ABSTRACT

Title of Dissertation:	An Environmental Anthropology of Modeling and Management on the Chesapeake Bay Watershed
	Jeremy M. Trombley, Doctor of Philosophy, 2017
Dissertation directed by:	Dr. Michael Paolisso, Professor and Interim Chair, Department of Anthropology

In the last few decades, computational models have become an essential component of our understanding of complex environmental processes. In addition, they are increasingly used as tools for the management of large-scale environmental problems like climate change. As a result, understanding the role that these models play in the socioecological process of environmental management is an important area of inquiry for an environmental anthropology concerned with understanding human-environment interactions. In this dissertation, I examine these roles through an ethnographic study of computational environmental modeling in the Chesapeake Bay watershed. The Chesapeake Bay region is an excellent place to investigate modeling and management because, for over thirty years, it has been the site of a watershed-scale effort to reduce nutrient pollution (nitrogen, phosphorous, and sediment) to the Chesapeake Bay. In order to carry out this management process, the Chesapeake Bay

Program (CBP) was created as a partnership between the federal government and seven watershed jurisdictions. In addition, modelers at the CBP have been developing a complex computational model of the watershed known as the Chesapeake Bay Modeling System (CBMS) in order to identify and track the sources and effects of nutrient pollution on the estuary. In this dissertation, I explore the role of the CBMS and other models in our understanding and management of nutrient pollution in the region through three articles written for publication in peer-reviewed journals, each of which addresses the question in a different way. The first discusses the ways that the *process* of building and implementing a computational model is affected by its inclusion in a management institution. The second describes the ways that the computational models *themselves* are affected by the management contexts in which they are developed and deployed. The third examines the various roles that they play in building and maintaining the relationships that underlie the management process. Together, these articles shed light on the ways that computational models mediate human-environment interactions by way of environmental management, and will help to plan more inclusive and effective modeling and management approaches in the future.

AN ENVIRONMENTAL ANTHROPOLOGY OF MODELING AND MANAGEMENT IN THE CHESAPEAKE BAY WATERSHED

by

Jeremy Michael Trombley

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in
Anthropology
2017

Advisory Committee:
Dr. Michael Paolisso, Chair
Dr. Shirley Fiske
Dr. Kim Fortun
Dr. Klaus Hubacek
Dr. Jen Shaffer

Dedication

I would like to dedicate this dissertation to my brother, Tim Trombley.

He passed away while I was working on it, and I miss him every day.

But I know he was proud to be my brother, just as I am proud to have been his.

Acknowledgements

There are many people who provided assistance and support in the process of conducting the research for and writing this dissertation. First, I would like to thank the staff at the Chesapeake Bay Program who gave me access to resources and invited me to meetings and other events. I would particularly like to thank Gary Shenk, Lewis Linker, and the other modeling team members who were always available to answer questions and provide guidance throughout my research. I would also like to acknowledge the participation of modelers from the University of Maryland Center for Environmental Studies, Johns Hopkins University, and the Virginia Institute of Marine Sciences, who were also open to answering questions and letting me sit in on modeling projects and meetings on a regular basis, particularly Jeremy Testa and Lora Harris.

Without support from the National Science Foundation, this research would not have been possible, and so I want to thank the NSF for giving me the opportunity to pursue this unique area of research. In particular, I want to thank Deborah Winslow for her promptness with responding to questions and providing additional information when requested.

Next I would like to thank my committee members, Jen Shaffer, Shirley Fiske, Kim Fortun, and Klaus Hubacek, for providing help and guidance along the way. Their advice enabled me to successfully apply for and receive National Science Foundation funding for my research and helped with the planning of the project. I also want to thank my fellow environmental anthropology PhD Students, Jo Johnson, Christy Miller-Hesed, and Elizabeth Van Dolah for their support and kindness over the years while we worked together to understand anthropology and plan our projects. I also owe a debt of gratitude to my friends David Colón-Cabrera, Michael Roller, and Kristin Sullivan for their friendship throughout my doctoral degree – our conversations have expanded my understanding of anthropology tremendously. My friend at Binghamton Universtiy, Joshua Reno, also helped me to think through the ideas and read some early drafts of the chapters that make up this dissertation. Lastly, Jane Gibson and Donald Stull, who were advisors during my undergrad at the University of Kansas, were always available for feedback and to provide advice as I made my way through graduate school.

My PhD advisor, Michael Paolisso, offered invaluable help and support over the past eight years. He deserves credit for putting up with my unusual anthropological interests, but also for helping to secure funding and other resources so that I could continue my doctoral studies. His influence has allowed me to work on a diverse array of projects in addition to my dissertation research, all of which have provided me opportunities to explore my own interests in ethnographic research.

Finally, I owe an enormous debt of gratitude to my family. My parents, Janet and Thomas Trombley, have always been there for me even through their own difficult times. They never stopped believing in me even when I did not believe in myself, and I would not be the person I am today without their love and influence. My wife, Trish Markert, is the joy of my life. She has been by my side every step of the way and her enthusiasm for my research and our many conversations about it has helped me to overcome innumerable challenges. I would not be here without her help.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ABM	Agent Based Model
AST	Assessment Scenario Tool
BayFAST	Bay Facilities Assessment Scenario Tool
BMP	Best Management Practice
CAST	Chesapeake Assessment Scenario Tool
CBF	Chesapeake Bay Foundation
CBHM	Chesapeake Bay Hydraulic Model
CBP	Chesapeake Bay Program
CHEMS	Chesapeake Environmental Modeling Symposium
CMAQ	Community Multiscalar Air Quality
CMBS	Chesapeake Bay Modeling System
CWA	Clean Water Act
EMS	Environmental Media Systems
EPA	Environmental Protection Agency
FSPs	Fundamental Science Practices
GIS	Geographic Information System
HSPF	Hydrological Simulation Program Fortran
IRB	Internal Review Board
JHU	John's Hopkins University
MAST	Maryland Assessment Scenario Tool
NADP	National Atmospheric Deposition Program

NRC	National Research Council
NSF	National Science Foundation
PI	Principle Investigator
RFP	Request for Proposals
STAC	Science and Technology Advisory Committee
STS	Science and Technology Studies
TMDL	Total Maximum Daily Load
UMCES	University of Maryland Center for Environmental Sciences
UPenn	University of Pennsylvania
USC	Upper Susquehanna Coalition
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VAST	Virginia Assessment Scenario Tool
VIMS	Virginia Institute of Marine Sciences
WIP	Watershed Implementation Plan
WQGIT	Water Quality Goal Implementation Team
WSC	Water, Sustainability, and Climate (NSF Program)

Chapter 1: An Ethnographic Approach to Computational Environmental Modeling and Management

As environmental anthropologists, we are interested in the ways that people conceptualize and interact with their environments. Modeling – the creation of simplified representations of complex systems – in various forms has always been part of the way we understand and respond to environmental conditions (Atran 2005; Geertz 1977; Paolisso 2010, 2002; Rappaport 1968). Over the last few decades, a new kind of modeling – based on the use of computational systems and referred to as computational modeling – has become increasingly influential in the way we understand and interact with environmental systems (Edwards 2010; Hastrup and skydstrup 2013; Lansing and Kremer 1993; Lansing 2006). In fact, it has become so pervasive that often we can no longer distinguish between pure data – data that are presented as empirical research – and modeled data – data that have been manipulated and transformed through computation (Edwards 1999). As a result, it is argued that computational modeling has become a defining technology and practice for contemporary environmental conceptualization (Edwards 2010; Ihde 2006; Knuuttila 2011). With this in mind, computational environmental modeling is a key topic for the further development of environmental anthropology and our understanding of human-environment interactions.

A great deal of work has been done to explore the peculiar epistemological characteristics of computational models (Edwards 1999; Knuuttila and Voutilainen

2003; Knuuttila 2006; Oreskes 1998) – the way these models produce knowledge differently from traditional empirical sciences – as well as the social factors that contribute to the production of models (Hastrup and Skydstrup 2013; Lahsen 2005; Morgan and Morrison 1999; Shackley et al. 1999; Sundberg 2009). This research demonstrates that models are not produced in vacuums, and that they affect and are affected by the social conditions in which they are produced and used. However, much of this literature focuses on the scientific context of computational modeling, and little has been done to investigate their role in the socioecological process of environmental management.

The management of shared resources is an important part of our collective relationship to the ecological systems in which we live. Management institutions determine the rules and constraints that shape our activities on the landscape (Ostrom 1990, 2008). Recently, these institutions have grown increasingly complex and large-scale in response to the increasing scale and complexity of the environmental problems that we face (Ostrom 2010). This also means that maintaining the underlying relationships of these institutions has become a significant challenge (Ostrom 2010). Since ecological systems like the global climate and large watersheds cannot be studied exclusively through empirical methods, computational models are essential for informing our understanding of these kinds of large-scale and complex problems (NRC 2007; Edwards 2010). As a result, they play an important part in the management institutions through which we attempt to address large-scale problems. Understanding how these computational environmental models affect and are affected by the socioecological management institutions in which they are produced and used, in addition to their informational role, is an important area for environmental anthropology research.

This dissertation addresses these concerns through ethnographic research on the use of computational environmental modeling for the management of complex socioecological contexts. In this research, I attempt to answer the question, "What is the role of computational models within the broader socioecological contexts in which they are produced and used?" In order to answer this broader question, I attempt to address three sub-questions in three chapters (four, five, and six) written as articles for peer-reviewed publication:

1. How are modeling practices affected by the environmental management institutions in which they take place?
2. How are the models themselves affected by the environmental management institutions in which they are developed and used?
3. How are the social relationships that constitute environmental management institutions affected by the production and use of computational environmental models?

The Chesapeake Bay watershed offers an ideal location for investigating the role of computational environmental models within their socioecological contexts for three reasons. First, it has been the subject of a significant management effort, led by the Chesapeake Bay Program (CBP), for over thirty years. Second, since 2010, it has been the site of the largest Total Maximum Daily Load (TMDL) restoration plan ever implemented by the Environmental Protection Agency (EPA). And third, these management processes have been informed by the use of a complex and state-of-the art computational environmental model known as the Chesapeake Bay Modeling System (CBMS). My goal in this research is not to determine the effectiveness of the CBP as a management organization, but to understand how computational modeling affects and is affected by the social relationships that underlie it. Through ethnographic study with modelers at the CBP and other organizations in the watershed, I attempt to explore the role of the CBMS within the broader Chesapeake Bay watershed socioecological context and answer the above research questions.

