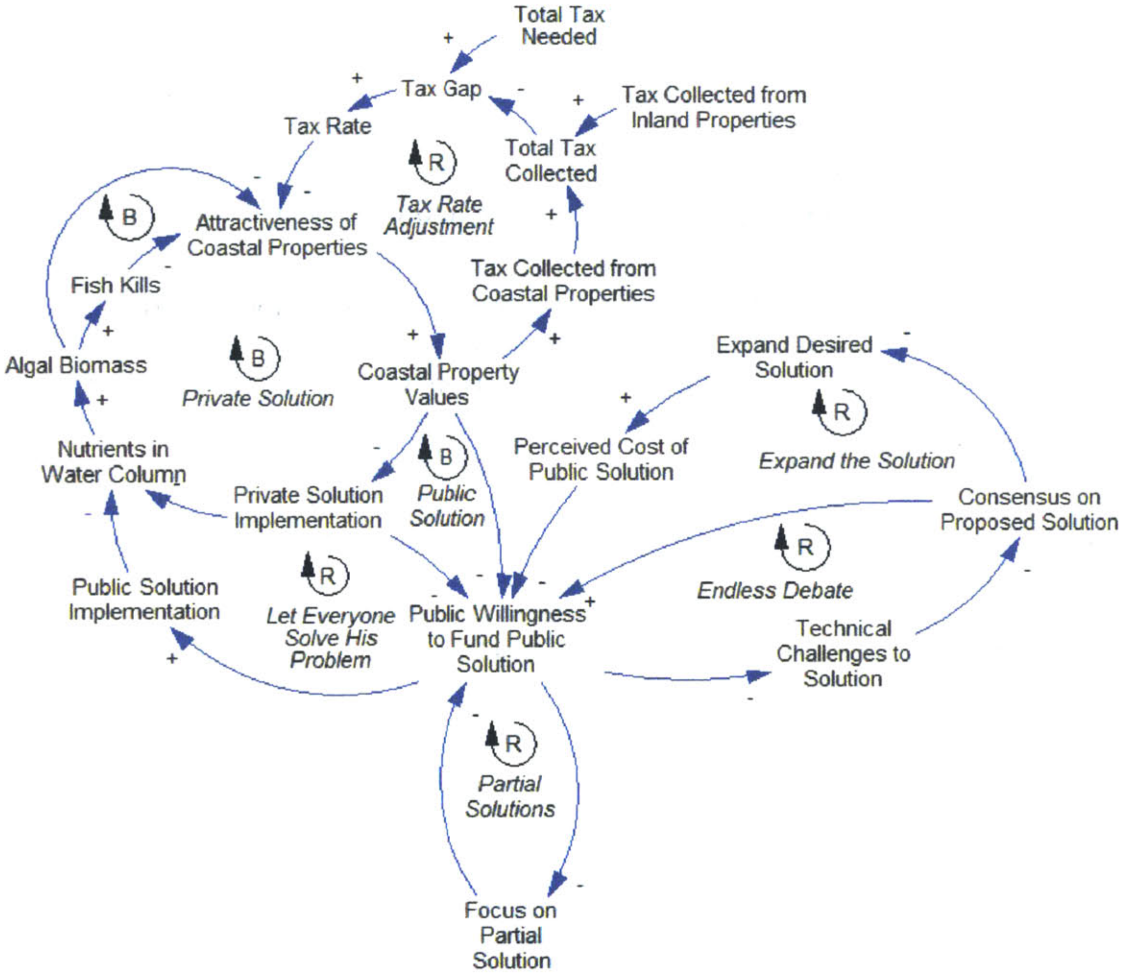

Figure 3-8: Willingness to Fund Public Solution Causal Loop Diagram

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 costs 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.

3.3 Model Formulation

After conceptualizing the system structure that creates the problematic behavior, the next step in the system dynamics model-building process is to formulate a simulation model. A carefully crafted simulation model enables the model-building team to explore the dynamic behavior of the system as well as to experiment with different policy interventions to address the problematic behavior. This section presents a high-level structure of the Cape Cod water quality management simulation model. The proposed model is composed of three main modules, which are explained below. Before introducing these modules, the system boundary for the simulation model is also discussed. For more details about the simulation model formulation, the reader is referred to Appendix D, which presents the complete model equations.

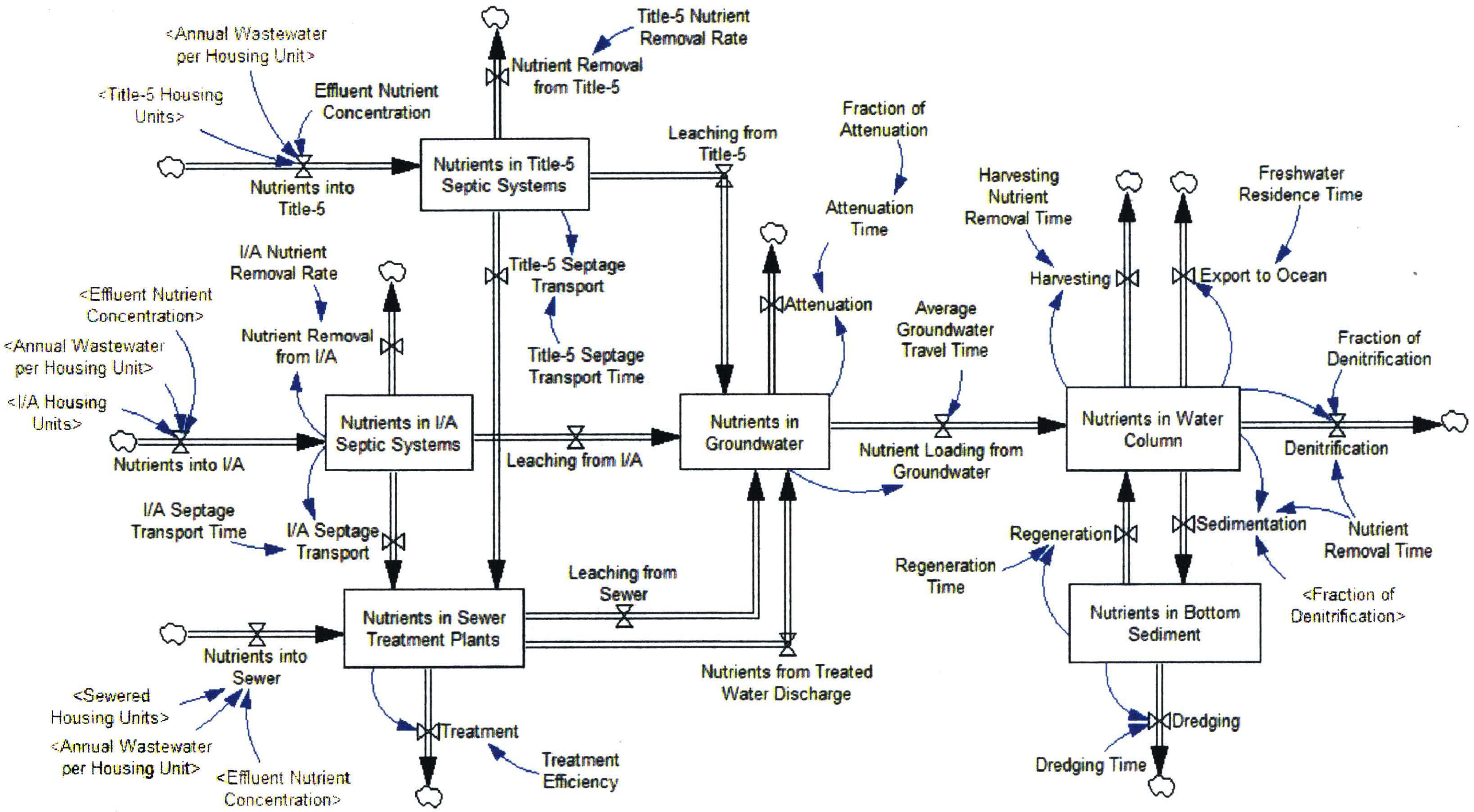

Figure 3-9: Nutrient Loading and Removal Module

3.3.1 Simulation Model System Boundary

The Cape Cod water quality management simulation model aims to explore long-term dynamics of 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 is built around the nutrient loading and removal conceptual model presented in Section 3.2.1. Short-term ecological responses and consensus building dynamics are intentionally left out of the simulation model.

3.3.2 Nutrient Loading and Removal Module

The nutrient loading and removal module conceptualized in Section 3.2.1 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 3-9 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).

Compared to its conceptual version in Figure 3-5, the nutrient loading and removal module contains a few additional stocks and flows. In addition to 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 system (*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, *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 the nutrient loading and removal module 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.

Before a model can be simulated on a computer, numerical value of parameters in the model must be estimated – the process known as *model calibration*. Table 3.1 specifies the parameter estimation for exogenous variables in the nutrient loading and removal module.

Table 3.1: 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

3.3.3 Policy Interventions Module

Once the system structure creating the decades-long degradation in Cape Cod's coastal waters is uncovered, the decision makers should explore what to change in the system to reverse the impairment. 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). Section 3.3.2 explains 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 in this thesis, 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 3-10 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.

To reduce the amount of nutrients flowing into *Nutrients in Title-5 Septic Systems* stock in Figure 3-9, *Title-5 Housing Units* must be decreased assuming that *Annual Wastewater per Housing Unit* and *Effluent Nutrient Concentration* are constant. As shown in Figure 3-10, 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.

3.3.4 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, shown in Figure 3-11, 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 3.2 summarizes parameter estimation for the exogenous variables in the cost module.

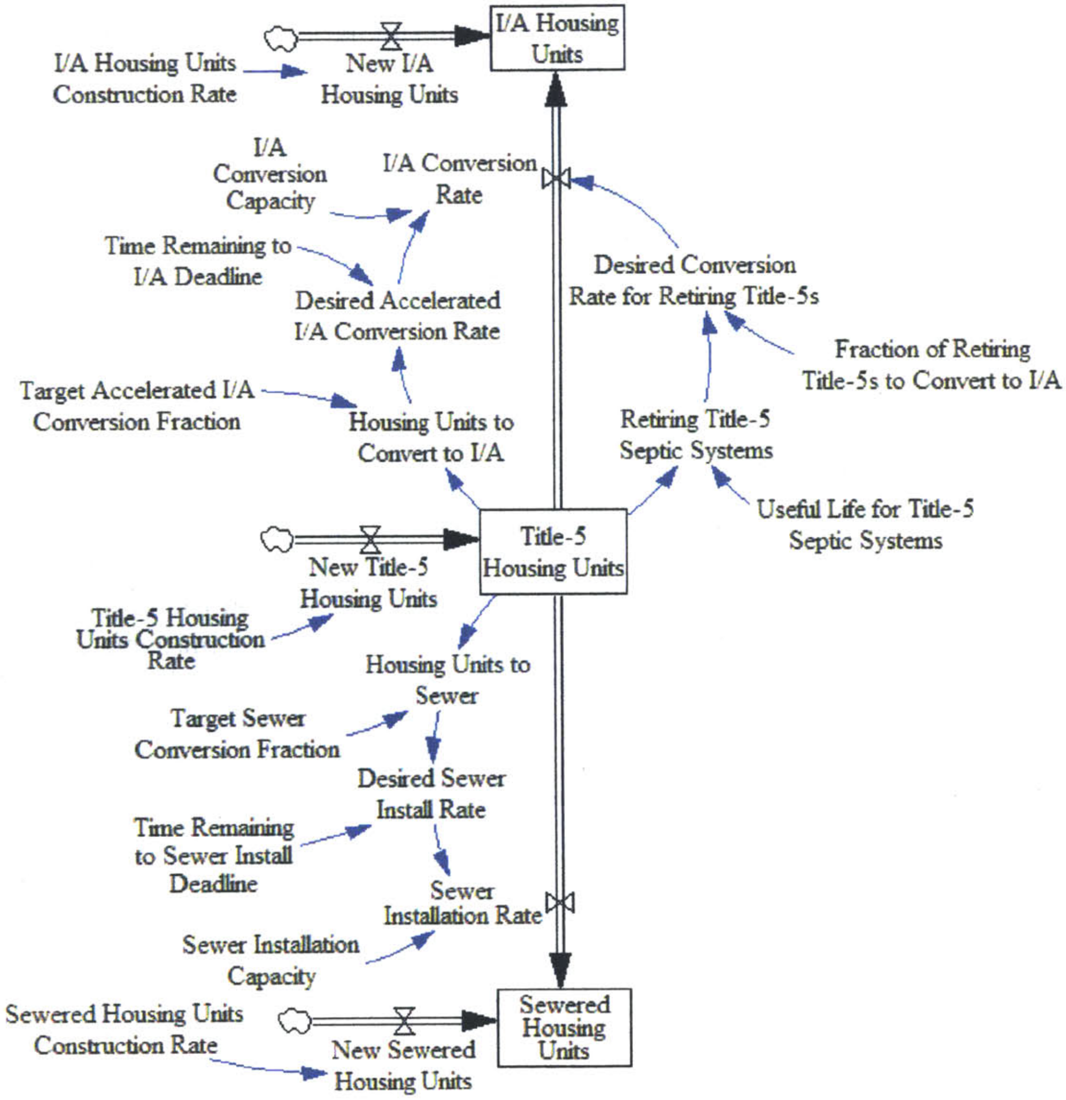

Figure 3-10: Policy Interventions Module

Table 3.2: Exogenous Variables in Cost Analysis Module

Variable	**Description**	**Value**
Title-5 Capital Cost	Capital cost for a Title-5 septic system	$13,000 per housing unit
I/A Capital Cost	Capital cost for an I/A on-site septic system	$26,000 per housing unit
I/A Conversion Cost	Capital cost of converting a Title-5 septic system to an I/A septic system	$15,000 per housing unit
WWTF Capacity	Capacity of a Wastewater Treatment Facility	1 million gallon per day
Construction Cost per WWTF	Construction cost of a wastewater treatment facility	$17 million per WWTF
Transport Distance	Total transport distances (collection to treatment and treatment to discharge) for a WWTF	10,000 feet
Unit Collection Cost	Construction cost per foot of collection pipe	$120 per foot of pipe
Pump Cost	Sewer collection cost spent on pumps for a property	$8000 per housing unit
Average Collection Pipe Length	Average collection pipe required to connect a property to the sewer system	200 feet
Title-5 O&M cost	Annual operation and maintenance cost of a Title-5 septic system	$110 per housing unit per year
I/A O&M Cost	Annual operation and maintenance cost of an I/A septic system	$2000 per housing unit per year
Sewer O&M Cost	Annual operation and maintenance cost per a housing unit served by a sewer system	$415 per housing unit per year