This research contributes to both the advancement of the field of environmental anthropology and the practical understanding of computational modeling and environmental management. For the latter, the research will help computational modelers, scientists, and environmental management staff to understand how the production and use of computational models shapes and is shaped by their social contexts. This information will help these groups to more effectively plan the implementation of computational environmental models. In the context of environmental anthropology, this research adds to our understanding of the role that science and technology play in the socioecological context of environmental management institutions. Given that management institutions are essential components of our relationship to ecological systems, and computational models play an increasingly important role within them, this will help to expand our understanding of human-environment interactions.

In the following sections of this chapter, I discuss how this dissertation fits within the broader field of environmental anthropology and the study of human-environment relationships. I then provide a brief description of the field site and research methods. Finally, I provide an outline of the remainder of the dissertation.

Environmental Anthropology, Computational Modeling, and Environmental Management

The purpose of this dissertation is to examine the relationship between socioecological practices and computational modeling – how computational models affect and are affected by the broader socioecological contexts in which they are produced and deployed. In order to examine this further, we must first understand the body of literature within environmental anthropology and other disciplines that address the use of computational models for environmental science and management. Additionally, since the research focuses on the use of computational models within environmental management institutions, understanding the body of environmental anthropology and other literature on the role of such institutions within socioecological contexts is essential as well.

Environmental Anthropology

Environmental anthropology, as a field, is primarily concerned with the relationships between human cultural practices and the nonhuman environment in which they operate. Early research focused on a materialist framework drawn from Marxism (Steward 1972) and cybernetics (Rappaport 1968; Bateson 2000). Steward's (1972) cultural ecology, for example, suggests that there is a "cultural core" – a set of practices that connects a cultural group to its environment, usually in terms of subsistence. The cultural core is shaped by these interactions and, subsequently, shapes other aspects of the culture. For example, Steward's analysis of the Shoshone peoples of the Great Basin shows that their dependence upon pine nuts as a primary source of subsistence results in a cultural system that is relatively simple in terms of its social and political organization (Steward 1938).

Rappaport expanded on the "cultural ecology" of Steward and incorporated elements of cybernetic systems theories drawn from the ecological sciences. Instead of focusing on individual "cultures" and their cultural core, Rappaport and other ecological anthropologists began to treat humans as a population within an ecosystem. They sought to show how these human groups contributed to maintaining ecological equilibrium within those systems (Rappaport 1968). Rappaport's (1968) most famous example is the *Rumbim* ritual of the Tsembaga Maring cultures of Papua New Guinea. The ritual involves a lengthy sequence of cultural practices organized around periods of war and peace among the various groups in the region. However, in addition to their ritualistic functions, Rappaport also shows that these practices help to regulate the pig population in the environment and prevent the degradation of the landscape (Rappaport 1968).

These ecological-based studies continue to remain important (Shaffer et al. 2010; Lansing 2006), but much of the interest in environmental anthropology has shifted in recent decades to more problem-oriented approaches such as helping communities to address environmental challenges (Kottak 1999). For example, ethnographic studies of the environmental and cultural impacts of climate change (Shaffer 2014; Crate 2009; Fiske et al. 2014) have helped to bring attention to factors that are not readily apparent from climate modeling and other sources of knowledge. Understanding the relationship between ecological resilience and environmental justice (Hesed and Ostergren 2017) allows us to address the challenges of climate change and other environmental issues with attentiveness to social justice concerns as well. And anthropological research that uses collaborative learning methods to understand and address the impacts of climate change helps to generate community involvement in the process of building resilience (Johnson et al. 2016).

In addition to these problem-oriented approaches, there has been a growing interest in the politics of environmental issues (Paulson and Gezon 2005). In this context, anthropologists are primarily interested in the imbalances of power that contribute to environmental degradation and unequal access to resources. For example, anthropologists can help to shed light on the limits and possibilities of advocacy in the wake of human-caused environmental disasters (Fortun 2009). In addition, they can examine the importance of social movements for creating spaces for environmental sustainability and social justice (Escobar 2008). They might also examine the role of global capitalist supply chains on localized human-environment relationships (Tsing 2015, 2011). Finally, they shed light on the politics of environmental management and the social and ecological networks that shape subjectivity and governance (Ogden 2011; Ogden et al. 2013).

All of these approaches underlie the conceptual basis for the research in this dissertation. They provide a framework for understanding human-environment relationships from a variety of perspectives. The early ecological approaches help to center this research in the assumption that human activities and ecological processes are inseparable from one another. The problem-oriented approaches further guide this research towards understanding the issues and challenges that we face within the Chesapeake Bay watershed. Finally, the political ecological approaches provide the research with a sensitivity to the broader political and economic dynamics that might be contributing to the watershed's environmental problems. Before moving onto a description of the research, I must first examine the ways that environmental anthropologists and researchers from other fields have addressed computational environmental modeling and environmental management institutions.

Anthropology, Science, and Computational Modeling

One emerging area of study within environmental anthropology is the ethnographic study of the role that scientific practices play in our understanding of and relationship to environmental systems. Helmreich's (2009) research with microbial oceanographers, for example, reveals an intimate connection between the scientists and the physical and biological environments that they study. The oceanographers find within the deep-sea volcanic vents an array of living organisms that challenge our conceptions of life and pose new questions for the fields of biotechnology, climate change, and extraterrestrial life. Similarly, Rabinow and Bennett's (2012) research on the field of synthetic biology shows how scientific practices interact with social interests, philosophical concerns, and our relationship with the nonhuman world.

In addition, environmental anthropologists have been long engaged with different forms of modeling. Indeed, understanding the way people represent their world in simplified form is central to the project of anthropology in general and environmental anthropology in particular (cf. Bateson 2000; Descola 2006; Geertz 1977; Rappaport 1968). Rappaport, for example, was concerned with the distinction between operational and cognized models – the actual ecological interactions versus the cultural perception of ecological interactions, respectively (Rappaport 1968). Geertz drew the distinction between "models of" and "models for" – the first being a symbolic representation of nonsymbolic structures and the second being symbolic representations used to produce non-symbolic structures (Geertz 1977). Modeling also seems to be a key feature of human cognition and our interaction with the world around us (D'Andrade 1995; Holland and Quinn 1987). Understanding how these cognitive models are formed and shared as well as how they influence our responses to environmental challenges has been a key line of inquiry for cognitive environmental anthropologists (Atran 2005; Dailey 2016; Kempton 1995; Paolisso 2002, 2010). In the course of that research, it has become clear that the way we model our environment has a significant effect on the way we interact with it as well.

These two interests overlap in this research, which investigates the scientific practice of building and implementing computational environmental models within an environmental management context. These models are similar to the cognitive models described above, in that they are conceptual simplifications of physical realities and processes (Oreskes 1998). Where they differ, however, is in the form of their representation and the degree of complexity that they are able to capture. Computational models are also known as mathematical or numerical models because they rely upon mathematical formulae to represent physical processes (Oreskes 1998; Edwards 2010). However, these formulae are often so complex that they cannot easily be calculated by human beings, and, as a result, they must be carried out by computers (Edwards 2010). Therefore, the benefit of computational models is that they can produce representations of extremely complex physical systems at a level of detail that is beyond the capacity of human knowledge alone. As a result, computational models have been used to simulate the global atmosphere (Edwards 1999), large hydrological systems (Shenk and Linker 2013), the Amazon Rainforest (Levine et al. 2016), and even human social dynamics (Lansing and Kremer 1993; Bruch and Atwell 2015). Understanding how these models influence our understanding of and relationship to the ecological systems that they represent is an important and underexplored area for environmental anthropology.

The majority of environmental anthropologists' encounters with computational models have involved using models to reproduce – and thereby validate – traditional environmental management methods (Dean et al. 2000; Lansing and Kremer 1993; Lansing 2006). Perhaps the most iconic of these has been Stephen Lansing's reproduction of the Balinese *subak* system (Lansing 2006). In response to the colonial attempts during the "green revolution" to modernize traditional rice cultivation in Bali – in which farm villages or *subaks* were organized around a system of water temples – Lansing used an agent based model (ABM) to reconstruct the social and environmental conditions in the region and showed that the *subaks* are self-organized systems that effectively manage water and address the collective environmental challenges that the farmers face. The result was a greater appreciation for the *subak* system among the western-trained environmental managers in the Indonesian capital of Jakarta. In another case (Dean et al. 2000), an ABM was used to simulate Anasazi settlement patterns based on soil and climatic conditions in order to understand the causes behind their sudden "collapse." The model showed continued settlement long after generally accepted "collapse" dates despite soil and climate changes. This indicates that there were broader cultural factors that played a role in their disappearance in addition to environmental factors (Dean et. al. 2000).

On the other hand, some anthropologists have been critical of the use of modeling to represent traditional environmental management systems. Focusing his critique on Lansing's research, Helmreich (1999) argues that this approach tacitly reinforces colonial inequalities and dependencies by using computational systems that are out of reach of those who the models are made to represent. Lansing (2000)) responds that his research – counter to colonial and neocolonial interests – demonstrates the effectiveness of bottom-up approaches to environmental management. However, Helmreich (2000) responds that Lansing also fails to account for social and political dynamics of the region such as the rise of the Suharto regime and the nation's increasing integration into global capitalist supply chains.

Others are critical of the use of computational models more generally. Tsing discusses the role of climate models in projecting a "...globe that is unified, neutral, and understandable through the collection and manipulation of information" (2004, 102). She describes her reaction to the experience of attending a conference on climate modeling through a series of three "surprises." Her first surprise was that the global scale takes precedence because it is the scale of the model. This suggests that, in terms of the models, local processes must fit neatly within the global scale – if they do not, they must be manipulated until they do. Her second surprise was that models breed more models suggesting that "...everything can be quantified and located as an element of a system of feedback and flow" (Tsing 2004, 105). Finally, her third surprise was that models must be charismatic and pedagogical. In other words, they are always embedded in social and political processes of knowledge production and discourse. Tsing (2004), in the end, is not entirely dismissive of modeling. She acknowledges that models can bring diplomats and others to the negotiating table, but they are unable to fully bridge the political divides that form around environmental problems like climate change in and of themselves.

All of this research with computational models within environmental anthropology has produced an interesting dialog about the cultural and ecological value of simplified representation and simulation. What is missing from the environmental anthropology literature is an understanding of the way that computational models mediate our relationship to the environment and their effects on those relationships. As computational models become increasingly essential to the practice of environmental management, understanding how they connect management institutions to the broader socioecological contexts in which they are produced and deployed is an important area of research for environmental anthropologists.

The Social Dimensions of Environmental Modeling

Computational environmental modeling has received more attention in the field of science and technology studies (STS). Since it became a prevalent scientific practice in the 1980s and 1990s, STS scholars have been using philosophical and ethnographic approaches to understanding their role in science and in addressing environmental challenges.

Computational modeling embodies a substantively different kind of knowledge production from traditional, empirical scientific methods. Ihde (2006) argues that models have become the new "epistemology engines" of scientific research. These new representations do not correspond to an observable reality, but instead refer to realities that cannot be seen except through composite representations based on computational modeling. For example, the global climate, which cannot be captured in a single measurement, can be effectively represented through computational models (Ihde 2006). In addition, Oreskes (1998) argues that although models may be evaluated as useful and effective at predicting certain factors, they cannot be validated in the traditional scientific sense due to inherent uncertainties in the modeling process. Specifically, because they must be compared with past data sets, their ability to predict future conditions can never be evaluated since we cannot know how future conditions might change. Knuutilla (2011) argues that computational models must be considered from a performative perspective rather than primarily for their representational characteristics. She argues that models are artifacts – epistemic tools – that purposefully reduce environmental systems to a specific set of characteristics and properties in order to foster new ways of thinking. In this sense, the simplification of models need not be seen as a shortcoming, but is rather "part of a consistent epistemic strategy making cognitive use of the constraints built into a concrete artefact, a model" (Knuutilla 2011, 263).

While these largely epistemological questions are important to address, it is also essential to understand the peculiar role that models play in the social systems in which they are embedded. Taking an ethnographic approach, we learn that there are a number of factors involved in whether a particular model will be accepted, and that not all of them have to do with the technical accuracy of the models themselves. In addition to their epistemic characteristics, it is important for models to be capable of circulating in networks, and, as a result, they must perform their credibility publically in order to gain the trust and acceptance of the broader public (Hulme 2013). Furthermore, we encounter a divide within the modeling community over the importance of accurate versus practical models (Shackley et al. 1999; Sundberg 2009). The proponents of accuracy believe that models should computationally reflect the physical processes involved and avoid parameterizations that represent forces inaccurately. Meanwhile, those who are interested in practical results are not as concerned with the physical accuracy of the models but more with the usefulness of the models for understanding and predicting complex systems (Sundberg 2009, Shackley et al. 1999). In that sense the accuracy of the *results* is more important than the accuracy of the *simulation* (Sundberg 2009).

Underlying these considerations is the sense of political urgency associated with many environmental issues. Edwards (2010) describes a series of such issues that brought modeling to the forefront in environmental decision-making starting with the controversies surrounding supersonic transport (SST) and concerns over "nuclear winter" and ozone depletion, and, ultimately, the problem of climate change. This sense of urgency allowed researchers and policy-makers to overlook the limitations of computational models because they offered a powerful tool for quickly understanding and addressing immediate environmental concerns. Once models gained traction within the environmental management community through the urgency of these issues, they quickly became essential tools for environmental management in general.

Finally, we can begin to ask what it is that models do socially – what role do they play in the social systems in which they circulate? Landström et al. (2013)

demonstrate how different models and different modeling scenarios offer different kinds of "obstacles and affordances" – similar to what Edwards (2010) refers to as "frictions." These "obstacles and affordances" are structural characteristics of the models that either enable or constrain certain ways of using and interacting with them. By improvising with these "obstacles and affordances," wholly different modeling structures were produced. Landström et al. (2013) describe the production of two different modeling systems – one used to address local flooding issues in rural England in which stakeholders were involved in the production and use of the models, and another developed by a contracting firm for generic flooding management scenarios across the UK. Both groups were confronted with different challenges – for example, difficulties finding models that can be used on small-scale versus models that need to operate at larger scales – and both had very different resources to draw upon – for example, a simplified model with a user-friendly interface versus a highly complex model with layers of simulation and parameterizations. In the end, these processes resulted in very different approaches to modeling and ways of learning about environmental systems.

Van Egmond and Zeiss (2010) found that models serve as "boundary objects" that facilitate relationships and communication between different social worlds. In addition, they reconfigure those worlds by reshaping the internal relationships that constitute them. For example, the researchers found that, by incorporating a market approach to health care long before such an option was on the table, the care model "helped to articulate, make stronger and put on the agenda a market based policy program" within the Dutch government (van Egmond and Zeiss 2010, 71). Similarly, Costelloe-Kuehn (2012) analyzes the role of computational models like the Community Multiscalar Air Quality (CMAQ) model as "environmental media systems" (EMS). These novel forms of EMSs help to bring together disparate forms of scientific and policy expertise in order to address complex and large-scale problems such as climate change.

This prior research has effectively explored the philosophical and social factors that contribute to the production of computational models. What is missing from this is a complementary understanding of their effects upon the socioecological systems in which they are embedded. As models become increasingly common in mediating human-environment interactions, it will be important to understand these effects and to evaluate different methods for addressing environmental and social concerns.

Environmental Management Institutions

As much of the above research makes clear, computational environmental models are not constructed in a vacuum, and, since my research focuses on the role that models play in the context of environmental management, an understanding of management institutions is essential.

Interest in environmental institutions – the ways that people manage shared resources – can be traced to the publication of Hardin's "Tragedy of the Commons" (1968). Hardin argues that shared resources will always be subject to overharvesting because humans operate under the rules of economic self-interest. He suggests that, because individuals want to maximize their self-interest in a resource, they will be incentivized to harvest as much of the resources as they can as quickly as they can before others are able to harvest more. Ultimately, this results in the tragedy as the resource becomes depleted and can no longer be relied upon to support the community. Hardin and others have argued that this effect justifies the implementation of private property regimes for environmental management. Private owners, according to the argument, are incentivized to maintain a sustainable relationship with the resource so as to maximize long-term benefits rather than competing with others to outstrip the environment.

Hardin's work has been roundly criticized, most effectively by scholars of environmental institution studies. McCay and Acheson's (1987) volume on the "Question of the Commons" provides a number of case studies that demonstrate ways that communities have organized sustainable common resource use without relying on state regulation or private property regimes. Ostrom's (1990) built upon these case studies with comparative research on "common pool" management regimes. Her research indicates that the tragedy of the commons is not an inevitable result of shared resources. Instead, she finds that people can find ways to manage these resources collectively without resorting to private property regimes or coercive regulatory frameworks. One example she draws from the work of Netting (1981) is the case of Torbel, Switzerland, a village in the Alps. The villagers of Torbel own property and use it for agricultural purposes. However, there is an extensive area of meadows and forests in the mountains that is open for the villagers to use. Access to the common areas is, however, restricted in multiple ways that have been agreed upon and are enforced by the villagers themselves. For example, cattle are often taken to the mountains in the summer for grazing. In order to limit the number of cows grazing in the common areas, there is a rule that restricts villagers from grazing more cows than they can reasonably feed over the winter. This “wintering” rule helps to keep grazing on common lands sustainable.

Ostrom’s (1990) research shows how essential institutional frameworks – defined as “*prescriptions that humans use to organize all forms of repetitive and structured interactions”* (Anderies and Janssen 2016, 14) – are to the management of collective environmental issues. Since our relationships to environmental systems are increasingly mediated by these institutions, and the institutions themselves are becoming more complex due to the complexity of the environmental problems we face (Ostrom 2010), they are an important research interest for environmental anthropologists.

Although the CBP is a state-based management institution, and so does not fit into the common pool resource regimes that Ostrom (1990) describes, it is, nevertheless, one of the many kinds of management institutions that exist. Furthermore, it is also a collaboration between the federal government and many other government and non-governmental partners. For this reason, I believe that the present research fits within the bounds of institutional management studies. My goal in this dissertation has not been to evaluate the effectiveness of the CBP in terms of managing nutrient pollution in the watershed. Instead, my focus has been on the role that computational models play in the CBP as a socioecological institution – how modeling affects and is affected by the institutional relationships that form the CBP. This will help further institutional studies by examining the role of science and technology within them.

By bringing together the bodies of literature on human-environment relationships, the anthropology of computational environmental modeling, STS approaches to computational environmental modeling, and environmental management institutions, this research will help to understand the broader relationship between social systems, science, technology, and ecological systems. The Chesapeake Bay watershed is an ideal context in which to pursue this research because, for the past three decades, it has been the subject of a significant environmental management effort led by the Chesapeake Bay Program with the help of a complex computational model. In the following section, I briefly describe the Chesapeake Bay watershed and why it is an excellent site for the research presented in this dissertation.

Overview of the Field Site and Methods

As a result of long-term environmental degradation on the landscape, the Chesapeake Bay has suffered from low-oxygen conditions caused by nutrient (nitrogen and phosphorous) and sediment pollution and eutrophication (Cooper and Brush 1993; Kemp et al. 2005). For over thirty years, the watershed has been the subject of an extensive effort to reduce the quantity of nutrients and sediment flowing into the Chesapeake Bay. In order to carry out this project, a watershed-scale management institution – the Chesapeake Bay Program (CBP) – was created from a partnership between the federal government and the seven jurisdictions within the watershed (Horton 2003; Ernst 2003, 2009). In addition, computational environmental modeling has been a key feature of the management effort since its start in the 1980s (Shenk and Linker 2013; Linker et al. 2002). The Chesapeake Bay

Modeling System (CBMS) plays a key role in the process of understanding and managing nutrient pollution throughout the watershed, and has grown increasingly influential with the implementation of a Total Maximum Daily Load (TMDL) nutrient pollution diet in 2010. Unlike previous agreements in the watershed, the TMDL imposes strict regulatory limits on the quantity of nutrients that can enter the water (CBP 2010). As a result of these factors, the Chesapeake Bay watershed provides a unique landscape for studying the role of computational modeling in the socioecological process of environmental management.