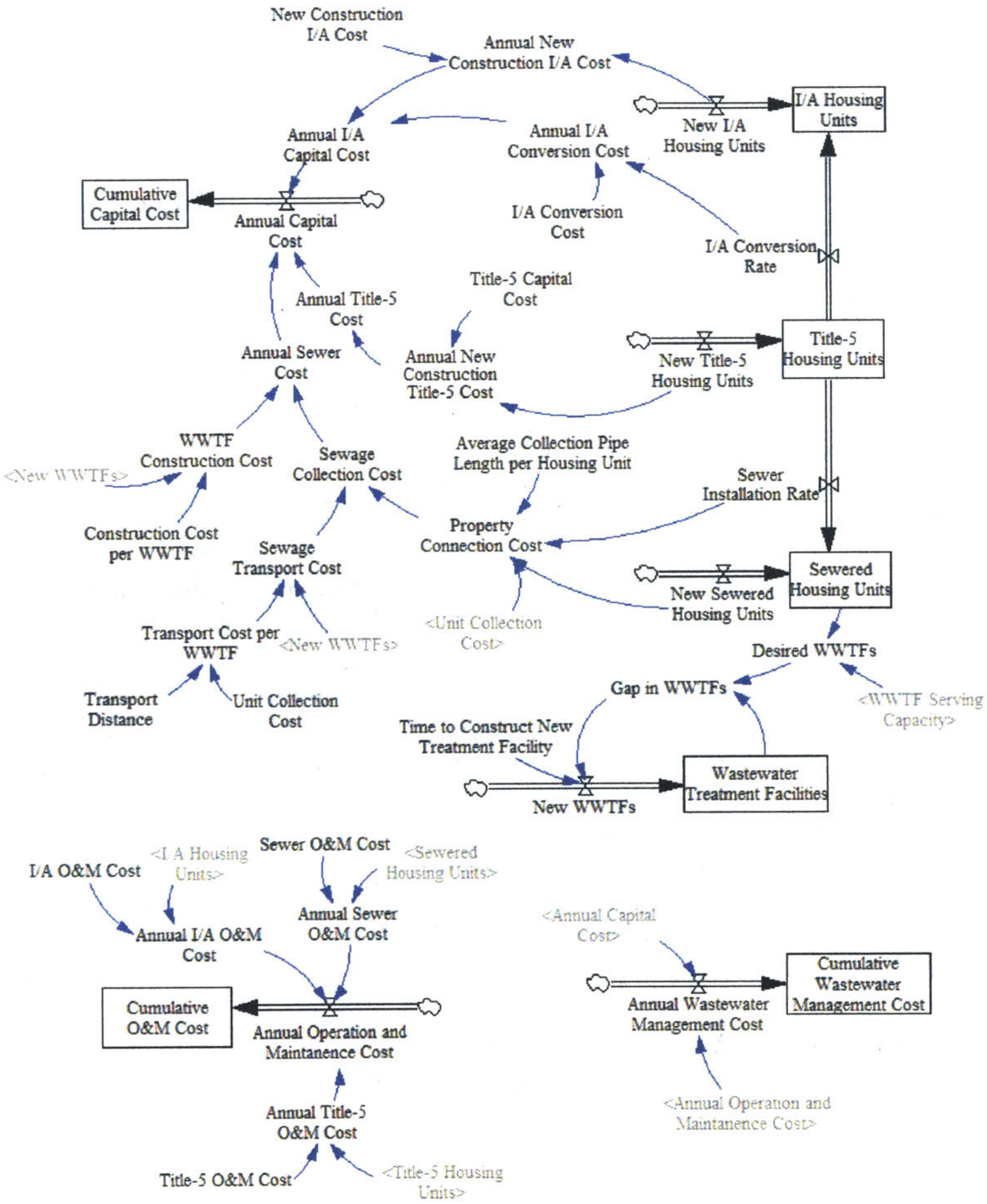

Figure 3-11: Cost Analysis Module

Chapter 4

Simulations and Policy Analysis

An important reason to build a system dynamics model is to increase understanding of a system's behavior over time. The goal is to develop more insight in the system under study and use this information to create effective policies that will improve the system performance especially in the long term. Simulation models are powerful devices both to test the system's behavior under different assumptions and to experiment with a variety of policies before a decision is made about how to intervene. During the group model-building sessions, these simulation experiments serve the purpose of fostering debate and learning about potential courses of action among stakeholders [Vennix, 1996].

After identifying the problem in a few reference modes and discussing several conceptual models, Chapter 3 has explained how a quantitative system dynamics model is formulated to analyze nutrient enrichment dynamics in Cape Cod's coastal waters. This chapter presents results of this analysis. First, a baseline scenario is determined and examined in detail to explore how the impairment in coastal water quality would evolve across the whole Cape Cod if no actions are taken to reverse it. Then a set of policy interventions, considered by the Cape Cod Commission and other stakeholders, are tested to evaluate if and how much they improve the baseline scenario. A similar analysis is also performed for a specific watershed to illustrate how the proposed model can be simulated at different scales as long as the system structure presented in Figure 3-9 remains applicable even though exogenous assumptions might vary.

4.1 Cape-Wide Simulations

The first set of simulation experiments conducted in this thesis are Cape-wide. Stated differently, all embayments and estuaries of Cape Cod are considered as an aggregate for these simulations. 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 under-

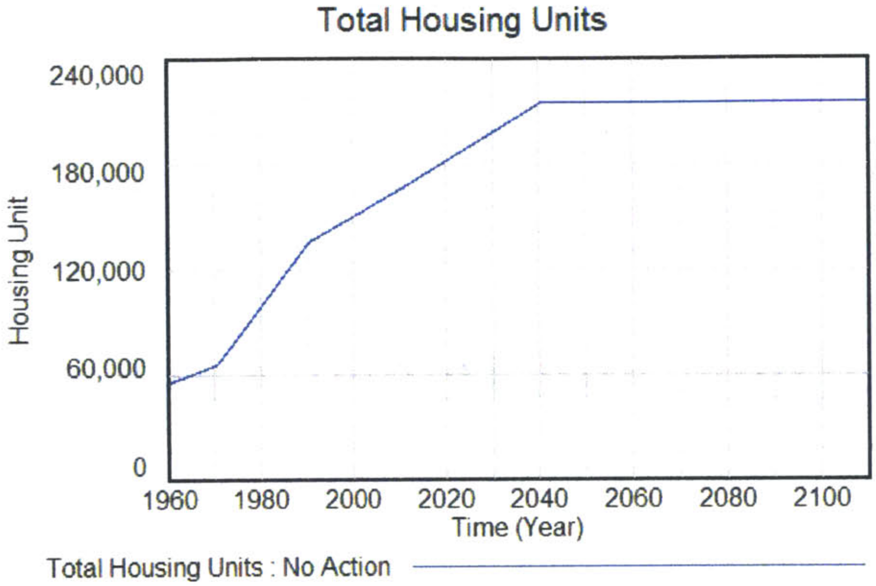

Figure 4-1: Cape-Wide Growth in Housing Units

standing long-term dynamics of coastal water quality impairment, which are believed to be common across most Cape Cod watersheds. On the other hand, different set of policies may be evaluated for different watersheds or each town may want to generate its own baseline scenario. Section 4.2 explains how the model can be simulated in smaller scales by changing the relevant exogenous assumptions as long as the system structure shown in Figure 3-9 remains adequate to describe the nutrient loading and removal in a given watershed.

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 4-1 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 3.1 and Table 3.2 are applicable for the Cape-wide simulations. Additional exogenous parameters are assigned numerical values as shown in Table 4.1.

Table 4.1: 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	5000 housing units per year
Sewer Installation Capacity	Maximum number housing units can be connected to the sewer within a year	1500 housing units per year

4.1.1 Baseline Scenario

To conduct experiments with a simulation model, first a baseline scenario should be defined and simulated. This standard run becomes a base of comparison to evaluate subsequent experiments. For the Cape-wide simulations, 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 4-2 displays how the Cape-wide nutrient accumulation in coastal waters is expected to grow if no actions are taken to control excessive nutrient enrichment (for more graphs of the Cape-wide simulations, please refer to Appendix C). 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.

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 4.2 provides a summary of the growth in major model variables compared 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

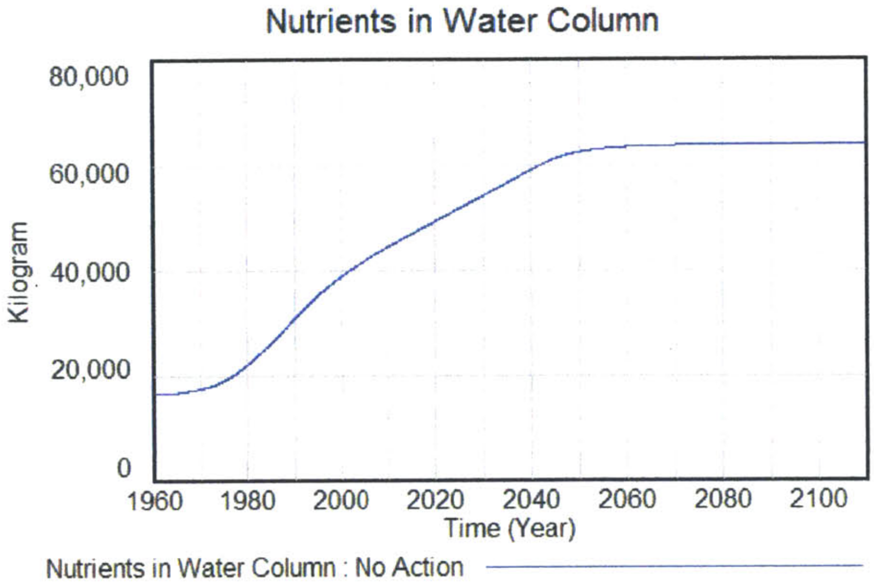

Figure 4-2: Cape-Wide Baseline Scenario: Nutrients in Water Column

stock itself grows by 44%. When the dynamic behavior of *Nutrients in Groundwater* stock along with its inflows and outflows (see Figure 4-3 and Figure 4-4) is examined more carefully, one can observe the following:

- The total inflows to *Nutrients in Groundwater* is always more than the total outflows during the timeframe that more housing units are constructed.
- 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.
- 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.

In summary, nutrients keep accumulating in groundwater 30 more years after the wastewater generation levels off. Similarly, nutrient loadings to embayments also increase during this timeframe as the amount of nutrients reaching embayments is proportional to how much nutrients are carried by groundwater. The critical question then becomes what causes the outflows from *Nutrients in Groundwater* to lag 30 years behind the inflows to the stock. The answer lies in *Groundwater Travel Time*, which specifies that if there were no more nutrients released to groundwater, it would take 10 years to clear all nutrients in groundwater through attenuation and discharge to coastal waters. Stated differently, only 10% of nutrients accumulated in groundwater outflow from *Nutrients in Groundwater* stock every year. Therefore, after the inflows stabilize, the stock keeps growing until its value becomes 10 times the inflows and the outflows balance the inflows.

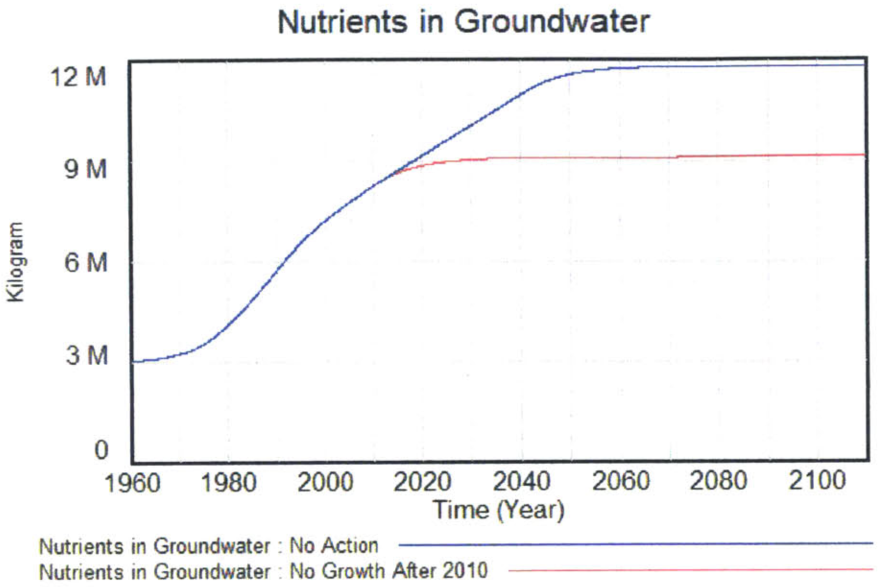

Figure 4-3: Cape-Wide Baseline Scenario: Nutrients in Groundwater

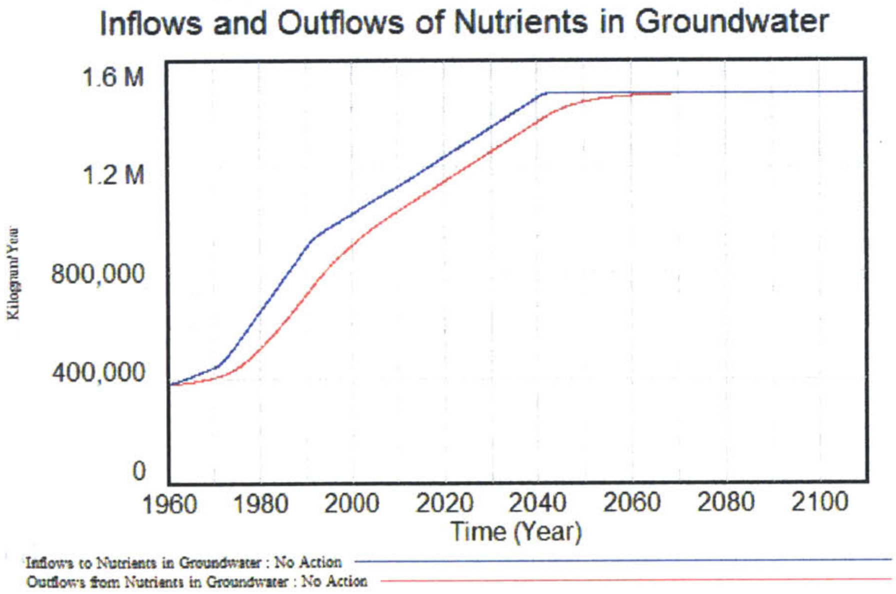

Figure 4-4: Cape-Wide Baseline Scenario: Inflows and Outflows of Nutrients in Groundwater

Table 4.2: 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%

4.1.2 Policy Intervention Scenarios

As explained earlier in this thesis, 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. Both sewer installation and conversion to innovative/alternative systems are subject to corresponding capacity constraints stated in Table 4.1.
- **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 de-

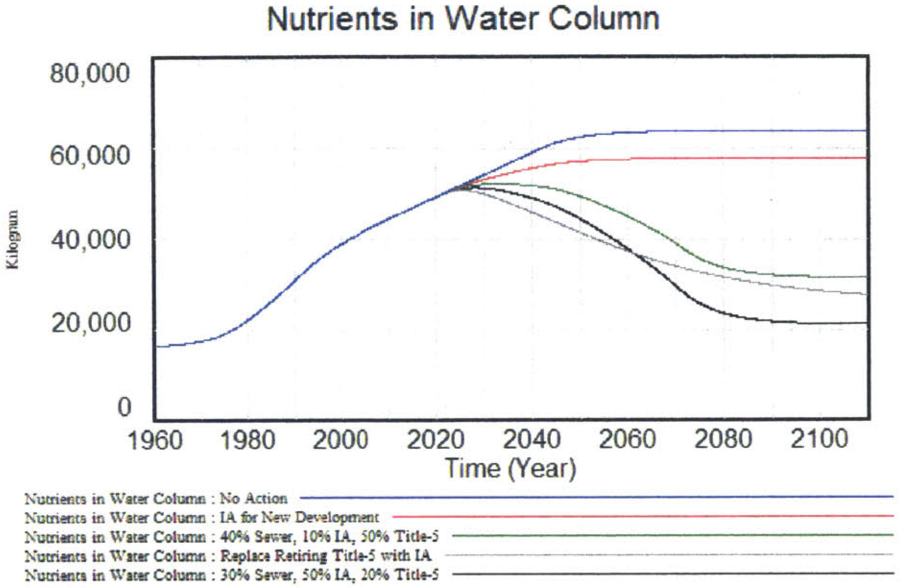

Figure 4-5: Cape-Wide Nutrient Loading Reduction Scenarios

velopment is assumed as follows: 30% sewered, 50% with innovative/alternative system, 20% with traditional Title-5 septic systems. Both sewer installation and conversion to innovative/alternative systems are subject to corresponding capacity constraints stated in Table 4.1.