The research for this dissertation was conducted using ethnographic methods. These methods allow the researcher to gain a rich and detailed understanding of the cultural practices of interest. Three sets of data were necessary to complete this research:

- Information about the process of building and implementing a computational model within an environmental management institution
- Information about the role that the CBMS plays within the CBP
- Information about how the CBMS and other models affect decision-making and management practices at the state and county levels

The first data set was collected using participant observation and semi-structured key informant interviews with computational modelers working on environmental issues in the watershed. This included interviewing modelers at the CBP and in academic settings as well as attending meetings of the CBP's modeling workgroup, which is a group of modelers, scientists, and management staff who contribute to the development of the CBMS. The second data set was collected using semi-structured interviews with CBP staff who are not part of the modeling process but who are familiar with the models and understand how they are used within the CBP. The third data set was collected through semi-structured interviews and participant observation with state and county level management staff in several of the watershed jurisdictions. Altogether, these data provide a detailed and nuanced understanding of the role that computational models play in the watershed management process.

Overview of the Dissertation

In the following chapters, I examine the question, "What is the role of computational models within the broader socioecological contexts in which they are produced and used?" The primary chapters in the dissertation – chapters four, five, and six – are written as articles for publication in peer-reviewed journals. Each of these article-chapters contributes to this broader question by addressing a specific sub-question: first, how are modeling practices affected by the environmental management institutions in which they take place; second, how are the models themselves affected by the environmental management institutions in which they are developed and used; and third, how are the social relationships that constitute environmental management institutions affected by the production and use of computational environmental models? Before answering these questions, however, I provide further background on the Chesapeake Bay watershed socioecological system, and the approach undertaken in this project.

Chapter 2 provides additional background on the Chesapeake Bay watershed, the Chesapeake Bay Program, and the Chesapeake Bay Modeling System. In it, I approach the Chesapeake Bay watershed as a socioecological system composed of human activities on the landscape, as well as those of animals and plants, and, of course, the flow of water. Altogether, these activities produce the socioecological system of the watershed and alter it over time. In the last few centuries, the watershed has undergone dramatic changes including deforestation, soil depletion, and overharvesting of resources. The result has been detrimental to the quality of water in the Chesapeake Bay, and, as a result, a watershed-scale management project has been organized in the form of the CBP. Driven by a scientific understanding of the estuary's nutrient pollution problem, the CBP has also undertaken the construction of a watershed-scale computational model. Altogether these elements constitute the Chesapeake watershed socioecological context. Understanding the role of computational modeling within this context will be the project of the remaining chapters.

Chapter 3 provides additional detail on the process of undertaking an ethnographic study of computational modeling in the Chesapeake watershed. The watershed is an enormous and extremely complex socioecological system that includes over 17 million people and numerous different landscapes, and sociocultural contexts. As a result, tracking all of the ways that computational modeling and management shapes the watershed would be a nearly impossible task. However, I have employed an ethnographic approach to examine some of the key contexts in which computational modeling plays an important role. The primary site has been the computational modeling that takes place within the Chesapeake Bay Program itself, and has involved working with the computational modeling team there as well as attending meetings, and conducting interviews with modelers and other staff involved in the modeling and management process. Secondary sites include observations and interviews with academic modelers working on other modeling projects in the region, as well as county-level environmental management agency staff who implement the CBP's watershed goals.

Chapter 4 (Article 1) begins the process of examining how computational models fit into the watershed socioecological context. In this chapter, I look specifically at the ways that environmental management structures like the CBP affect the process of modeling. I argue that modeling is not simply a process of representing and reproducing ecological systems, because it is always mediated by the social conditions in which it takes place. However, the conditions of management are different from those of more scientifically motivated modeling contexts. Management modelers must build relationships with the broader scientific community in order to establish credibility for the model and the management process. They have to be able to navigate the rules and requirements for accessing necessary data across institutional boundaries. And they must learn to work with different incentive structures among collaborating institutions. As a result, modelers involved in the socioecological process of environmental management have to not only be capable of accurately and effectively representing the ecological processes, but also must be adept at navigating the institutional structures of management. This suggests, further, that modeling is not a singular process, but many different processes depending upon the specific institutional contexts in which it takes place.

Chapter 5 (Article 2) continues this line of thought by looking at the way that different social contexts and different conceptions of the ecological system affect the *content* and role of computational models. Again, I contrast the scientific context of modeling with the management context. In this case, scientific modelers are driven by an interest in and curiosity about ecological systems and processes. As a result, their conception of those systems and processes embraces their full complexity, and the models reflect this because they are always being expanded to include more complexity and more of the system. On the other hand, management staff are focused on the costs and benefits of various management practices – figuring out how to get “the biggest bang for their buck.” As a result, the management models only represent the essential features of the ecological system. Their role in this situation is described as “accounting tools” that allow the management staff to identify priorities in terms of costs and benefits. This suggests that models are not monolithic – they take on different characteristics depending on the social contexts in which they are constructed and deployed, and potentially reinforce existing social conceptions of environmental systems.

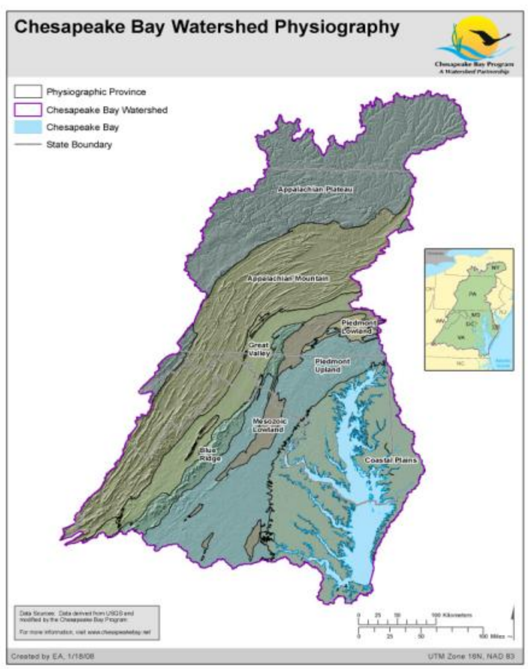
Chapter 6 (Article 3) expands to look at the broader socioecological process of environmental management. Management is more than simply the process of implementing management practices on the ground. It also involves building social institutions that can organize people to work towards a common set of management goals. This is, perhaps, especially true in a socioecological system as large and diverse as the Chesapeake Bay watershed. Computational environmental modeling, I argue, plays many roles in this process of organizing people toward management goals. Here, I offer three examples of roles that computer modeling plays in the CBP’s management framework. First, models help to organize the efforts of the scientific community, directing their research towards the needs and goals of the CBP by providing something that all of the partners can work on collectively. Second, models help to organize the various institutions and organizations that make up the CBP partnership by tracking progress towards goals and serving as a reminder that they are all part of the management process. Third, models organize the on-the-ground work of implementing management practices by identifying priorities and providing incentives for specific projects. All of this suggests that models are important management tools beyond their ability to inform decision-making and track progress.

Chapter 7 is the conclusion in which I summarize the main points in the previous chapters and reexamine how the conclusions in each chapter contribute to answering the broader question, “How do computational models and modeling practices affect the socioecological systems in which they are produced and used?” I also explore some possible areas for future research and the applied implications of this research.

Chapter 2: The Chesapeake Bay Watershed, Modeling and Management

The Chesapeake Bay watershed (Fig. 2.1) is produced from the intersections of many different physical, biological, and social dynamics. At its core, the watershed is a hydrological unit, also known as a drainage basin – a region in which water flows towards a common confluence before draining into an ocean or lake (USGS 2017). The central feature of the watershed is the Chesapeake Bay, a tidal estuary where the various rivers and streams converge before flowing into the Atlantic Ocean (Wennersten 2000).

Figure 2.1 The Chesapeake Bay Watershed Physiography



The underlying structure of the estuary was created through a number of forces, but a key event 35 million years ago played a significant role in shaping the

Chesapeake Bay we know today. At that time, a large meteor struck what was then the Atlantic Ocean just off the coast. As sea level receded during the ice ages, the 52-mile diameter crater that resulted from this impact formed the impression that now marks the mouth of the bay (Poag 1996). As the glaciers receded, the meltwater flowed down the Susquehanna River and carved out the valley that now forms the bed of the Chesapeake Bay. Rising sea levels, augmented by land subsidence, began to fill in the valley approximately 10-15,000 years ago, and the Chesapeake Bay took its present form approximately 6-7,000 years ago (Larsen 1998) (Fig. 2.2).

Figure 2.2 The Chesapeake Bay

The Chesapeake Bay extends approximately 200 miles north to south from Havre de Grace, Maryland to Virginia Beach, Virginia (Wennersten 2000). Its deepest spot is just south of Annapolis near Bloody Point and is 174 feet deep, but in general, the estuary is very shallow at an average of about 21 feet (Wennersten 2000). This shallowness allows for significant light penetration, which helps to support the various seagrasses and other organisms who live there. The estuary and its tributaries are tidal up to the fall line – the geological boundary between the Atlantic Coastal Plain to the east and the Piedmont Plateau to the west, visible as a series of waterfalls as the tributaries flow across it. This mix of tidal and fresh waters makes for a very diverse ecological system with varying salinity from north to south (Horton 2003). As a result, the Bay supports an abundance of different species, including 348 species of finfish and 173 species of shellfish (CBP 2017). The most well known of these, due to their popularity as seafood, are the Chesapeake Bay blue crabs (*Callinectes sapidus*), oysters (*Crassostrea virginica*), and striped bass (*Morone saxatilis*), also known as rockfish (Wennersten 2000). Many migratory birds and fish also make their way to or through the estuary at different times of the year for spawning and/or wintering (Steadman 2001; Miller 2001). All of these features make the Chesapeake Bay a very productive ecosystem.

The Chesapeake Bay watershed covers 64,000 square miles from the Atlantic Coastal Plain across the Piedmont Plateau, over the Blue Ridge, and into the Appalachian range to the west and north (Wennersten 2000). It includes portions of six states – Maryland, Virginia, Pennsylvania, West Virginia, Delaware, and New York – and the District of Columbia. The land-to-water ratio is the largest of any coastal water body in the world (Kemp et al. 2005). This landscape drains more than 51 billion gallons per day into the estuary (CBP 2017). Five major rivers – the James, the York, the Potomac, the Susquehanna, and the Choptank – contribute most of the fresh water to the estuary with the Susquehanna alone accounting for more than half (CBP 2017). In fact, the Chesapeake Bay is more appropriately thought of as the tidal portion of the Susquehanna River, since the Susquehanna forms its main stem (Dunn 2014). Its northernmost extent is Lake Otsego at Cooperstown, New York. From there, the Susquehanna River flows approximately 400 miles south to the head of the Chesapeake Bay (Mancall 1991). The other major tributaries wind their way east from the Appalachian range to the Chesapeake Bay. It is a very diverse landscape encompassing mountainous forests, urban centers, wetlands, coastal regions, and farmlands.

Humans in the Chesapeake Watershed

Humans have been a part of the Chesapeake Bay watershed for the entirety of its 6000 to 10000 years (Wennersten 2000; Miller 2001). Over this period there would have been many changes in population, social organization, and subsistence; however, there is evidence that humans have lived in the region for at least 13,000 years (Miller 2001). Archaeologists divide the time period prior to European contact into three periods – the Paleo-Indian period from 13,000 to 10,000 years ago, the Archaic period from 10,000 to 3,000 years ago, and the Woodland period from 3,000 to 400 years ago (Miller 2001). Evidence suggests that populations in the Paleo-Indian period were foragers depending primarily on small game, fish, and plants for subsistence and living in small, nomadic bands (Miller 2001; Beisaw 2012). In the Archaic Period, the landscape became more forested and the people in the region continued to be semi-nomadic, moving with the seasons to exploit different resources.

This was also the time period when the Chesapeake Bay began to form, and so the first evidence of utilizing shellfish and other estuarine resources starts to appear (Miller 2001). Farther up in the watershed, there is evidence for hunting, collecting plant resources, and catching anadromous fish like sturgeon (Miller 2001).

In the Woodland period, there is evidence for increased exploitation of estuarine resources near the shore as well as increased populations and sedentism throughout the watershed (Miller 2001). White-tailed deer were a major source of subsistence in the early Woodland period, but later sites begin to show evidence of the cultivation of corn, beans, and squash, with concomitant increase in population and sedentary villages (Miller 2001). At the time of contact, the major groups in the watershed were the Powhatans and Piscataway who lived close to the estuary, and, farther up in the watershed, the Shawnee and Susquehannocks (Wennersten 2000; Miller 2001; Mancall 1991). These peoples not only depended upon the landscape, but also transformed it through their foraging and horticultural activities (Beisaw 2012; Wennersten 2000). For example, regular burning of underbrush helped to return nutrients to the soil for horticulture and cleared areas for deer and other grazing animals (Beisaw 2012). Additionally, near-shore oyster harvesting contributed to the long-term sustainability of the fishery (Rick et al. 2016). However, the watershed underwent a dramatic change after the arrival of European colonists in the 17th Century.

European settlement brought with it disease and warfare, larger populations, and integration into the transatlantic economy – together these three factors would change the socioecological relationships in the Chesapeake watershed dramatically.

As a result of disease and warfare, the indigenous populations in the region declined rapidly. The Powhatans and Piscataways were reduced to living on reservations or migrating to other regions by the 18th century (Wennersten 2000). The Susquehannocks, caught between conflict with the new settlers and with the Iroquois Nation, were decimated by the end of the 19th century and the few remaining individuals eventually joined the Iroquois to the north (Mancall 1991). The Shawnee were pushed progressively westward by the British after the French and Indian War and subsequently by the US after the War of 1812, in which the Shawnee Chief Tecumseh sided with the British (Mancall 1991).

Population increased dramatically after initial European settlement with both a steady influx of European settlers and the import of African people as slaves (Wennersten 2000). This increasing population put a strain on the landscape and the waters of the region. Throughout the 19th century, the rivers were used by colonists for discarding human waste. As a result, by the early 20th century many of the tributaries were unusable for fishing and subsistence. The clearing of land for residence and agriculture to feed the growing population exacerbated the problem as eliminating the forests caused erosion and soil depletion (Wennersten 2000).

Integration into an increasingly globalized market also took its toll on the watershed. Many extractive industries have had their time on the landscape, but three stand out as exemplars of the declining Chesapeake Bay. First, a growing desire for tobacco in Europe meant that large tracts of land were converted to tobacco farms (Wennersten 2000). In addition to contributing further to the deforestation of the region, the tobacco agriculture seeped nutrients – primarily nitrogen and phosphorous

– from the soil, causing widespread depletion. The response was to supplement the depleted nutrients with external sources – initially guano mined from islands off the coast of South America, and then synthetic fertilizers in the 20th century (NMAH 2016). These nutrients run off of the farms and into the water causing eutrophication.

Second, the demand for furs brought about a rapid decline in the beaver population. Beavers are "ecological engineers" who create vast wetland habitats through their damming activities. With fewer beavers in the region, their dams fell into disrepair and the wetlands began to decline as well (Mancall 1991; Wennersten 2000). Wetlands help to filter pollutants like nutrients from the water and reduce the flow of sediments. The loss of wetlands further contributed to the decline of the Chesapeake Bay (Wennersten 2000).

Third, the consumption of oysters increased in Europe in the 18th and 19th centuries, and the Chesapeake Bay became the world's leading supplier of oysters during that time (Wennersten 2000). Watermen from New England came down to the Chesapeake region in the 19th century to claim their share of the harvest, resulting in the "Oyster Wars" in the late 19th century (Wennersten 2000). By the mid-20th century the oyster population in the estuary had been severely depleted due to overharvest (Rick et al. 2016). Oysters are highly efficient filter feeders, and can remove a substantial amount of nutrients and sediment from the water in a short amount of time – it is estimated that oyster populations in the colonial period could have filtered the entire Chesapeake Bay in a few days (Rick et al. 2016). With their population depleted, the Chesapeake Bay had no way to remove the ever-increasing quantity of nutrients and sediment entering it from the watershed.

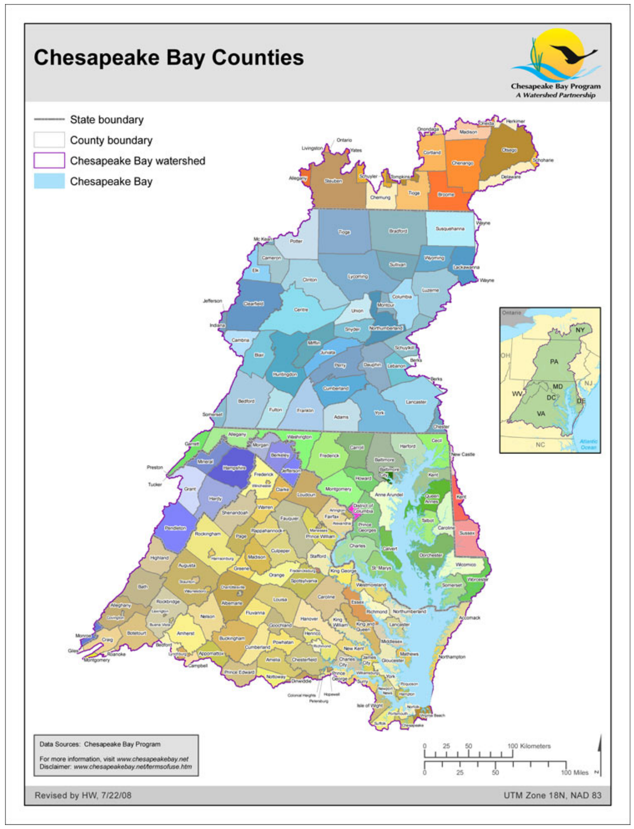
Together, these processes resulted in significant decline in the region's water quality by the early 19th century (Black et al. 2017). Since the 1930s, scientists have documented low- and no-oxygen (hypoxic and anoxic) conditions in portions of the Chesapeake Bay (Newcombe 1938; Cooper and Brush 1993; Kemp et al. 2005). These conditions result from the eutrophication of the Bay system due to excessive nutrient and sediment loads flowing into its waters. The nutrients – primarily nitrogen and phosphorous – result in an overgrowth of algae that clouds the waters, preventing the growth of aquatic vegetation which contribute oxygen to the water column (Kemp et al. 2005). Sediments make the water murky, but also carry nutrients of their own which can dissolve in the water and contribute to eutrophication. This lack of oxygen then results in the depletion of other macro-organisms such as fish, which depend on dissolved oxygen in the water (Cooper and Brush 1993; Kemp et al. 2005). Eutrophicaton accelerated in the 20th century due in large part to the intensification of agriculture in the region, including the use of synthetic fertilizers and the introduction of large-scale poultry farming (Kemp et al. 2005). Synthetic fertilizers applied in excess of the amount necessary for growing crops run off into the water and make their way to the estuary. Large poultry farms generate an abundance of manure that must either be applied to the landscape as fertilizer or stored, and when it is improperly applied or stored, the nutrients contained within it will seep into the soil and water (Jordan, Correll, and Weller 1997). Other agricultural practices like tilling the soil and using irrigation contribute by increasing erosion and the consequent flow of sediment into the water.

All of these practices have contributed to the decline of the Chesapeake Bay and its watershed. There has been a growing interest since the early 20th century in cleaning up the bay, but managing such a large and complex watershed has proven difficult – many political, social, and scientific barriers lay in the way.

Obstacles to Watershed Management

Managing these ecological problems has proven difficult for a number of practical and social reasons. First, since the watershed covers six states and the District of Columbia (Fig. 2.3), convincing all of the governments to agree to reducing nutrient pollution in the region proved difficult. Each jurisdiction has its own set of political and economic interests, making it difficult to agree on a management plan. Furthermore, only two of the states – Maryland and Virginia – contain portions of the estuary, meaning that the others have no direct economic of political interest in protecting the Chesapeake Bay itself (Ernst 2003).

Figure 2.3 The Chesapeake Bay Watershed Jurisdictions



The first attempt to form a multi-state agreement to address the growing pollution problems in the estuary took place in 1936 at a meeting between the governors of Maryland, Virginia, the District of Columbia, and Delaware along with a representative of the federal government (Ernst 2003). It was agreed at this meeting that an interstate commission should be formed to address the environmental concerns in the Chesapeake, but the commission never materialized. The federal government, lacking the authority at the time to manage interstate waters for water quality, could do nothing (Ernst 2003).