- **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 4-5 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 4.3 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

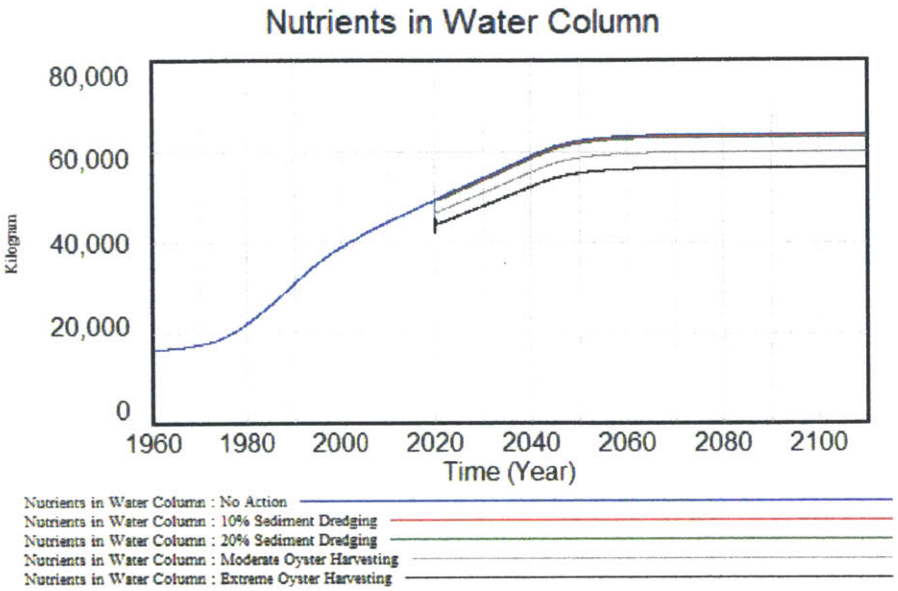

Figure 4-6: Cape-Wide Nutrient Removal Enhancement Scenarios

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 bottom sediment are evaluated through simulations. Figure 4-6 depicts how the system responds to nutrient removal enhancement interventions while Table 4.3 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.

Table 4.3: 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**	**Cumulative O&M Cost**
No Action	64% higher	Never	44% higher	Never	$2.58 billion	$3.50 billion
I/A for New Development	49% higher	Never	30% higher	Never	$3.04 billion	$10.53 billion
40% Sewer, 10% I/A, 50% Title-5	34% higher	In 2070	17% higher	In 2061	$6.88 billion	$12.56 billion
Replace Retiring Title-5 with I/A	30% higher	In 2055	14% higher	In 2043	$5.37 billion	$39.54 billion
30% Sewer, 50% I/A, 20% Title-5	32% higher	In 2058	15% higher	In 2050	$7.32 billion	$27.41 billion
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
40% Sewer, 10% I/A, 50% Title-5 as of 2020	34% higher	In 2070	17% higher	In 2061	$6.88 billion	$12.56 billion
40% Sewer, 10% I/A, 50% Title-5 as of 2050	61% higher	In 2103	41% higher	In 2096	$6.61 billion	$7.56 billion

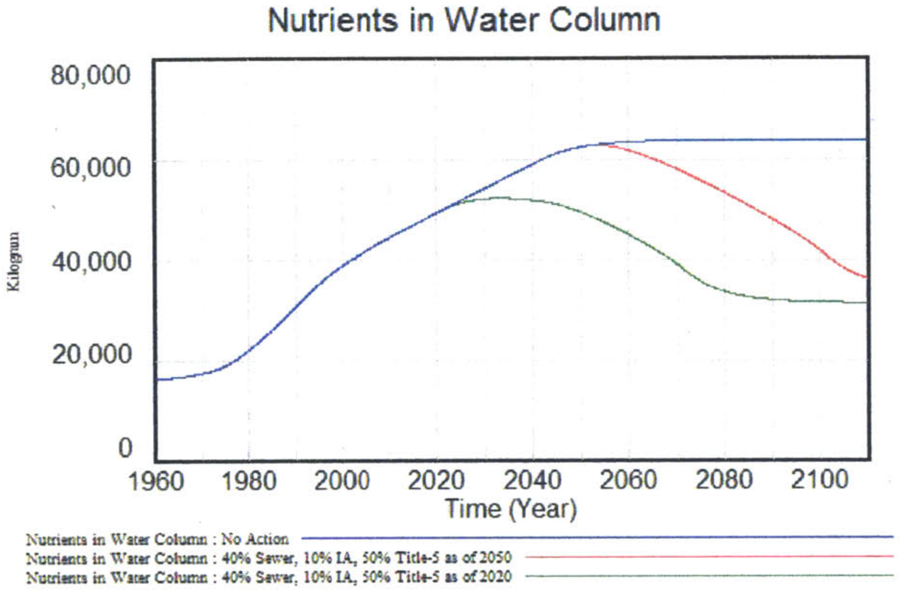

Figure 4-7: Impacts of Postponing the Solution

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 enhancement interventions are not as effective as nutrient loading reduction policies in coping with nutrient pollution on Cape Cod.

4.1.3 Implications of Wait-and-See Policies

Complex system problems often build slowly over long time periods 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 and Sweeney, 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 (see Section 4.1.2), it is crucial to further analyze implications of such wait-and-see policies.

Figure 4-7 presents how the nutrient accumulation in water columns change over time when the same policy is implemented with a 30-year delay (see Table 4.3 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, described in Section 4.1.2, is implemented starting from year 2020. On the other hand, if the same policy is implemented as of 2050, 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, wait-and-see policies may cause Cape Cod to face significantly higher degradation in its coastal waters, which lasts much longer. Therefore, the risk is enormous.

4.2 Three Bays Watershed Simulations

Cape-wide simulations reveal critical insights about the nature of coastal water quality degradation such as the nonlinear growth in nutrient concentration in response to additional development or the significance of timely actions. However in practice, different solution alternatives may need to be evaluated on watershed by watershed basis to increase the precision of the analysis. This section illustrates how the proposed simulation model can be used to conduct watershed specific policy analysis.

A system dynamics simulation model is composed of two major parts: the system structure, which expresses how different elements of a system interact with each other to create the emergent behavior, and a set of exogenous assumptions such as constants and parameter values. The same model can be used to analyze similar systems by changing the exogenous assumptions as long as the underlying system structure remains adequate. For the Cape Cod coastal water quality management model, the system structure explained in Chapter 3 is believed to represent how the water quality degradation occurs in most Cape Cod estuaries and embayments. Therefore, it is possible to simulate the model for individual watersheds by updating the exogenous assumptions accordingly.

This section presents simulation results for Three Bays watershed. Upper reaches of the Three Bays estuary are already classified as severely degraded and the lower reaches as significantly impaired due to nitrogen loadings [MA DEP, 2006]. Through a set of simulations, impacts of additional 33% growth (between 2011-2040) on the degradation is analyzed and three different solution alternatives are tested. Figure 4-8 depicts the estimated growth in housing units in the watershed area. Currently, all properties in Three Bays watershed area are assumed to use traditional on-site septic systems that are not capable of filtering nutrients. Other exogenous variables

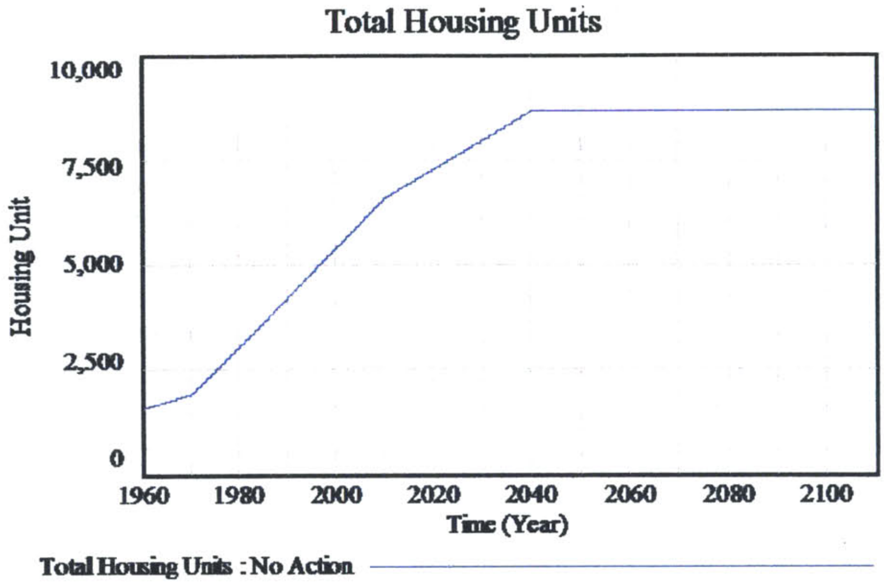

Figure 4-8: Three Bays Growth in Housing Units

are kept the same as specified in Table 3.1, Table 3.2 and Table 4.1. Similar to Cape-wide simulations, the baseline scenario is defined as no actions are taken to resolve problem. After generating the baseline behavior of the system, the following three intervention scenarios are examined:

- **Scenario 1**. Two phases of sewering are implemented starting from year 2020. During the 34-year first phase, 2551 parcels are sewered to capture 184 million gallon per year (mgy) of wastewater flow (equivalent of 2960 housing units in this model based on 210 gpd wastewater per household assumption). 25% of the watershed-wide growth is assumed to take place in the phase 1 area. Then during the 16-year second phase, 1304 more parcels are sewered to capture additional flow of 120 mgy (equivalent of 2960 housing units).

- **Scenario 2**. Two phases of sewering are implemented starting from year 2050. During the 37-year first phase, 2434 parcels are sewered to capture 227 mgy flow (equivalent of 2960 housing units) . Similar to Scenario 1, 25% of the watershed-wide growth is assumed to take place in the phase 1 area. Then in the 16-year second phase, 827 more parcels units are sewered to capture additional flow of 77 mgy (equivalent of 2960 housing units).

- **All Sewer**. The complete watershed area is sewered in 50 years starting from 2020.

Figure 4-9 displays how the nutrient accumulation in the Three Bays estuary vary over time when no solution actions are taken and when each of these policy interventions is implemented. Table 4.4 provides a numerical comparison of these scenarios based on different criteria. Below are some important observations to note:

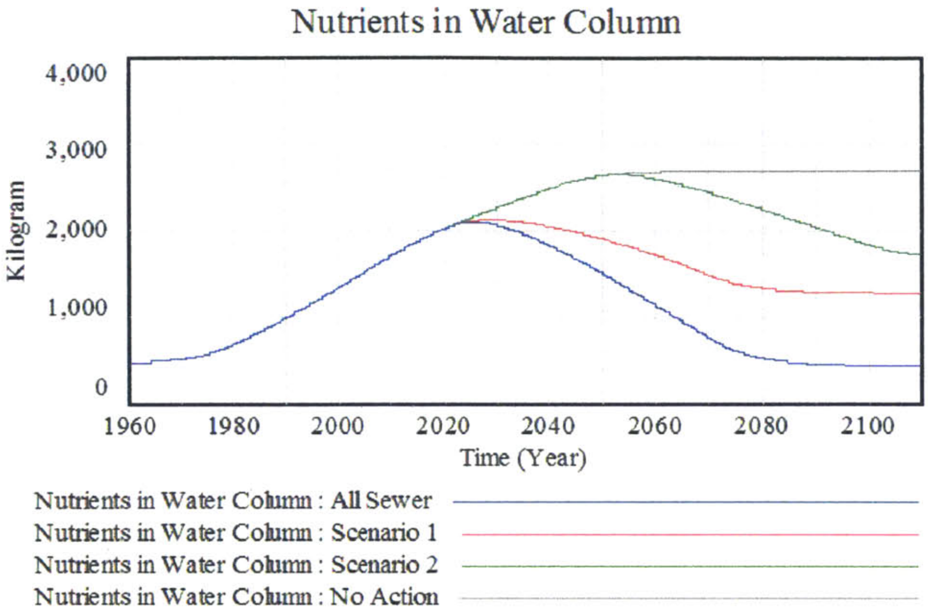

Figure 4-9: Three Bays Policy Interventions: Nutrients in Water Column

Table 4.4: Summary of Three Bays Watershed Policy Interventions

Scenario	**Peak vs. 2000 Level**	**Returns to 2000 Level**	**Cumulative Capital Cost**	**Cumulative O&M Cost**
No Action	100% higher	Never	$93 million	$112 million
Scenario 1	66% higher	2100	$232 million	$224 million
Scenario 2	100% higher	Never	$200 million	$155 million
All Sewer	63% higher	2056	$304 million	$290 million

- In the baseline scenario, nutrient concentration of the estuary increases up to 100% compared to 2000.
- Scenario 1 is able to revert the nutrient concentration of the estuary but it takes 80 years after the implementation starts. Moreover, the nutrient concentration first grows up to 65% more than the 2000 level before it starts going down.
- Scenario 2 cannot even achieve reduction in the nutrient concentration back to 2000 levels even though its capital cost is not much different than Scenario 1. Note that the implementation of Scenario 2 starts 30 years later with respect to Scenario 1. This emphasizes again that there is not much benefit in wait and see policies.
- Although complete sewering across the watershed area costs 50% more than Scenario 2 and 30% more than Scenario 1 in terms of undiscounted cumulative capital cost, its performance is significantly better compared to the other scenarios. It reduces the nutrient concentration down to 35% of the 2000 level.