In addition to these political challenges, our scientific understanding of the estuary and its environment was limited by disciplinary boundaries. The Chesapeake

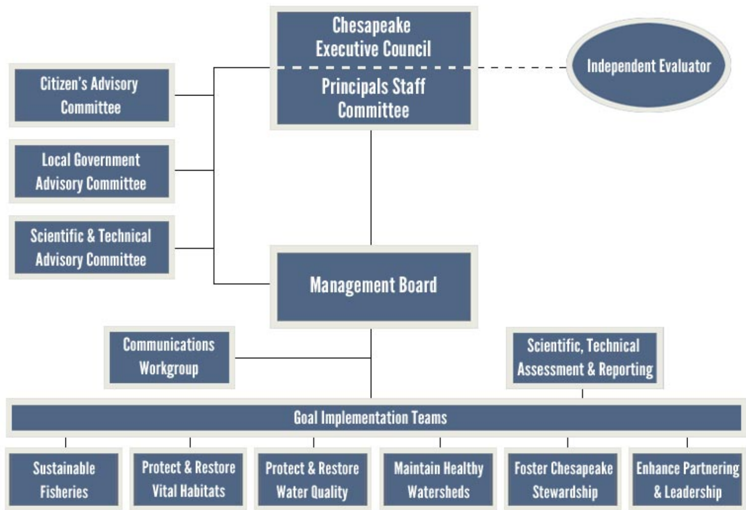
Bay was primarily studied by oceanographers, meaning that it was conceptualized as an extension of the ocean into the landscape rather than as the tidal portion of its tributaries (Malone et al. 1993). This meant that the effects of the watershed on the estuary were discounted initially, and it was not until the 1970s that the watershed started to be taken seriously as a significant factor in the ecology of the bay (Malone et al. 1993). As a result, the watershed has been largely shaped by factors external to it, primarily the regional and global demand for goods and resources produced there (Wennersten 2000; Mancall 1991).

In order to build a system of common management for the watershed, it was necessary to overcome these two obstacles. The first was done with the development of the Chesapeake Bay Program (CBP), which enabled watershed-scale management through a partnership between the various watershed jurisdictions and the federal government. The second was addressed through improved science and monitoring in the region, but also through the adoption of computational environmental modeling.

The Chesapeake Bay Program

In order to address the growing nutrient pollution problem for the Chesapeake Bay, the Chesapeake Bay Program (CBP) was created in 1983 (CBP 1983). Its origins extend a little further back, however. In 1976, the US congress – led by Senator Charles Matthias of Maryland – commissioned a study of the environmental problems facing the Chesapeake Bay (Ernst 2003; Horton 1991). This extensive study determined that the estuary's water quality was declining due to nutrient pollution and recommended an interstate partnership to address the problem (US EPA 1982). The CBP was this partnership (Fig. 2.4).

Figure 2.4 The Chesapeake Bay Program Organizational Structure



The CBP is unique in the US for being a watershed-scale environmental management organization. There are other examples of watershed-scale management that predate the CBP – the Tennessee Valley Authority, for example. However, these organizations are primarily oriented towards managing water *quantity* for hydroelectric dams (Carse 2014). The CBP, on the other hand, is primarily organized around managing water *quality* in the Chesapeake Bay and its tributaries.

Originally, the CBP was primarily a research organization based in Annapolis Maryland (Horton 1991; Ernst 2003). The first Chesapeake Bay Agreement was a one-page document signed by the governors of Maryland, Virginia, and Pennsylvania, the Mayor of the District of Columbia, the head of the Chesapeake Bay Commission, and the Administrator of the US Environmental Protection Agency (EPA) (CBP 1983). It was a voluntary agreement that simply acknowledged the need for a cooperative approach between the various jurisdictions involved. A follow-up agreement in 1987 was much more extensive and was the first to set a specific goal to reduce nutrient loads by 40% by 2000 (CBP 1987). However, this agreement was also voluntary and the required reductions were not met (Ernst 2003).

In 2000, as a result of the failure to meet the 1987 goals, a new agreement was signed, known as Chesapeake 2000 (CBP 2000). This agreement had some significant differences to the 1987 agreement. First, instead of focusing on water quality and the nutrient reduction goal, it set 102 goals in several areas including: pollution reduction, habitat restoration, protect living resources, promote responsible land use practices, and engage the public in the restoration process. Second, it was the first agreement that included all of the watershed states, though the upper watershed states – Delaware, New York, and West Virginia – were not signatories, but agreed to the goals as part of a memorandum of understanding with the CBP. Each of the signatories was required to produce a "tributary strategy" that would outline specific plans and practices to help achieve the broader watershed goals (CBP 2000).

Still, these goals and practices were voluntary, and, when it became clear that the nutrient reductions would not be achieved by the 2010 deadline, and as a result of lawsuits filed by activist groups and the watershed states, the EPA was required to implement a total maximum daily load (TMDL) nutrient pollution diet for the Chesapeake Bay and its tributaries before 2011 (CBP 2010). Furthermore, an executive order signed by President Barack Obama committed the EPA to a renewed effort to restore the Chesapeake Bay and its tributaries. As a result, in 2010, a TMDL was set for the entire watershed – the largest TMDL ever implemented by the EPA (CBP 2010).

The TMDL is authorized under the Clean Water Act (CWA) of 1972, which grants the federal government regulatory authority to manage interstate waters for water quality issues (CBP 2010). Nevertheless, this authority is limited. Pollution can come from various sources that can be categorized as "point sources" - those that can be traced to a single source - and "nonpoint sources" - those that are distributed across a landscape. The federal government's regulatory authority under the CWA is limited to the management of point sources (Malone 1991). Since nutrient pollution comes largely from runoff from farms and other distributed effects, managing it under the CWA is challenging and limited primarily to addressing deficiencies in wastewater treatment. However, the states may still regulate non-point sources if they choose to do so under a TMDL. As a result, the nutrient management process on the Chesapeake Bay watershed must continue to be a partnership despite the regulatory authority of the EPA – what is known as "cooperative federalism" in legal terminology (Fischman 2005).

With that in mind, in 2014, a new Chesapeake Bay Watershed Agreement was signed including all of the seven watershed jurisdictions and the EPA. Under this agreement:

> "The Chesapeake Bay Program partners envision an environmentally and economically sustainable Chesapeake Bay watershed with clean water, abundant life, conserved lands and access to the water, a vibrant cultural heritage, and a diversity of engaged citizens and stakeholders" (CBP 2014; 1).

The agreement sets ten interrelated and measureable goals (Table 2.1). These goals are tied to outcomes that are measurable targets for restoration, which must be achieved by 2025.

Table 2.1 2014 Chesapeake Bay Agreement Goals and Measures

2014 Agreement Goals	Measures
Sustainable Fisheries	Reduce pollutants to achieve the water quality necessary to support the aquatic living resources of the Bay and its tributaries and protect human health.
Vital Habitats	Restore, enhance and protect a network of land and water habitats to support fish and wildlife and to afford other public benefits, including water quality, recreational uses and scenic value across the watershed.
Water Quality	Reduce pollutants to achieve the water quality necessary to support the aquatic living resources of the Bay and its tributaries and protect human health.
Toxic Contaminants	Ensure that the Bay and its rivers are free of effects of toxic contaminants on living resources and human health.
Healthy Watersheds	Sustain state-identified healthy waters and watersheds, recognized for their high quality and/or high ecological value.
Climate Resiliency	Increase the resiliency of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure and communities, to withstand adverse impacts from changing environmental and climate conditions.
Land Conservation	Conserve landscapes treasured by citizens in order to maintain water quality and habitat; sustain working forests, farms and maritime communities; and conserve lands of cultural, indigenous and community value.

Stewardship	Increase the number and diversity of local citizen stewards and local governments that actively support and carry out the conservation and restoration activities that achieve healthy local streams, rivers and a vibrant Chesapeake Bay.
Public Access	Expand public access to the Bay and its tributaries through existing and new local, state and federal parks, refuges, reserves, trails and partner sites.
Environmental Literacy	Enable students in the region to graduate with the knowledge and skills to act responsibly to protect and restore their local watershed.

Carrying out the TMDL is a multiple stage process. The first stage was setting the TMDL limit and then allocating load reductions to the jurisdictions in order to reach the limit. The jurisdictions were then required to submit watershed implementation plans (WIPs) that outline the practices they would undertake in order to reach their allotted nutrient reduction (CBP 2010). Next, the counties were expected to submit their own WIPs – known as Phase II WIPs. These plans were evaluated by the CBP and subsequently implemented by the state and local jurisdictions (CBP 2010). Currently, the CBP is in a process of undergoing its midpoint assessment to determine what progress has been made. Following the assessment, the jurisdictions are required to submit Phase III WIPs that indicate their management goals from 2018 to 2025 (CBP 2010).

The CBP partnership does not only include the various governmental actors in the watershed. It also extends to many academic institutions, non-profits, private firms, and other organizations in the region. Today there are a total of 98 partners in the management process (CBP 2017c). Organizing all of these partners and keeping them involved in the process is a difficult task. However, the CBP management process, including the TMDL, has withstood legal challenges up until this point, primarily as a result of its partnership approach. For example, with the introduction of the TMDL, the American Farm Bureau and several other organizations, including several non-watershed states, sued the EPA for overstepping its authority. In September of 2013, federal district court judges in Pennsylvania ruled in favor of the EPA, affirming that the partnership meets the requirements of cooperative federalism (CBF 2016).

The creation of the CBP was an important first step in the process of managing nutrient pollution on the Chesapeake Bay watershed. However, our understanding of the processes that contribute to eutrophication in the watershed were still limited. Furthermore, there was no efficient way to identify and track the sources of nutrient pollution in the 64,000 square mile watershed. A new set of tools were needed, and the emerging field of computational environmental modeling provided the answer.

The Chesapeake Bay Modeling System

Addressing nutrient pollution in the Chesapeake Bay watershed has taken more than the creation of a collaborative governance institution in the CBP. It also required developing a scientific understanding of the Chesapeake Bay's eutrophication problems and how to resolve them. This has been done through extensive empirical research on the estuary and the watershed including the creation of a network of monitoring stations, but also through the use of computational modeling (Ernst 2003).