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Chapter 5

Conclusions

Coastal waters of the world are facing significant problems as a result of growing human activity. Excessive nutrient enrichment, also know 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. 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. Carefully going through each step of the model-building process, this thesis introduced the Cape Cod water quality management model. 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.
- 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.

Appendix A

How to Read System Dynamics Models

The underlying premise of the systems theory is that the behavior of a system is never imposed from the outside but it is rather created by the internal structure of the system [Forrester, 1969]. Therefore, in order to improve the dynamic behavior of a system, it is essential to first uncover how different elements of the system are interconnected to produce the observed behavior. In system dynamics, two main diagramming tools are used to capture the structure of systems: causal loop diagrams and stock and flow diagrams. This appendix briefly overviews these diagramming tools as well as explains how to read graphs of dynamic system behavior, which are used extensively by systems thinkers to understand the trends over time. For more details on system dynamics modeling, the reader is referred to the following books, from which the content of this appendix is mostly adapted:

- *Business Dynamics: Systems Thinking and Modeling for a Complex World* by John Sterman [Sterman, 2000];
- *Group Model Building: Facilitating Team Learning Using System Dynamics* by Jac Vennix [Vennix, 1996]; and
- *Thinking in Systems: A Premier* by Donella Meadows [Meadows, 2008].

A.1 Causal Loop Diagrams

Feedback loops are basic operating units of a system [Meadows, 2008]. They make the system behavior persist over time. Yet human mental models often fail to include critical feedback governing the dynamics of systems. Causal loop diagramming is a powerful way to conceptualize causal structure of a system concisely and identify feedback loops. Through causal loop diagrams, modelers describe hypotheses about the

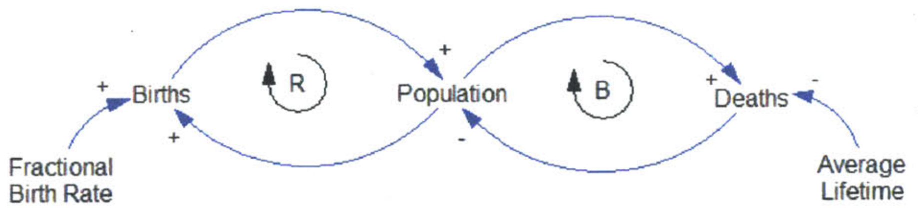

Figure A-1: Simple Population Model Causal Loop Diagram

causes of dynamics, elicit mental models, and communicate the important feedback loops that are believed to create a problematic behavior [Sterman, 2000].

A causal loop diagram consists of variables connected by arrows, called *causal links*, representing a causal relationship between two variables. A causal link denotes that the variable at the tail has a causal effect on the variable at the point. Each causal link is marked with a polarity sign, either positive (+) or negative (-) , to indicate the type of causal relationship. A positive causal link implies that both variables change in the same direction while a negative causal link denotes that variables change in opposite directions. In addition to expressing one-way causality between two variables, causal loop diagrams also identify important feedback loops, which is one of the main purposes in system dynamics modeling. Figure A-1 displays a causal loop diagram for a simple population model. Below are some remarks:

- A positive causal link is interpreted as follows: if the cause increases, all else being equal, the effect also increases above what it would otherwise have been. Similarly, if the cause decreases, all else being equal, the effect decreases below what it would otherwise have been. For instance, if the fractional birth rate (i.e., fertility) increases, the number of births will also increase assuming there has been no change in the population in the mean time. Likewise, if the fractional birth rate decreases, births would decrease below what it would have otherwise been.
- If the number of births increases, the population will also increase (assuming no change in deaths) above what it would have been. In a larger population, there will be more births assuming that the fertility remains same. Therefore, the number of births will further increase. This type of feedback loops are know as *reinforcing feedback loops* and marked with letter R. Reinforcing feedback loops amplify changes in a variable in the same direction. Stated differently, if the births decrease, this reinforcing loop will try to reduce it further.
- A negative causal link is interpreted as follows: if the cause changes in one direction, all else being equal, the effect changes in the opposite direction. For instance, if the average lifetime increases, the number of deaths will decrease; and when the deaths decrease, the population will increase.
- The second kind of feedback loops in system dynamics models are *balancing*

feedback loops, which try to stabilize the change in a variable by eventually affecting it in the opposite direction. For instance, if the population increases, the deaths will also increase above what it would otherwise have been assuming that the average lifetime remains the same. An increase in the number of deaths will cause a decrease in the population. Therefore, the initial increase in the population is balanced by this feedback loop. Balancing feedback loops are marked with letter B in system dynamics models.

A.2 Stock and Flow Diagrams

An important limitation of causal loop diagrams is that they may be misleading when it comes to representing the notion of accumulations in systems. Causal loop diagrams do not distinguish between stocks and flows in a system, which represent the accumulations of resources and the rates of change in those resources, respectively. For example, in the population model, an increase in the births causes the population to increase. However, a decrease in the births does not reduce the population. In fact, the population still increases even though there are fewer births. Therefore, causal loop diagrams can be deceptive when attempting to derive dynamic consequences from them about the system behavior [Richardson, 1986, Vennix, 1996, Sterman, 2000]. This problem would disappear when a stock and flow diagram is used, in which the population is represented as a stock and the births as the inflow to the stock.

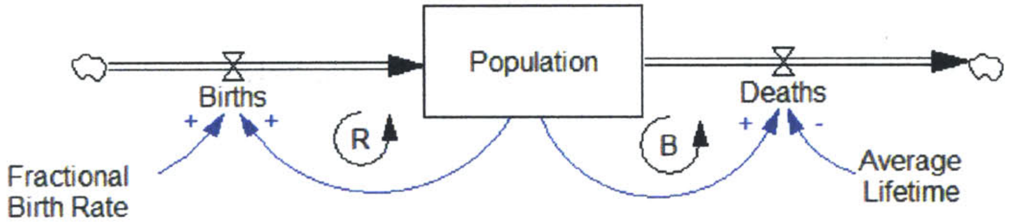

Figure A-2: Simple Population Model Stock and Flow Diagram

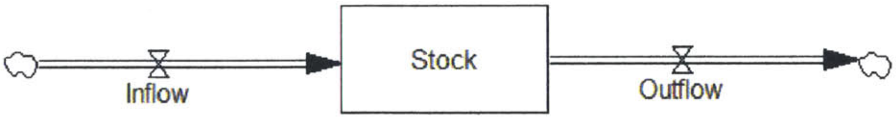

Figure A-3: Generic Stock and Flow Diagram

Figure A-2 displays the stock and flow diagram for the same population model while Figure A-3 depicts a generic stock and flow diagram with a single stock. A stock is the foundation of any system and represents an accumulation of material or information that builds up over time. Stocks change over time through actions of inflows and outflows. A stock is the present memory of the history of changing flows within the system [Meadows, 2008]. In stock and flow diagrams, stocks are shown as boxes while flows are shown as arrow-headed pipes. The clouds represent sources and sinks that are considered out of the system boundary. Several remarks are in order about the dynamic behavior of a stock:

- As long as the total inflows exceed the total outflows, the level of the stock will rise.
- When the total outflows surpass the total inflows, the level of the stock will fall.
- If the total outflows are equal to the total inflows, the level of the stock will not change (e.g., it will be held in dynamic equilibrium).
- A stock can be increased in one of two ways: increasing its inflow rate or decreasing its outflow rate.
- Stocks usually change slowly. They act as delays and respond to change only by gradually rising or falling. It takes a long time for populations to grow or to stop growing, for nutrients to accumulate in groundwater or water columns.
- Stocks create disequilibrium in systems behavior by decoupling inflows and outflows by acting as delays.

A.3 Reading Graphs of System Behavior Over Time

In system dynamics modeling, time graphs are used extensively to understand trends of a system's behavior over time, rather than focusing on individual events. In those graphs, the horizontal axis is always time. The graph may display the behavior of a stock or a flow. The pattern of the behavior as well as the points at which the line changes shape or direction are important. However, the precise numbers on the axes are often less significant [Meadows, 2008]. Therefore, the reader is advised to stay focused on patterns of behavior depicted on time graphs and not put lots of emphasis on precise values on diagonal axes.

Appendix B

Stakeholder Feedback

B.1 Stakeholder Team Members

Table B.1 displays the list of people who participated in the Cape Cod Water Quality Management model-building workshops as members the stakeholder team.

B.2 Problem Description: Variables

Below is the list of variables that the team identified as related to the coastal water quality degradation problem in Cape Cod Embayments. Variables are grouped into categories. Variables that were not listed during the workshop but were mentioned during preparation interviews are shown in *italics*.

Water Quality Metrics:

- Nitrogen loadings
- Nitrogen concentration
- Phosphorus loadings
- Dissolved Oxygen
- Water clarity
- Chlorophyll
- Pathogens
- Seaweed on beaches
- Drinking water quality
- Contaminants of Emerging Concern (CEC)

Table B.1: Stakeholder Team Members

Name	**Affiliation**
Paul Niedzwiecki	Cape Cod Commission
Leslie Richardson	Cape Cod Commission
Scott Michaud	Cape Cod Commission
Tom Cambareri	Cape Cod Commission
Andrew Gottlieb	Cape Cod Water Protection Collaborative
Robert Ciolek	Consultant to the Cape Cod Commission
George Allair	Town of Yarmouth
Roger Parsons	Town of Barnstable
Larry Ballantine	Town of Harwich Selectman
Paul Gobell	Town of Mashpee
Marilyn tenBrink	U.S. EPA
Ellen Weitzlwer	U.S. EPA
Nick Ashbolt	U.S. EPA
Marisa Mozzotta	U.S. EPA
Joanna Hunter	U.S. EPA
Brian Dudley	Massachusetts DEP
David DeLorenzo	Massachusetts DEP
Sharon Nunes	IBM - Retired
Phil Boudreau	Resident
Lindsey Counsell	Resident
Allan McClennen	Resident

- Freshwater quality
- *Algal Growth Potential*

Sources of Nutrients:

- Wastewater
- Atmospheric deposition
- Storm water run off
- Fertilizer use
- Nutrient recycling
- *Pet waste*
- *Fossil fuels*
- *Bottom sediment of estuaries*

Geology and Hydrology:

- Groundwater velocity
- Water availability
- Watershed delineation
- Cross watershed exchange
- Natural attenuation of Nitrogen
- Tidal flushing
- Sea level rise

Environment:

- Shellfish landings
- Fin fish populations
- Fish kills
- Greenhouse gas (GHG) emissions
- Climate change
- Energy use
- Eelgrass habitat

Economy:

- Property values
- Tourism spending

- Household income
- Diversity of economic base
- Return on Investment (ROI)
- Total Employment
- Full time employment percentage
- Houses for sale
- State revenue
- Sources of revenue
- Natural resource value
- Perceived resource value
- Local budgets

Development:

- Impervious cover
- Availability of publicly owned land
- Appropriateness of land use controls
- Expected future growth
- Density of development
- Frequency of cluster zoning
- Incentives for development
- Expansion requests
- Limitations on business expansion

Society:

- Resident population
- Seasonal population
- Second homeowners
- Retirees
- Recreational activities
- Public understanding of coastal water quality problem
- Desirability of living on Cape
- Public health impacts

- Beach closures
- Boil orders
- Local services
- Personal responsibility for problem
- Average age of populations
- Public education
- Landscaping education
- Water use

Regulatory Issues:

- Fear of over-regulations
- Concern for government largeness
- Number of regulatory bodies involved
- Regulatory mandates
- Political will
- Lawsuits
- Organizational responsibility

Solution Alternatives

- Success of solution
- Projects begun
- Projects completed
- Innovativeness of technology
- Public understanding of treatment options
- Merits of no action alternative
- Expected length of time to resolve
- Source of revenue
- Affordability of proposed solutions
- Funding of solution
- Cost of solution

Septic Systems:

- Availability of disposal sites

- Failed septic systems
- Effluent disposal constraints
- Number of treatment plants

B.3 Problem Description: Reference Modes

Among the variables listed in Section B.2, the team selected three that effectively describe the problem: (1) nutrient loading; (2) property values; and (3) understanding of coastal water quality degradation problem. In addition to these three, two other variables – energy use to resolve problem and percentage of the capital program completed in order to resolve the problem – were also considered by the team. For each of these variables, the team created a *reference mode*, a plot that describes how the behavior of the variable has been changing until now and how it might change over the next few decades. Reference modes for nutrient loading, property values, and understanding of coastal water quality degradation problem are shown in Section 3.1. Below are reference modes for the other two variables.

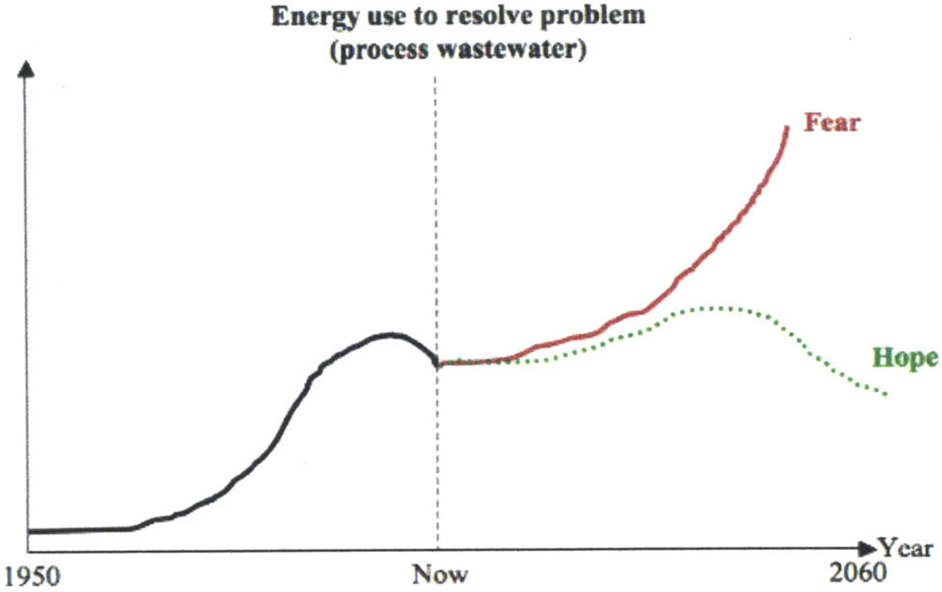

Figure B-1: Energy Use Reference Mode

B.4 Greatest Fears

Below is a collection of concerns the team raised when they were asked about their greatest fear within the domain of the coastal water quality degradation:

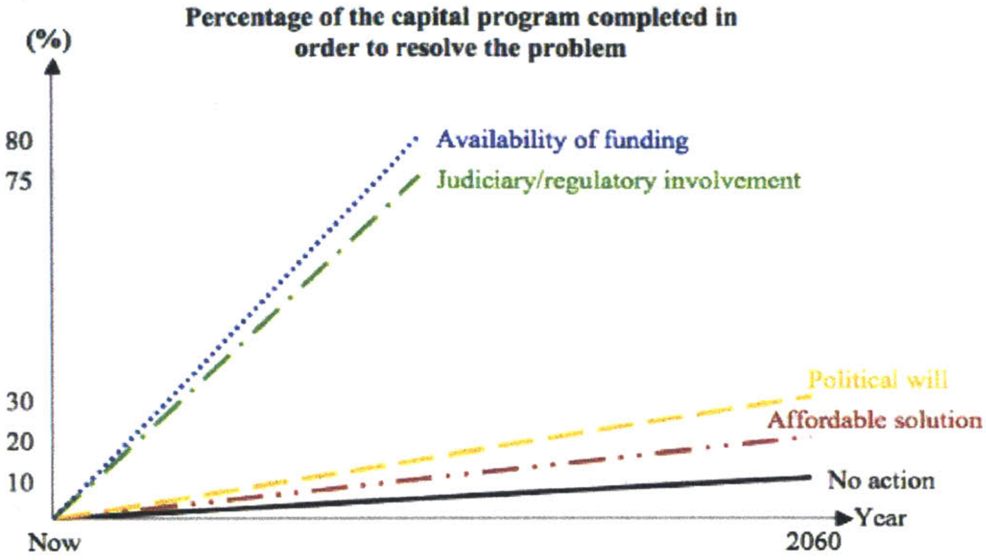

Figure B-2: Capital Program Completion Reference Mode

- The solution may transfer the problem to somewhere else in the system
- Drop off in tourism
- Court-ordered solution
- Court-ordered solution might not allow flexibility
- Court-ordered solution might not allow affordability
- Court-ordered solution may not be the right one
- Lack of action in a timely manner either because of cost, complexity or another reason
- Failure to achieve public buy-in
- Framing the problem as a coastal water issue or waste disposal issue rather than a complex system and therefore not achieving a sustainable solution. What if we consider it as a resource that we can gain from?
- Not able to translate the end points of the analysis (cost, benefit, environmental impacts, etc.) into terms that people can relate to

B.5 What Happens If No Actions Are Taken

When the team is asked about what they think would happen if no action is taken to resolve the ongoing impairment in coastal water quailty, they provided the following answers:

- More fish kills
- Shellfish disappear
- Shellfish closures increase
- Diminishing property values with a greater loss in coastal property values
- Coastal problems get worse and reach an irreversible point
- Diminishing coastal property values significantly reduce municipal tax revenue received from coastal properties and the burden shifts to those who can least afford it.
- Tremendous economic dislocation as a result of tax burden shift
- The economy is broken both seasonally and year-round
- Unmanageable costs on year-round residents when the solution is built for peak seasonal population
- Expensive court-ordered solution could be imposed as a result of inaction
- Potential enforcement mechanisms from the state or the federal government will not even fix the problem
- Start seeing public health impacts from septic systems
- Second home owner economy could reduce and this could impact the construction industry, arts, culture, architecture and things related to that engine keeps the Cape economy going

Appendix C

Simulation Outputs

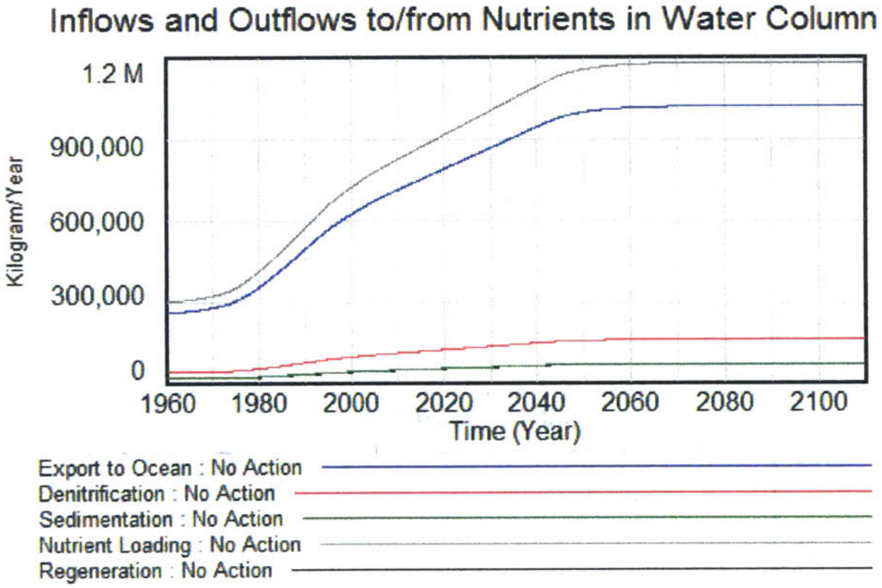

Figure C-1: Cape-Wide Inflows and Outflows to/from Nutrients in Water Column

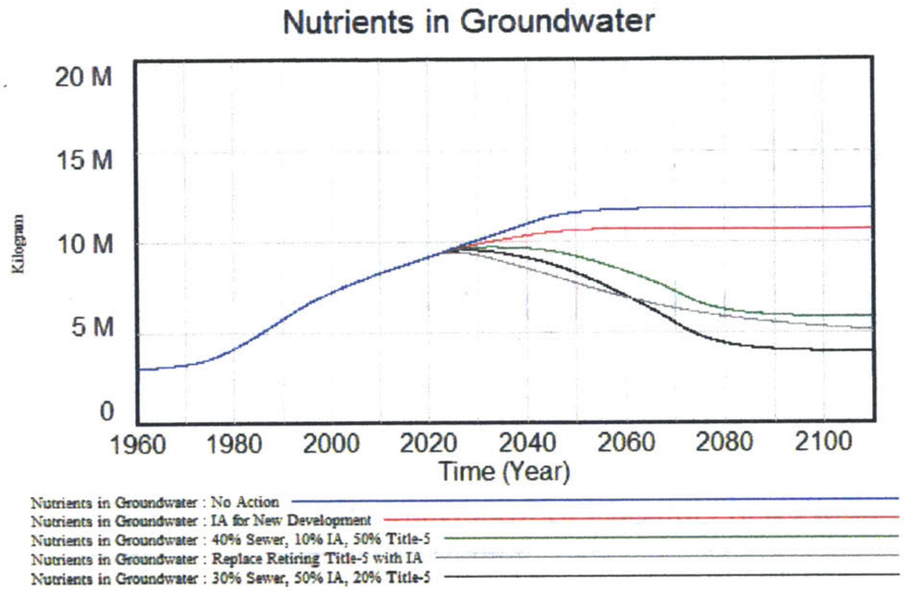

Figure C-2: Cape-Wide Nutrient Loading Reduction Scenarios: Nutrients in Groundwater

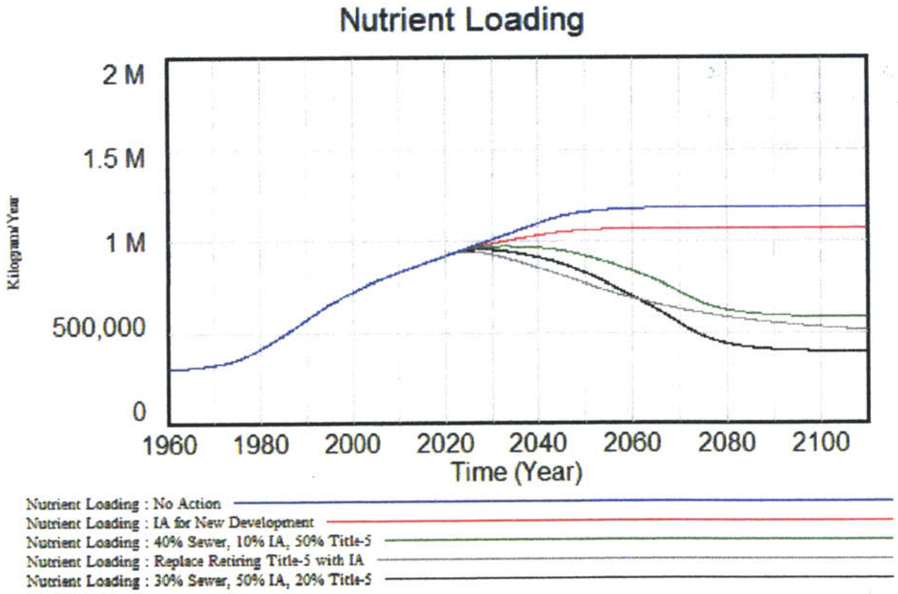

Figure C-3: Cape-Wide Nutrient Loading Reduction Scenarios: Nutrient Loading

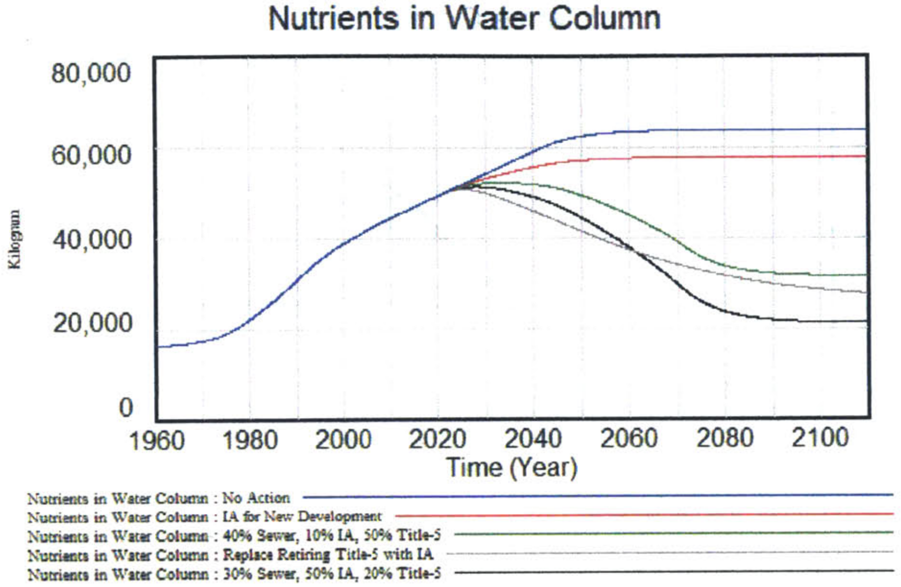

Figure C-4: Cape-Wide Nutrient Loading Reduction Scenarios: Nutrients in Water Column

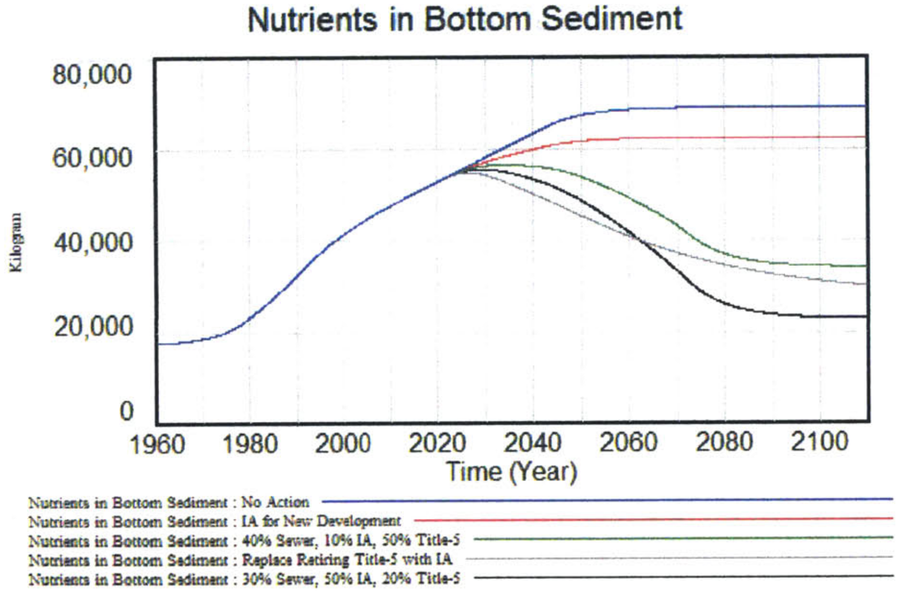

Figure C-5: Cape-Wide Nutrient Loading Reduction Scenarios: Nutrients in Bottom Sediment

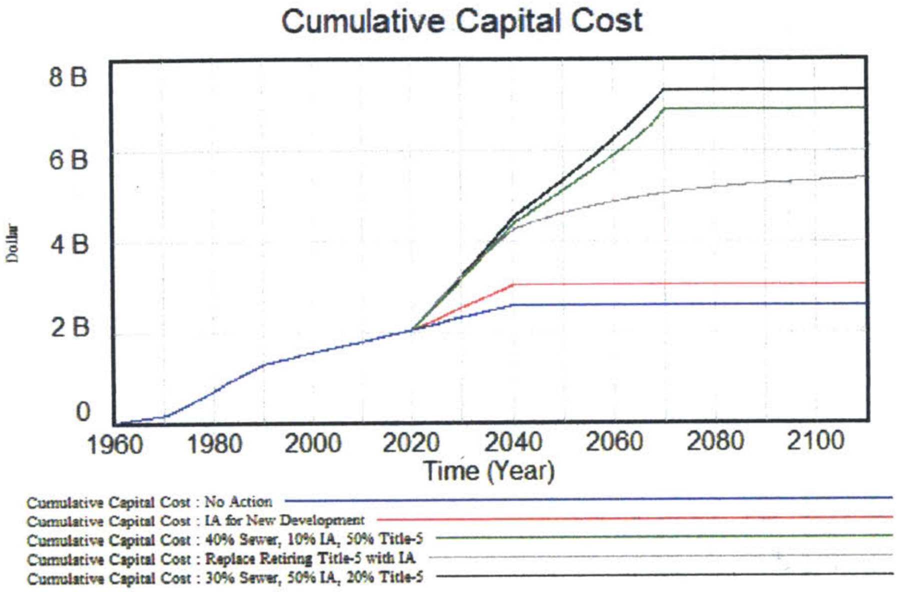

Figure C-6: Cape-Wide Nutrient Loading Reduction Scenarios: Cumulative Capital Cost