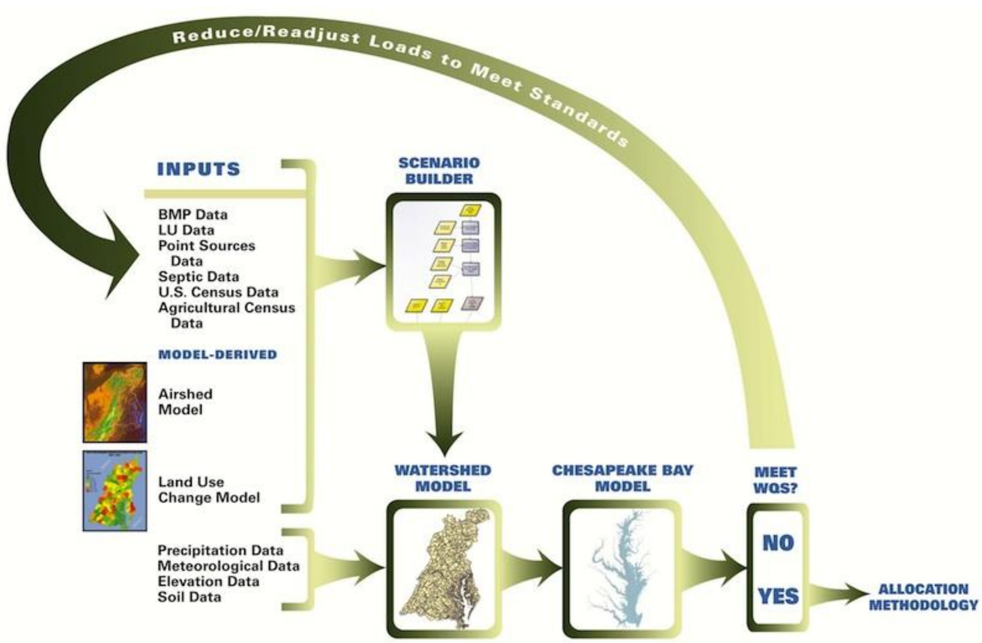
While there is a long history of scientific study of the effects of nutrient pollution on the Chesapeake Bay (Newcombe 1936), the process of understanding its causes and effects was accelerated in 1965 with the passage of the Rivers and Harbors Act of 1965 which authorized an extensive study of the environmental state of the Chesapeake Bay, led by the US Army Corps of Engineers (US Congress 1965). The results of the study were published in 1973 in a seven-volume report that found substantial deterioration in the estuary (US ACE 1973). A follow up called *The Chesapeake Bay Future Conditions Report* was published in 1977 determining that a multistate effort was needed to address the growing environmental problems facing the bay (US ACE 1977). It was also as a result of this study that the first model of the Chesapeake Bay was constructed. A physical model of the estuary and its tidal tributaries, the Chesapeake Bay Hydraulic Model (CBHM), was built under a 17-acre warehouse in Matapeake, Maryland on the shore of the actual Chesapeake Bay. It took 25 years to complete, but was never fully utilized due to operating costs and lack of funding (CLUI 1998). In addition, the physical model was superseded by the emergence of computational models, which made it obsolete (Keiner 2004).

When the US Congress commissioned a second study of the Chesapeake Bay in 1976, the results were very much the same as those of the early study (US EPA 1982). However, this research also brought about a number of scientific and technical advancements for the watershed. The first of these was the creation of a monitoring program for the entire Chesapeake Bay. Monitoring continues to be carried out by buoys placed strategically throughout the estuary to collect detailed information on water quality and how it changes over time (CBP 2017b). This program has helped the CBP and other researchers to understand the effects of nutrient pollution and other factors on the bay.

In addition to the monitoring program, a computational model of the watershed was also created to understand the sources of nutrient pollution and how they get from the landscape to the estuary (Hartigan 1983). The model was initially created using Hydrological Simulation Program Fortran (HSPF) in 1983 in order to answer a simple set of management questions; primarily, what percentage of the nutrients in the watershed come from nonpoint sources (Hartigan 1983; Linker et al. 2002)? The model was well received, and computational modeling has been an important aspect of the CBP's research and management efforts ever since.

The first model, as I mentioned, only simulated the flow of water on the landscape (Hartigan 1983; Linker et al. 2002). However, it was quickly expanded to include more aspects of the watershed as an ecological system. The next iteration of the model, released in 1987, increased its resolution and also included a linked model of the Chesapeake Bay estuary – a three-dimensional hydrodynamic model of the bay itself (Linker et al. 2002). The next few iterations, released in the 1990s, increased the resolution further and also added a land use change model to provide high-temporal-resolution land use data, and an atmospheric deposition model to simulate the deposition of nitrates from the burning of fossil fuels (Linker et al. 2002). Finally, in 2010, a Phase 5 model was developed specifically to address the TMDL. This model added a Scenario Builder model, which converts county data such as zoning, best management practice (BMP) implementation, and acres of cropland into pounds of nitrogen, phosphorous, and sediment that can then be used by the watershed model. It also increased the resolution of the watershed and estuarine models even further (Shenk and Linker 2013). Together, this suite of models is known as the Chesapeake Bay Modeling System (CBMS) (Fig. 2.5).

Figure 2.5 The CBMS Phase 5.3.2 Structure



Each iteration of the CBMS undergoes a three-part series of year-long stages starting with a "build year" during which new features are added to the model and existing features are upgraded (CBP 2010). Following this, the model enters the "review year" during which it undergoes a rigorous examination by the modeling workgroup, and the CBP's Science and Technology Advisory Committee (STAC). Finally, once it passes the review, it enters the "implementation phase" where it is employed to evaluate the current state of the Chesapeake Bay and its watershed and to make predictions about possible future scenarios. The overarching purpose of the CBMS is to provide answers to resource management questions and, ultimately, for setting regulatory TMDL limits on nutrient and sediment runoff (CBP 2010).

Within the CBP, there are two levels of interaction through which the CBMS is produced. First, there is the CBP modeling team. This is made up of approximately twelve CBP staff based in Annapolis who are employed by a number of agency and academic partners including the US Geological Survey, Environmental Protection Agency, Johns Hopkins University, and University of Pennsylvania. The modeling team works on the day-to-day aspects of building and implementing the CBMS. The second level is the CBP modeling workgroup. This is a group of approximately 25 individuals representing various organizations within the partnership (CBP 2010). In addition to some of the modeling team members, the modeling workgroup also includes management staff from the various watershed states, as well as academic partners. This group is overseen by the water quality goal implementation team (WQGIT), which is another group of partner organization representatives that makes decisions about the water quality goals and management processes of the partnership (CBP 2010). The modeling workgroup's purpose is "...to provide state-of-the-art decision-support modeling tools that are built through community and participatory principles" (CBP 2017a). Together, the modeling team and workgroup collaborate to build and implement the CBMS for the broader watershed partnership.

The CBMS is considered state-of-the art, and helps to inform decision-making on the watershed (Shenk and Linker 2013). It was used to determine the initial 40%

load reduction goal in the 1987 agreement, and was then used to establish the nutrient reduction goals in Chesapeake 2000 agreement and evaluate the tributary strategies (Linker et al. 2003; Ernst 2003). In the TMDL, it serves the same purpose – establishing the TMDL limit and evaluating the WIPs (CBP 2010). In addition, however, the CBMS is also used to track progress towards the TMDL goal during its midpoint assessment. Ultimately, though the CBMS plays an enormous role in the management process, the evaluation of attainment of the goals will be based on empirical monitoring and not the model. The goal will be achieved if the water is cleaner and has a lower concentration of nutrients, not whether the model predicts that it does (CBP 2010).

In the following chapters, I draw upon my ethnographic research with modelers and management staff in the Chesapeake Bay watershed to examine the role that the CBMS and other models play in the socioecological process of environmental managment. After describing my research approach, I present three chapters written as articles for publication in peer-reviewed journals. Each article addresses the question of the role of computational modeling in the Chesapeake Bay watershed in a different way. First I examine the ways that being situated within a management context affects the process of producing and using the CBMS. I argue that the modelers at the CBP must be capable of building and navigating social relationships between organizations involved in the partnership. Second, I explore the effects that environmental management has on the structure of the CBMS and other models through comparison with models produced in a scientific context. I find that scientific models are part of a dynamic feedback process with other models and empirical data in which modelers continually attempt to push the limits of our understanding of ecological processes. On the other hand, management models are more oriented towards a cost-benefit analysis of various management projects, and, as a result, they are generally less complex and more focused on a specific set of processes that are relevant to management. Finally, I discuss the role that modeling plays within the CBP partnership and the different ways that the CBMS and other models are used to build and maintain relationships and organize effort towards a common set of management goals.

Chapter 3: Research Approach

Ethnography has been described as an "open-ended, emergent learning" method, meaning that, rather than conducting a controlled experiment, the researcher is engaged in an ongoing, iterative process of making observations, asking questions, and adjusting the research design to pursue questions that arise along the way (Whitehead 2005). This approach is more-or-less inevitable, as the researcher immerses themselves in the cultural practices and contexts they seek to understand and encounters "breakdowns" in the schema that informs their research (Agar 1982). But it is, in part, these breakdowns that make understanding possible, because they force the researcher to resolve the contradiction and find a new "coherence" (Agar 1982). The research that informs this dissertation underwent such a breakdown, which forced me to reconsider the initial approach. Although my research question – what is the role of computational models within the broader socioecological contexts in which they are produced and used? – ultimately remained intact, the approach to answering the question changed due to a revised understanding of the way that computational models are constructed and used within the Chesapeake Bay watershed.

My initial plan for this project was to conduct a comparative ethnographic study of the process of computational environmental modeling and how it affects and is affected by the socioecological contexts within which it takes place. I selected three modeling projects within the Chesapeake Bay watershed for comparison. The initial motivation for focusing on the Chesapeake Bay watershed was to ensure a degree of comparability between the three cases. The first project was the most prominent in the region – the Chesapeake Bay Program's (CBP) computational modeling effort. The CBP produces a large, complex model that plays a significant role in the TMDL. For comparison, I selected two other projects that were smaller scale and took place within different social contexts. The second project was a participatory modeling project organized by researchers at the University of Maryland Center for Environmental Science (UMCES) and the Virginia Institute for Marine Sciences (VIMS) with funding from National Sea Grant. This project was technically outside of the watershed, since it deals with nutrient pollution management for the coastal bays of Delaware, Maryland, and Virginia. However, many of the actors involved are the same, and the environmental problems are similar, if not quite as large-scale. The third project was funded by a grant from the National Science Foundation's Water, Sustainability, and Climate (WSC) program. The goal of this project was to improve various aspects of computer modeling in the region in order to understand the long-term effects of climate change on nutrient pollution in the watershed. The project consisted of a loose team of academic modelers working on different aspects of modeling – the effect of climate change on the landscape, human responses to climate change, shallow water modeling, and simulating the lag time between application of nutrients on the landscape and their entry into rivers and streams.