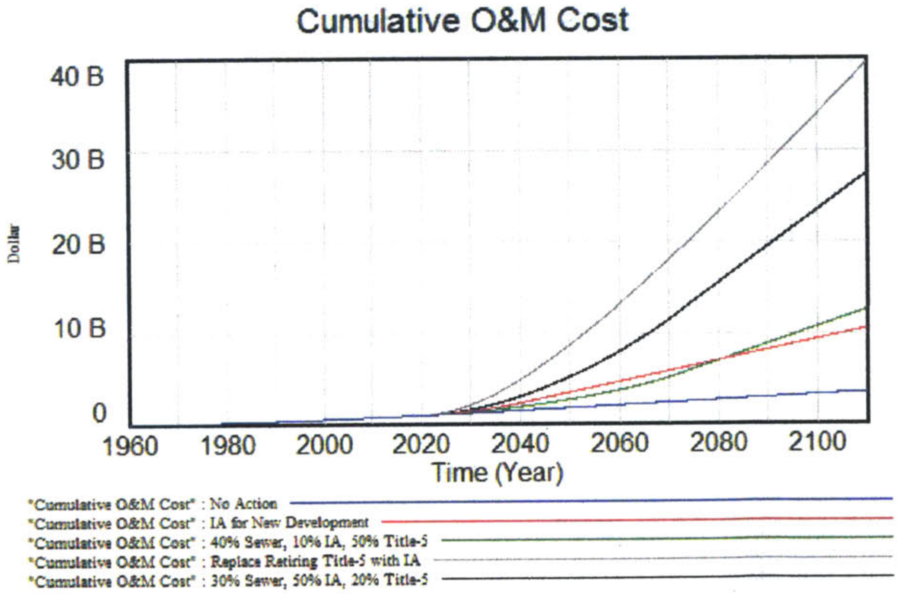

Figure C-7: Cape-Wide Nutrient Loading Reduction Scenarios: Cumulative O&M Cost

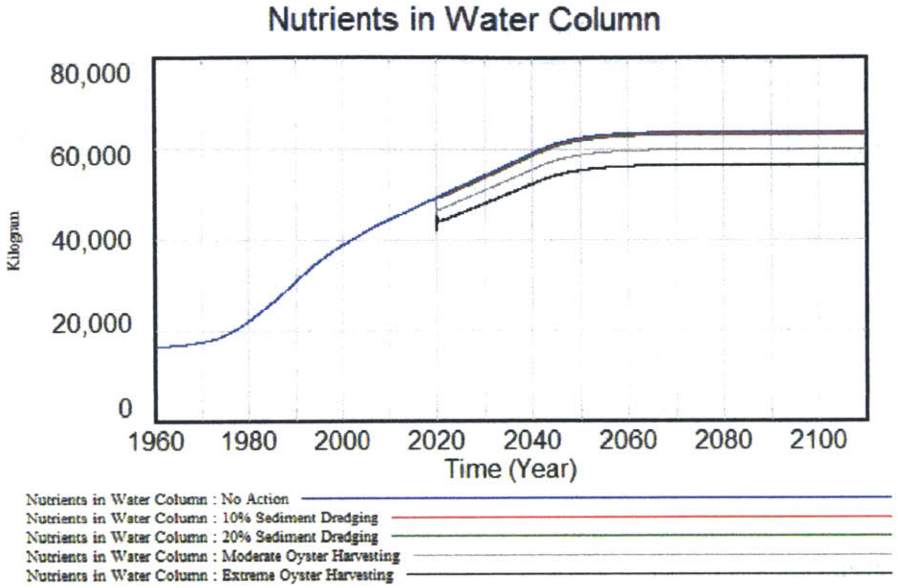

Figure C-8: app:Cape-Wide Nutrient Removal Enhancement Scenarios: Nutrients in Water Column

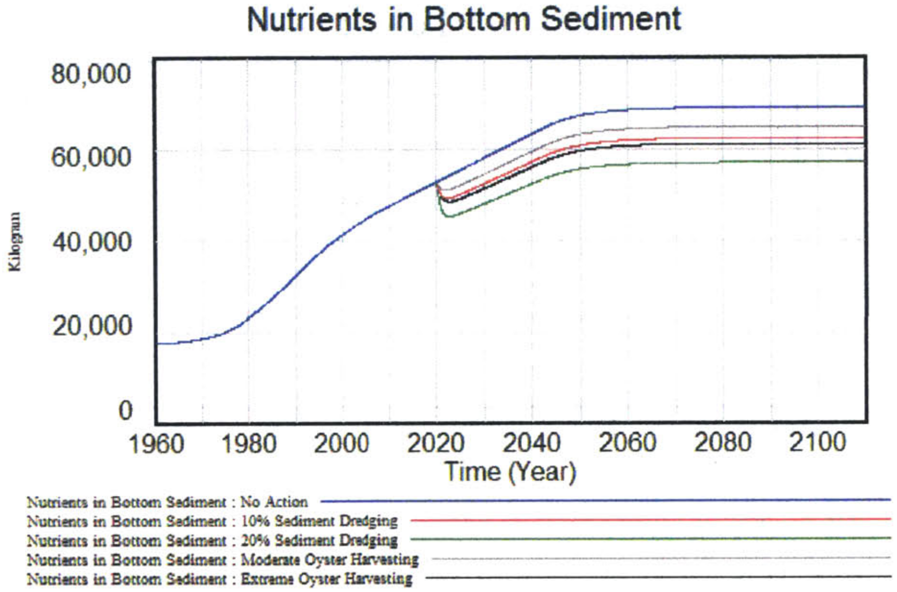

Figure C-9: Cape-Wide Nutrient Removal Enhancement Scenarios: Nutrients in Bottom Sediment

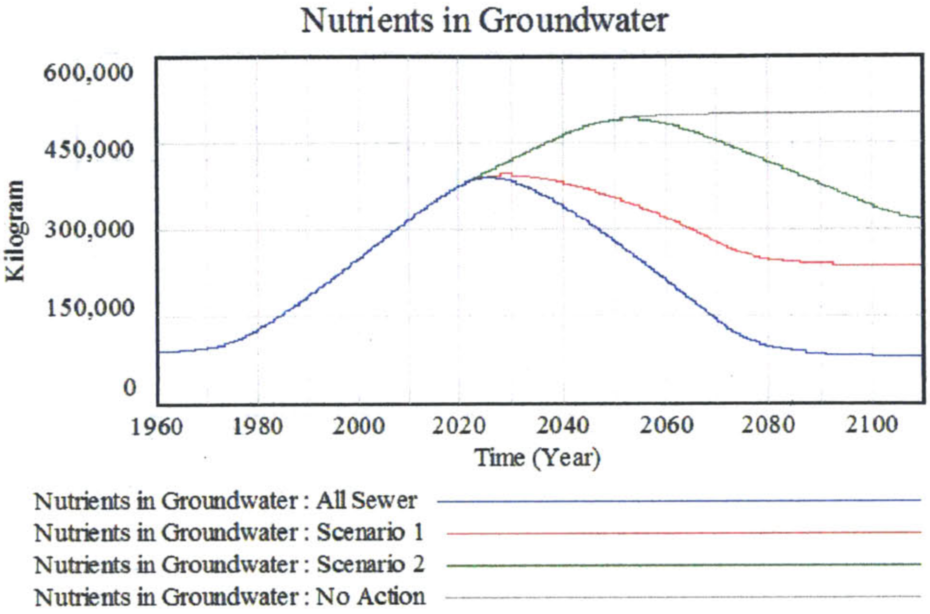

Figure C-10: Three Bays Watershed Scenarios: Nutrients in Groundwater

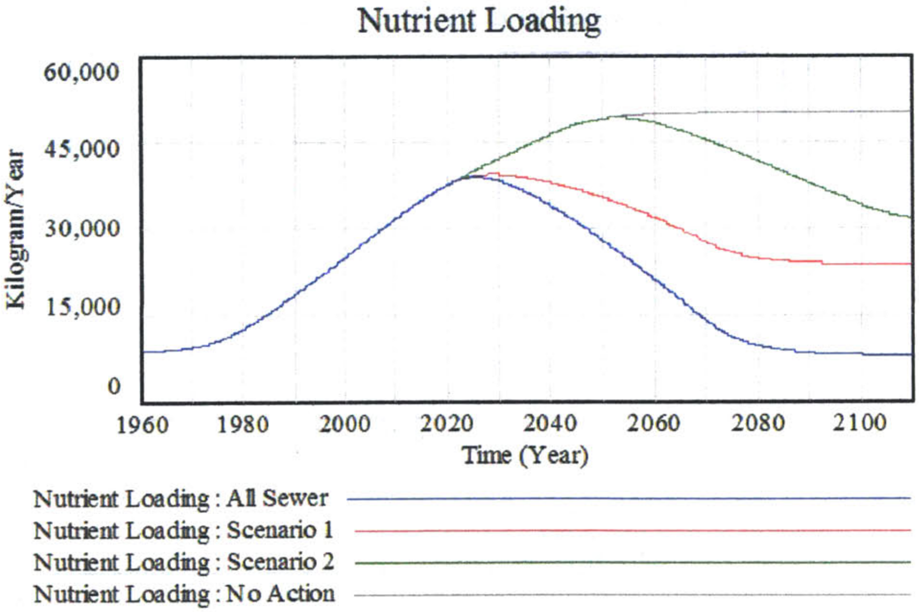

Figure C-11: Three Bays Watershed Scenarios: Nutrient Loading

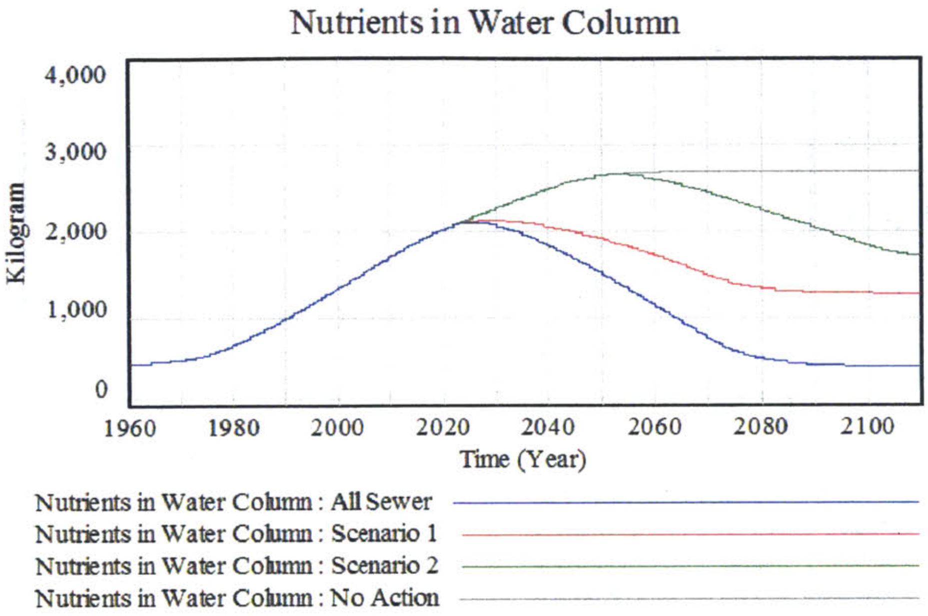

Figure C-12: Three Bays Watershed Scenarios: Nutrients in Water Column

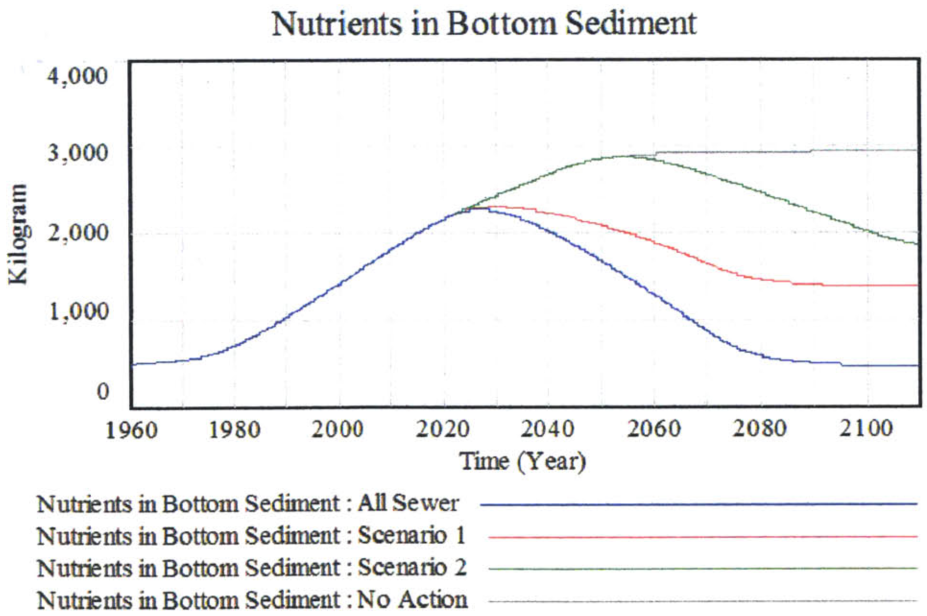

Figure C-13: Three Bays Watershed Scenarios: Nutrients in Bottom Sediment

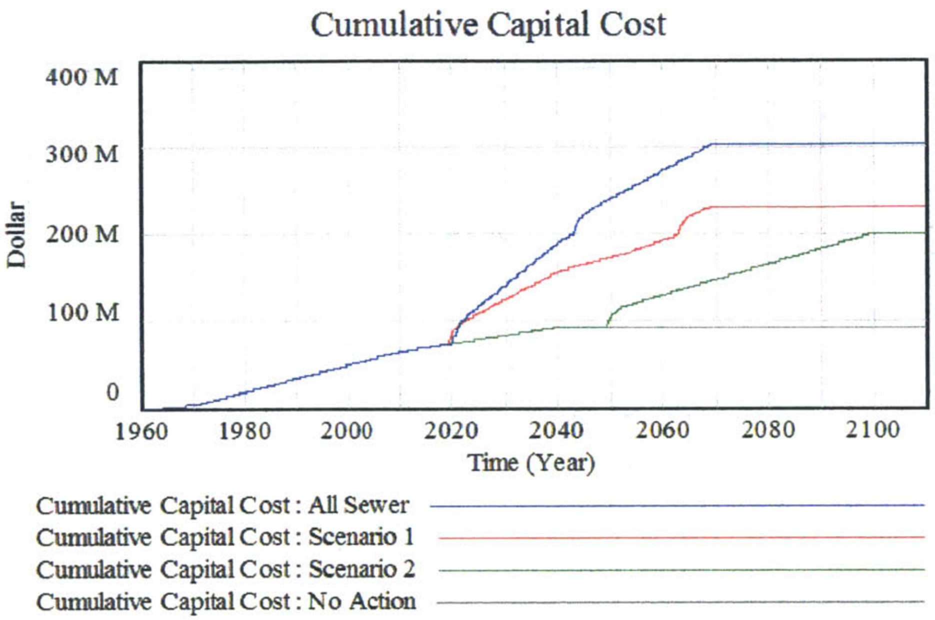

Figure C-14: Three Bays Watershed Scenarios: Cumulative Capital Cost

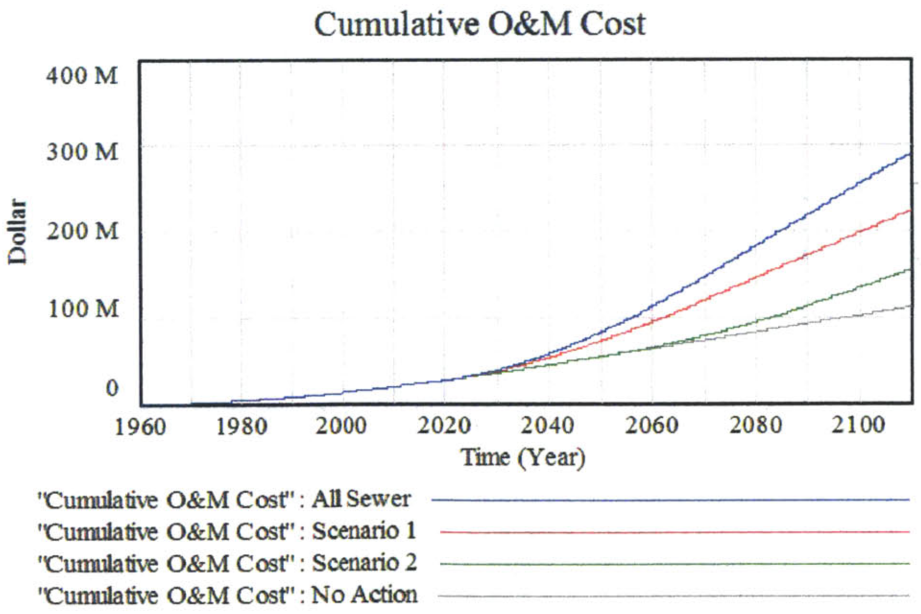

Figure C-15: Three Bays Watershed Scenarios: Cumulative O&M Cost

Appendix D

Model Equations

```
(001) Acres to Square Meter Coefficient=
4046
Units: meter*meter/Acre

(002) Annual Capital Cost=
Annual Sewer Cost+"Annual Title-5 Cost"+"Annual I/A Capital Cost"
Units: Dollar/Year

(003) "Annual I/A Capital Cost"=
"Annual New Construction I/A Cost"+"Annual I/A Conversion Cost"+
"Annual I/A Reconstruction Cost"
Units: Dollar/Year

(004) "Annual I/A Conversion Cost"=
"I/A Conversion Cost"*"I/A Conversion Rate"
Units: Dollar/Year

(005) "Annual I/A O&M Cost"=
"I/A Housing Units"*"I/A O&M Cost"
Units: Dollar/Year

(006) "Annual I/A Reconstruction Cost"=
Include Septic System Reconstruction Cost*
"Retiring I/A Septic Systems"*"I/A Reconstruction Cost"
Units: Dollar/Year

(007) "Annual New Construction I/A Cost"=
"New Construction I/A Cost"*"New I/A Housing Units"
```

```
Units: Dollar/Year

(008) "Annual New Construction Title-5 Cost"=
"New Title-5 Housing Units"*"Title-5 Capital Cost"
Units: Dollar/Year

(009) Annual Operation and Maintanence Cost=
"Annual Title-5 O&M Cost"+"Annual Sewer O&M Cost"+
"Annual I/A O&M Cost"
Units: Dollar/Year

(010) Annual Sewer Cost=
WWTF Construction Cost+Sewage Collection Cost
Units: Dollar/Year

(011) "Annual Sewer O&M Cost"=
Sewered Housing Units*"Sewer O&M Cost"
Units: Dollar/Year

(012) "Annual Title-5 Cost"=
"Annual New Construction Title-5 Cost"+
"Annual Title-5 Reconstruction Cost"
Units: Dollar/Year

(013) "Annual Title-5 O\&M Cost"=
"Title-5 Housing Units"*"Title-5 O&M Cost"
Units: Dollar/Year

(014) "Annual Title-5 Reconstruction Cost"=
"Title-5 Capital Cost"*Include Septic System Reconstruction Cost*
"Retiring Title-5 Septic Systems"*
(1-"Fraction of Retiring Title-5s to Convert to I/A"*
"Switch for I/A Conversion")
Units: Dollar/Year

(015) Annual Wastewater Management Cost=
Annual Capital Cost+Annual Operation and Maintenance Cost
Units: Dollar/Year

(016) Annual Wastewater per Housing Unit=
Daily Wastewater per Housing Unit*Day to Year Conversion
Units: Liter/(Housing Unit*Year)

(017) Attenuation=
Nutrients in Groundwater/Attenuation Time
```

Units: Kilogram/Year

(018) Attenuation Time=
Groundwater Travel Time/Fraction of Attenuation
Units: Year

(019) Average Collection Pipe Length per Housing Unit=
200
Units: foot/Housing Unit

(020) Groundwater Travel Time=
10
Units: Year

(021) Average Household Water Use=
240
Units: Gallon/(Housing Unit*Day)
Calibrated based on
http://www.capecodcommission.org/resources/waterresources/CapeCodRegionalWastewater.pdf to make sure that the total Cape-wide wastewater generation in year 2000 is about 12 billion gallon annually.

(022) Average Nearshore Bay Depth=
Average Nearshore Bay Depth in Foot*Foot to Meter Coefficient
Units: meter

(023) Average Nearshore Bay Depth in Foot=
33
Units: foot

(024) Average Treated Water Travel Time=
1
Units: Year

(025) "Base Fraction of I/A Housing Units"=
0
Units: Dmnl [0,1]

(026) Base Fraction of Sewered Housing Units=
0.1
Units: Dmnl

(027) "Base Fraction of Title-5 Housing Units"=

```
0.9
Units: Dmnl [0,1]


(028) Coastal Water Volume=
Nearshore Bay Surface Area*Average Nearshore Bay Depth*
Cubic Meter Unit Conversion
Units: Cubic Meter

(029) Construction Cost per WWTF=
INTEGER(WWTF Capacity in Gallon*
Table of WWTF Construction Cost(WWTF Capacity in Gallon
))
Units: Dollar/WWTF


(030) Cumulative Capital Cost= INTEG (
Annual Capital Cost,
0)
Units: Dollar

(031) "Cumulative O&M Cost"= INTEG (
Annual Operation and Maintenance Cost,
0)
Units: Dollar

(032) Cumulative Wastewater Management Cost= INTEG (
Annual Wastewater Management Cost,
0)
Units: Dollar

(033) Daily Wastewater per Housing Unit=
Daily Water Use per Housing Unit*Fraction of Wastewater
Units: Liter/(Housing Unit*Day)

(034) Daily Water Use per Housing Unit=
Average Household Water Use*Gallon to Liter Conversion
Units: Liter/(Housing Unit*Day)


(035) Denitrification=
Fraction of Denitrification*Nutrients in Water Column/
Nutrient Removal Time
Units: Kilogram/Year
```

```
(036) "Desired Accelerated I/A Conversion Rate"=
"Housing Units to Convert to I/A"/"Time Remaining to I/A Deadline"
Units: Housing Unit/Year

(037) "Desired Conversion Rate for Retiring Title-5s"=
"Retiring Title-5 Septic Systems"*
"Fraction of Retiring Title-5s to Convert to I/A"
Units: Housing Unit/Year

(038) Desired Sewer Install Rate=
Housing Units to Sewer/Time Remaining to Sewer Install Deadline
Units: Housing Unit/Year

(039) Desired WWTFs=
IF THEN ELSE( Sewered Housing Units/WWTF Serving Capacity =
INTEGER(Sewered Housing Units/WWTF Serving Capacity) ,
INTEGER(Sewered Housing Units/WWTF Serving Capacity) ,
INTEGER(Sewered Housing Units/WWTF Serving Capacity)+1 )
Units: WWTF

(040) Dissolved Oxygen=
Relative Dissolved Oxygen*Base Dissolved Oxygen
Units: Milligram/Liter

(041) Dredging  = A FUNCTION OF( Dredging Switch,Dredging Time,
Nutrients in Bottom Sediment)
Dredging=
Dredging Switch*(Nutrients in Bottom Sediment/Dredging Time)
Units: Kilogram/Year


(042) Dredging Switch=
IF THEN ELSE(Time >= Dredging Start Time, 1 , 0 )
Units: Dmnl

(043) Dredging Time=
10
Units: Year


(044) Effluent Nutrient Concentration=
2.6e-005
Units: Kilogram/Liter
Based on 13.5 pound nutrients per household per year. In other
words, 26 mg per liter.
```

```
(045) Export to Ocean=
Nutrients in Water Column/Freshwater Residence Time
Units: Kilogram/Year

(046) Fraction of Attenuation=
0.25
Units: Dmnl

(047) Fraction of Denitrification=
0.7
Units: Dmnl

(048) "Fraction of I/A Housing Units"=
STEP("Base Fraction of I/A Housing Units",0) +
STEP("Post-solution Fraction of I/A Housing Units"-
"Base Fraction of I/A Housing Units",Policy Implementation Start Time)
Units: Dmnl

(049) "Fraction of Nutrients in I/A Septage"=
0.15
Units: Dmnl

(050) "Fraction of Nutrients in Title-5 Septage"=
0.15
Units: Dmnl

(051) "Fraction of Retiring Title-5s to Convert to I/A"=
0
Units: Dmnl

(052) Fraction of Sewer Leaching=
0.2
Units: Dmnl

(053) Fraction of Sewered Housing Units=
STEP(Base Fraction of Sewered Housing Units, 0) +
STEP("Post-solution Fraction of Sewered Housing Units"-
Base Fraction of Sewered Housing Units,Policy Implementation Start Time)
Units: Dmnl

(054) "Fraction of Title-5 Housing Units"=
STEP("Base Fraction of Title-5 Housing Units",0) +
STEP("Post-solution Fraction of Title-5 Housing Units"-
"Base Fraction of Title-5 Housing Units",Policy Implementation Start Time
```

```
)
Units: Dmnl

(055) Fraction of Wastewater=
0.9
Units: Dmnl
90\% of indoor water use becomes wastewater.
Cape Cod Commission Documents

(056) Freshwater Residence Time=
0.0625
Units: Year

(057) Gap in WWTFs=
Desired WWTFs-Wastewater Treatment Facilities
Units: WWTF

(058) Harvesting=
Switch for Harvesting*Nutrients in Water Column/
Harvesting Nutrient Removal Time
Units: Kilogram/Year

(059) Harvesting NRT in Months=
10
Units: Month

(060) Harvesting Nutrient Removal Time=
Harvesting NRT in Months*Month to Year Conversion
Units: Year

(061) "Housing Units to Convert to I/A"=
"Title-5 Housing Units"*"Target Accelerated I/A Conversion Fraction"
Units: Housing Unit

(062) Housing Units to Sewer=
"Title-5 Housing Units"*Target Sewer Conversion Fraction
Units: Housing Unit

(063) "I/A Conversion Capacity Utilization"=
"I/A Conversion Rate"/"I/A Conversion Capacity"
Units: Dmnl

(064) "I/A Conversion Capacity"=
5000
Units: Housing Unit/Year
```

```
(065) "I/A Conversion Cost"=
15000
Units: Dollar/Housing Unit

(066) "I/A Conversion Deadline"=
"I/A Conversion Start Time"+"I/A Conversion Duration"
Units: Year

(067) "I/A Conversion Rate"=
IF THEN ELSE("Incremental I/A Conversion"=0,
MIN("Desired Accelerated I/A Conversion Rate"+
"Desired Conversion Rate for Retiring Title-5s", "I/A Conversion Capacity"
)*"Switch for I/A Conversion"
 , MIN("Incremental I/A Conversion Rate","I/A Conversion Capacity"))
Units: Housing Unit/Year

(068) "I/A Housing Units Construction Rate"=
Table for New Construction Rate(Time-INITIAL TIME)*
"Fraction of I/A Housing Units"*Switch for New Construction
Units: Housing Unit/Year

(069) "I/A Housing Units"= INTEG (
"I/A Conversion Rate"+"New I/A Housing Units",
0)
Units: Housing Unit

(070) "I/A Leaching Rate"=
1 - ("I/A Nutrient Removal Rate"+"Fraction of Nutrients in I/A Septage")
Units: Dmnl

(071) "I/A Leaching Time"=
1
Units: Year

(071) "I/A Nutrient Removal Rate"=
0.5
Units: Dmnl
50\% nutrient removal efficiency is assumed for the I/A system.
This is based on the Cape Cod Commission's "Comparison of Cost for
Wastewater Management Systems" report.
13 mg/L effluent nutrient concentration is achieved by the
selected enhanced denitrifying individual septic system option
compared to 26 mg/L base case.
```

```
(072) "I/A Nutrient Removal Time"=
1
Units: Year

(073) "I/A O&M Cost"=
3000
Units: Dollar/Housing Unit/Year

(074) "I/A Reconstruction Cost"=
28000
Units: Dollar/Housing Unit

(075) "I/A Septage Transport Time"=
1
Units: Year

(076) "I/A Septage Transport"=
"Nutrients in I/A Septic Systems"*
"Fraction of Nutrients in I/A Septage"/
"I/A Septage Transport Time"
Units: Kilogram/Year

(077) Include Septic System Reconstruction Cost=
0
Units: Dmnl

(078) "Incremental I/A Conversion Rate"=
"Table for Incremental I/A Conversion Rate"(Time-INITIAL TIME)
Units: Housing Unit/Year

(079) "Incremental I/A Conversion"=
0
Units: Dmnl

(080) Incremental Sewer Installation=
0
Units: Dmnl

(081) Incremental Sewer Installation Rate=
Table for Incremental Sewer Installation Rate(Time-INITIAL TIME)
Units: Housing Unit/Year

(082) Initial Nutrient Mass in Coastal Waters=
(Initial Nutrients in Groundwater/Groundwater Travel Time+
Regeneration)/(1/Freshwater Residence Time + 1/
```

Nutrient Removal Time)
Units: Kilogram

(083) Initial Nutrients in Groundwater=
("Initial Nutrients in Title-5"*(1-"Title-5 Nutrient Removal Rate"-
"Fraction of Nutrients in Title-5 Septage")/"Title-5 Leaching Time"
 + Initial Nutrients in Sewer Treatment Plants*
 ((1-Treatment Efficiency)/Sewer Leaching Time)) /
 (1/Groundwater Travel Time + 1/Attenuation Time)
Units: Kilogram

(084) Initial Nutrients in Sewer Treatment Plants=
((Initial Sewered Housing Units*Annual Wastewater per Housing Unit*
Effluent Nutrient Concentration)+("Initial Nutrients in Title-5"*
"Fraction of Nutrients in Title-5 Septage"/
"Title-5 Septage Transport Time"))/
(Treatment Efficiency/Treatment Time+(1-Treatment Efficiency)*
Fraction of Sewer Leaching/Sewer Leaching Time
+(1-Treatment Efficiency)*(1-Fraction of Sewer Leaching)/
Average Treated Water Travel Time
)
Units: Kilogram

(085) "Initial Nutrients in Title-5"=
("Initial Title-5 Housing Units"*Annual Wastewater per Housing Unit*
Effluent Nutrient Concentration)/("Title-5 Nutrient Removal Rate"/
"Title-5 Nutrient Removal Time"
+"Fraction of Nutrients in Title-5 Septage"/"Title-5 Septage Transport Time"
+(1-"Title-5 Nutrient Removal Rate"-"Fraction of Nutrients in Title-5 Septage"
)/"Title-5 Leaching Time")
Units: Kilogram

(086) Initial Sewered Housing Units=
5000
Units: Housing Unit
Cape had 54,703 housing units in 1960 according to the Cape Cod
Commission's "Cape Trends" document, available at
http://www.capecodcommission.org/resources/economicdevelopment/Ca
peTrends.pdf. We assume that 90\% of these properties used
Title-5 Septic System and 10\% used Sewer.

(087) "Initial Title-5 Housing Units"=
50000
Units: Housing Unit
Cape had 54,703 housing units in 1960 according to the Cape Cod

Commission's "Cape Trends" document, available at http://www.capecodcommission.org/resources/economicdevelopment/CapeTrends.pdf. We assume that 90\% of these properties used Title-5 Septic System and 10\% used Sewer.

(088) Kilogram to Miligram Conversion=
1e+006
Units: Miligram/Kilogram

(089) "Leaching from I/A"=
"Nutrients in I/A Septic Systems"*"I/A Leaching Rate"/
"I/A Leaching Time"
Units: Kilogram/Year

(090) Leaching from Sewer=
(Nutrients in Sewer Treatment Plants*Sewer Leaching Rate)/
Sewer Leaching Time
Units: Kilogram/Year

(091) "Leaching from Title-5"=
"Nutrients in Title-5 Septic Systems"*"Title-5 Leaching Rate"/
"Title-5 Leaching Time"
Units: Kilogram/Year

(092) "New Construction I/A Cost"=
28000
Units: Dollar/Housing Unit

(093) "New I/A Housing Units"=
"I/A Housing Units Construction Rate"
Units: Housing Unit/Year

(094) New Sewered Housing Units=
Sewered Housing Units Construction Rate
Units: Housing Unit/Year

(095) "New Title-5 Housing Units"=
"Title-5 Housing Units Construction Rate"
Units: Housing Unit/Year

(096) New WWTFs=
Gap in WWTFs/Time to Construct New Treatment Facility
Units: WWTF/Year

```
(097) Nutrient Loading from Groundwater=
Nutrients in Groundwater/Groundwater Travel Time
Units: Kilogram/Year


(098) "Nutrient Removal from I/A"=
"Nutrients in I/A Septic Systems"*"I/A Nutrient Removal Rate"/
"I/A Nutrient Removal Time"
Units: Kilogram/Year

(099) "Nutrient Removal from Title-5"=
"Nutrients in Title-5 Septic Systems"*
"Title-5 Nutrient Removal Rate"/"Title-5 Nutrient Removal Time"
Units: Kilogram/Year

(100) Nutrient Removal Time=
Nutrient Removal Time in Months*Month to Year Conversion
Units: Year

(101) Nutrient Removal Time in Months=
3.33
Units: Month
alpha = 0.3/month
      = 0.3*12/year
t = 1/0.3*12 = 3.3 year

(102) Nutrients from Treated Water Discharge=
Nutrients in Sewer Treatment Plants*((1-Treatment Efficiency)*
(1-Fraction of Sewer Leaching))/Average Treated Water Travel Time
Units: Kilogram/Year


(103) Nutrients in Groundwater= INTEG (
"Leaching from I/A"+Nutrients from Treated Water Discharge+
Leaching from Sewer+"Leaching from Title-5"-Attenuation-
Nutrient Loading from Groundwater,Initial Nutrients in Groundwater)
Units: Kilogram

(104) "Nutrients in I/A Septic Systems"= INTEG (
"Nutrients into I/A"-"I/A Septage Transport"-"Leaching from I/A"-
"Nutrient Removal from I/A"
,
0)
Units: Kilogram
```

```
(105) Nutrients in Sewer Treatment Plants= INTEG (
"I/A Septage Transport"+Nutrients into Sewer+
"Title-5 Septage Transport"-Leaching from Sewer-
Nutrients from Treated Water Discharge-Treatment,
Initial Nutrients in Sewer Treatment Plants)
Units: Kilogram

(106) "Nutrients in Title-5 Septic Systems"= INTEG (
"Nutrients into Title-5"-"Leaching from Title-5"-
"Nutrient Removal from Title-5"-"Title-5 Septage Transport",
"Initial Nutrients in Title-5")
Units: Kilogram

(107) Nutrients in Water Column= INTEG (
Nutrient Loading from Groundwater+Regeneration-Denitrification-
Export to Ocean-Harvesting-Sedimentation,
Initial Nutrient Mass in Coastal Waters)
Units: Kilogram
(Nutrient Loading+Nitrofication)/((1/Residence Time) + Nutrient
Removal Coefficient)

(108) "Nutrients into I/A"=
"I/A Housing Units"*Annual Wastewater per Housing Unit*
Effluent Nutrient Concentration
Units: Kilogram/Year

(109) Nutrients into Sewer=
Sewered Housing Units*Annual Wastewater per Housing Unit*
Effluent Nutrient Concentration
Units: Kilogram/Year

(110) "Nutrients into Title-5"=
"Title-5 Housing Units"*Annual Wastewater per Housing Unit*
Effluent Nutrient Concentration
Units: Kilogram/Year

(111) "Post-solution Fraction of I/A Housing Units"=
0
Units: Dmnl

(112) "Post-solution Fraction of Sewered Housing Units"=
1
Units: Dmnl

(113) "Post-solution Fraction of Title-5 Housing Units"=
```

```
0
Units: Dmnl [0,1]

(114) Property Connection Cost=
Unit Collection Cost*Average Collection Pipe Length per Housing Unit*
(Sewer Installation Rate+New Sewered Housing Units)
Units: Dollar/Year

(115) Regeneration=
Nutrients in Bottom Sediment/Regeneration Time
Units: Kilogram/Year

(116) Regeneration Time=
1
Units: Year

(117) Relative Dissolved Oxygen=
Table for Effect of Microalgae on Dissolved Oxygen(Effect of Microalgae
on Dissolved Oxygen
)
Units: Dmnl

(118) "Retiring I/A Septic Systems"=
"I/A Housing Units"/"Useful Lifetime for I/A Septic Systems"
Units: Housing Unit/Year

(119) "Retiring Title-5 Septic Systems"=
"Title-5 Housing Units"/"Useful Life for Title-5 Septic Systems"
Units: Housing Unit/Year

(120) Sedimentation=
(1-Fraction of Denitrification)*Nutrients in Water Column/
Nutrient Removal Time
Units: Kilogram/Year

(121) Sewage Collection Cost=
Sewage Transport Cost+Property Connection Cost
Units: Dollar/Year

(122) Sewage Transport Cost=
New WWTFs*Transport Cost per WWTF
Units: Dollar/Year

(123) Sewer Installation Capacity=
1500
```

Units: Housing Unit/Year

(124) Sewer Installation Capacity Utilization=
Sewer Installation Rate/Sewer Installation Capacity
Units: Dmnl

(125) Sewer Installation Deadline=
Sewer Installation Start Time+Sewer Installation Duration
Units: Year

(126) Sewer Installation Rate=
IF THEN ELSE(Incremental Sewer Installation=0,
MIN(Desired Sewer Install Rate, Sewer Installation Capacity) *
Switch for Sewer Installation , MIN(Incremental Sewer Installation Rate
,Sewer Installation Capacity))
Units: Housing Unit/Year

(127) Sewer Leaching Rate=
(1-Treatment Efficiency)*Fraction of Sewer Leaching
Units: Dmnl

(128) Sewer Leaching Time=
1
Units: Year

(129) "Sewer O&M Cost"=
350
Units: Dollar/Housing Unit/Year

(130) Sewered Housing Units= INTEG (
New Sewered Housing Units+Sewer Installation Rate,
Initial Sewered Housing Units)
Units: Housing Unit
Sewered properties are assumed to constitute 10\% of the Cape
housing units.

(131) Sewered Housing Units Construction Rate=
Switch for New Construction*Table for New Construction Rate(Time-
INITIAL TIME)*Fraction of Sewered Housing Units
Units: Housing Unit/Year

(132) Switch for Harvesting=
IF THEN ELSE(Time >= Harvesting Policy Start Time, 1 , 0)

```
Units: Dmnl

(133) "Switch for I/A Conversion"=
(1-"Incremental I/A Conversion")*STEP(1, "I/A Conversion Start Time") +
 STEP(-1, "I/A Conversion Deadline") + "Incremental I/A Conversion"
*"Table for Incremental I/A Conversion Switch"(Time-INITIAL TIME)
Units: Dmnl
1 - if Convert Title-5 to I/A is enabled
0 - if Convert Title-5 to I/A is disabled

(134) Switch for New Construction=
1
Units: Dmnl

(135) Switch for Sewer Installation=
(1-Incremental Sewer Installation)*STEP(1,
Sewer Installation Start Time)+ STEP(-1, Sewer Installation Deadline) +
 Incremental Sewer Installation*
 Table for Incremental Sewer Installation Switch(Time-INITIAL TIME)
Units: Dmnl
1 - if Install Sewer is enabled
0 - if Install Sewer is disabled

(136) Table for Effect of Microalgae on Dissolved Oxygen(
[(0,0)-(5,2)],(0,1.4),(1,1),(2,0.65),(3,0.31),(5,0.31))
Units: Dmnl

(137) "Table for Incremental I/A Conversion Rate"(
[(0,0)-(150,10)],(0,0),(54,0),(55,5000),(74,5000),(75,0),(150,0))
Units: Housing Unit/Year

(138) "Table for Incremental I/A Conversion Switch"(
[(0,0)-(150,10)],(0,0),(54,0),(55,1),(74,1),(75,0),(150,0))
Units: Dmnl

(139) Table for Incremental Sewer Installation Rate(
[(0,0)-(150,10)],(0,0),(50,0),(150,0))
Units: Housing Unit/Year

(140) Table for Incremental Sewer Installation Switch(
[(0,0)-(150,10)],(0,0),(50,0),(150,0))
Units: Dmnl

(141) Table for New Construction Rate(
[(0,0)-(151,5000)],(0,1000),(10,1000),(11,3500),(30,3500),(31,1500),
```

```
(50,1500),(51,1650),(80,1650),(81,0),(150,0))
Units: Housing Unit/Year
30\% Growth in the next 30 Years:
[(0,0)-(151,5000)],(0,1000),(10,1000),(11,3500),(30,3500),(31,150
0),(50,1500),(51,1650),(80,1650),(81,0),(150,0)

45\% Growth in the next 30 Years:
[(0,0)-(151,5000)],(0,1000),(10,1000),(11,3500),(30,3500),(31,150
0),(50,1500),(51,2500),(80,2500),(81,0),(150,0)

(142) Table of WWTF Construction Cost(
[(10000,0)-(3e+006,80)],(10000,70),(37431.2,52.9825),
(55718.7,47.0175),(110581,37.5439),(256881,27.7193),
(512905,21.0526),(741499,18.2456),
(1e+006,17),(1.26269e+006,16.1404),(1.537e+006,15.4386),
(1.70159e+006,15.0877),(1.89361e+006,15.0877),
(2.0582e+006,14.386),(2.23193e+006,14.09),
(2.43309e+006,13.6842),(2.63425e+006,13.5),
(2.78969e+006,13.38),(2.91771e+006,13.3),(3e+006,13.25
))
Units: Dollar*Day/Gallon

(143) "Target Accelerated I/A Conversion Fraction"=
0
Units: Dmnl [0,1]

(144) Target Sewer Conversion Fraction=
1
Units: Dmnl [0,1]

(145) "Time Remaining to I/A Deadline"=
MAX( "I/A Conversion Deadline"-Time , 1 )
Units: Year

(146) Time Remaining to Sewer Install Deadline=
MAX( Sewer Installation Deadline-Time , 1 )
Units: Year

(147) Time to Construct New Treatment Facility=
1
Units: Year

(148) "Title-5 Capital Cost"=
13000
Units: Dollar/Housing Unit
```

\$13000 capital cost for a current Title-5 system is assumed by
following the Cape Cod Commission's "Comparison of Cost for
Wastewater Management Systems" report.

(149) "Title-5 Housing Units Construction Rate"=
Switch for New Construction*Table for New Construction Rate(
Time-INITIAL TIME)*"Fraction of Title-5 Housing Units"
Units: Housing Unit/Year

(150) "Title-5 Housing Units"= INTEG (
"New Title-5 Housing Units"-"I/A Conversion Rate"-
Sewer Installation Rate
,
"Initial Title-5 Housing Units")
Units: Housing Unit
Cape had 54,703 housing units in 1960 according to the Cape Cod
Commission's "Cape Trends" document, available at
http://www.capecodcommission.org/resources/economicdevelopment/CapeTrends.pdf

(151) "Title-5 Leaching Rate"=
1 - ("Title-5 Nutrient Removal Rate"+
"Fraction of Nutrients in Title-5 Septage"
)
Units: Dmnl

(152) "Title-5 Leaching Time"=
1
Units: Year

(153) "Title-5 Nutrient Removal Rate"=
0
Units: Dmnl

(154) "Title-5 Nutrient Removal Time"=
1
Units: Year

(155) "Title-5 O&M Cost"=
110
Units: Dollar/Housing Unit/Year

(156) "Title-5 Septage Transport Time"=
4
Units: Year

```
(157) "Title-5 Septage Transport"=
"Nutrients in Title-5 Septic Systems"*
"Fraction of Nutrients in Title-5 Septage"
/"Title-5 Septage Transport Time"
Units: Kilogram/Year

(158) Total Housing Units=
"Title-5 Housing Units"+Sewered Housing Units+"I/A Housing Units"
Units: Housing Unit

(159) Transport Cost per WWTF=
Transport Distance*Unit Collection Cost
Units: Dollar/WWTF

(160) Transport Distance=
10000
Units: foot/WWTF

(161) Treatment=
Nutrients in Sewer Treatment Plants*Treatment Efficiency/
Treatment Time
Units: Kilogram/Year

(162) Treatment Efficiency=0.85
Units: Dmnl

(163) Treatment Time=
1
Units: Year

(164) Unit Collection Cost=
200
Units: Dollar/foot

(165) "Useful Life for Title-5 Septic Systems"=
30
Units: Year

(166) "Useful Lifetime for I/A Septic Systems"=
30
Units: Year

(167) Wastewater Treatment Facilities= INTEG (
New WWTFs,
```

INTEGER(Initial Sewered Housing Units/WWTF Serving Capacity))
Units: WWTF

(168) WWTF Capacity=
WWTF Capacity in Gallon*Gallon to Liter Conversion
Units: Liter/(Day*WWTF)

(169) WWTF Capacity in Gallon=
1e+006
Units: Gallon/(Day*WWTF)

(170) WWTF Construction Cost=
New WWTFs*Construction Cost per WWTF
Units: Dollar/Year

(171) WWTF Serving Capacity=
WWTF Capacity/Daily Wastewater per Housing Unit
Units: Housing Unit/WWTF

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