While all three of these projects were interesting and I continued to work with the researchers on each of them throughout my research, I quickly learned that it would be difficult to separate out the three projects from one another due to a significant degree of overlap between the people and social contexts involved. The problem that arose in the process of doing my comparative study was that all three projects were linked in many ways, and, ultimately, the two "alternates" were in some ways subsumed by the CBP modeling effort. The participatory modeling project was linked because the modelers and scientists involved also work with the CBP modelers through the modeling workgroup or STAC, and also because much of the data for the project was provided by the CBP through the CBMS. The WSC project was linked, again, by the people involved but also because the models being developed in this project are meant to inform future modeling at the CBP. As a result, I came to recognize that there was no effective way to separate out modeling projects that would be distinct enough to make a useful comparison. Instead, I came to see all three projects as part of a larger modeling community working within the watershed. As a result, rather than conducting a comparative study of different modeling projects, my research shifted to become an ethnographic study of the broader role that computational modeling plays within the socioecological context of the Chesapeake Bay watershed. Nevertheless, some degree of comparison was still possible because, despite being part of a larger modeling community, the modelers work within different social contexts – primarily, an academic context in which models are used to understand the ecological processes affecting the estuary and the watershed, and a management context, in which models are used to evaluate and track progress towards a specific set of management goals. This kind of comparison helped to illustrate the role that models play within environmental management institutions specifically, as compared with those that are more scientifically oriented.

Data Collection

The research for this project covered three years starting in 2014 and ending in 2016. The preponderance of data was collected in 2015, which was the "build year" for the Phase 6 version of the CBMS. The methods utilized were ethnographic, consisting of participant-observation and semi-structured key informant interviews. Participant-observation is a method that allows the researcher to gain a first-hand understanding of cultural practices and collect many different kinds of data in the process (Bernard 2006). Semi-structured interviews provide a way to confirm findings from participant-observation and gain more of an "insider's perspective" on the cultural practices of interest. Utilizing key informants, rather than seeking a representative sample, enables ethnographers to identify those who best know the cultural practices in question and can provide a detailed account of them. The goal is not, therefore, to obtain a representative *opinion* of a topic, but to develop a representative *understanding* that is "emically valid" (Whitehead 2005). In the context of the Chesapeake Bay watershed modeling and management process, these methods have enabled me to develop a first-hand understanding of the processes and practices involved in building and implementing a computational model for environmental management and provide a rich and detailed understanding of the social conditions in which computational modeling takes place.

For this project there were three primary sets of data that I needed to collect. These three data sets roughly correspond with the three sub-questions that I sought to answer: first, how are modeling practices affected by the environmental management institutions in which they take place; second, how are the models themselves affected by the environmental management institutions in which they are developed and used;

and third, how are the social relationships that constitute environmental management institutions affected by the production and use of computational environmental models? Answering these questions required collecting three sets of data: first, information about the construction and implementation of computational models within the CBP as well as for the watershed as a whole; second, information about how models are used within the CBP; and third, information about the role that models play in management processes throughout the watershed.

First, I had to understand the process of building and implementing computational environmental models. For this purpose, I conducted participant observation and semi-structured key informant interviews with environmental modelers and scientists involved in modeling in the Chesapeake Bay watershed (see Appendix 1 for a list of key informant roles and affiliations). This included working with modelers at the CBP itself to understand the process of modeling within an environmental management institution, but also working with modelers in academic settings. This combination provided me with a substantial amount of data on the process of producing computational environmental models in different circumstances, and enables me to draw some comparisons between the scientific context and the management context.

Participant-observation, in this case, included: spending two weeks each working with the computational modeling staff at the CBP office in Annapolis Maryland and at the University of Maryland Center for Environmental Sciences (UMCES) in Solomons, Maryland; attending 25 meetings of the CBP's modeling workgroup, modeling team, and other scientific and modeling projects; and participating in the biannual Chesapeake Environmental Modeling Symposium (CHEMS) in June of 2016. The primary focus of my research was the meetings of the CBP modeling workgroup because it was during these meetings that many of the details of the models were discussed and hashed out among the partnership participants. They provided an excellent insight into the process of building the model within the institutional context of the CBP partnership and the kinds of social relationships that are necessary for that process to take place. Observing at the CBP office and at UMCES provided little insight into the process of modeling itself, since the day-to-day aspects of coding and data management are relatively insulated and also beyond my capabilities. As a result, I was only able to observe and ask questions as they arose. However, these experiences were excellent opportunities to build rapport with the modelers and learn more about their lives and personalities outside of the context of modeling.

The CHEMS conference offered an excellent perspective on the broader Chesapeake Bay modeling community and the relationships within it, though it was primarily oriented towards the scientific aspects of modeling. Nevertheless, management questions arose in some instances, particularly during the keynote addresses given by the science coordinator of the CBP, the EPA's region three agriculture coordinator, and a modeler who had taken part in some participatory modeling projects. Some issues addressed in these keynotes were progress towards nutrient reduction goals in the watershed, public perception of the modeling and management practices, and ways to include farmers and other stakeholders in the modeling and decision-making process. In all of these participant observation contexts, I paid particular attention to the ways in which modeling and management intersect in the CBP and otherwise, as well as the social relationships that are needed to develop the CBMS and other modeling tools and to carry out the watershed management process. These experiences were important for providing a deeper understanding of the watershed modeling and management processes.

In addition to participant-observation, I also conducted thirteen semi-structured interviews with modelers and other scientists working on environmental issues in the region. Initially, I selected these informants based on their participation in three modeling projects that were taking place during my research. However, as it turned out, many of them were also involved in other modeling projects at the same time, which made them excellent informants for understanding the broader role of modeling within the watershed. In this context, I designed the interview questions (see Appendix 2 for sample questions) to elicit information about: how models are constructed; the kinds of data and other resources that are needed to develop a computational model; the modelers' participation in or interaction with management institutions, particularly the CBP; and the way these interactions affect their modeling practices and the models themselves. The interviews provided me with insight into the process of modeling and its role within the CBP management institution as well as the perspectives of the modelers on the management process and different aspects of the modeling.

The second set of data that I needed to answer my research questions was information about the role that computational environmental modeling plays in the CBP's environmental management process. The modelers themselves were able to provide some of this context in interviews, and I was able to glean some of it through my own observations. However, in order to gain a broader perspective on the CBP and the management partnership, I conducted semi-structured interviews with four key CBP staffers who are familiar with the modeling process and understand how the models get used within the CBP partnership.

Informants for these interviews were selected primarily based upon suggestions from the modelers, as well as from my own observations of who was involved in the modeling and management processes. Questions asked of the CBP staff were designed to elicit information about: the use of computational models for decision-making in the CBP; the social relationships that underlie the CBP partnership; management practices and how they are informed by computational modeling; and the effect that models have on the social relationships and management practices of the CBP. These interviews provided me with an understanding of how the CBMS is used in different aspects of the CBP's management process, and also gave me some insight into the perspectives of CBP staff on the models and the broader management process.

The third set of data that I found helpful in answering my research questions was on the role that computational modeling plays in the social relationships that make up the CBP partnership. Once again, the modelers themselves and the CBP staff were able to provide some of this context, but a full understanding required conducting semi-structured interviews with key informants from the various watershed states and some of the counties. I was able to interview five environmental management representatives from all of the watershed states except the representative from Delaware, with whom I was unable to schedule a meeting. In addition, I was able to interview three county-level management staff – two from the Southern Tier of New York, and one from the Eastern Shore of Maryland. Collectively, these informants were able to provide me with insight into the interactions among the various CBP partners and the perspectives of the states and counties on the management and modeling processes. Informants for these interviews were identified by my contacts in the CBP and through my observation of the modeling process, as some of the state and county management staff were involved in the CBP workgroup and other aspects of the modeling. Questions to the management staff were designed to elicit information about: the management process and their participation within the CBP partnership; the role of models in decision-making at the state and county levels; and their perspectives on the broader CBP management and modeling processes.

In order to augment the interviews with state and county management staff, I also choose to conduct participant observation with county-level management in the Southern Tier of New York. This region was not only chosen for practical reasons (I moved to Binghamton in 2015), but also because of the unique context of management in the region. Unlike other areas, the counties in the New York portion of the watershed and three counties in Northern Pennsylvania have formed a collaborative management group known as the Upper Susquehanna Coalition (USC). Attending USC meetings helped me to understand the on-the-ground process of environmental management, as well as the role that computational modeling plays in it. Since this is, perhaps, the farthest region from the Chesapeake Bay, attending these meetings also allowed me to understand how the CBP watershed management approach affects those who do not live close to the estuary. The participants at these meetings are not only county-level management staff, they are residents, and, in some cases, farmers. In addition, representatives from the State of New York and the region's Farm Bureau also attend. As a result, there is a diverse array of perspectives represented at the USC meetings, and they proved very informative. At these meetings, I paid particular attention to the kinds of management practices that the counties are involved in implementing, how their activities are shaped by the broader CBP management process, and how computational models inform their management practices. Attending these meetings provided me with a different perspective about the watershed management process than either my research with modelers or with CBP staff – it was invaluable for helping me to see the broader context of the watershed.

Data Analysis

Altogether, I attended over two dozen meetings at the CBP and other locations, I participated in one modeling conference, spent four weeks working with modelers in the CBP and UMCES offices, and conducted 25 interviews (see Appendix 1 for a list of informants). Data collected from these experiences were then analyzed using a qualitative data analysis software package known as MaxQDA (VERBI Software 2014). Participant observation notes were written in MS Word and imported into MaxQDA. Interviews were recorded using a Zoom H2n voice recorder. These recordings were then transcribed into MS Word and imported into MaxQDA.

All of the data was coded using an inductive coding method in which key themes were identified from the data themselves (Bernard 2006). In particular, I attempted to identify themes that related to: 1) the process of building and implementing a computational environmental model, 2) the data and other resources that are needed to build and implement a computational environmental model, 3) the social relationships that form around the process of building and implementing a computational environmental model, 4) the social relationships that underlie the CBP environmental management institution, and 5) the process of implementing the CBP management process at various levels. Together these themes helped to identify ways that computational models and modeling practices are affected by the CBP management process, and, in turn, how the management process is shaped by computational modeling.

Altogether, I utilized 37 codes clustered into two overarching groups – modeling and management – with sub-categories under each group (Table 3.1). I then used a "grounded theory" approach to examine the relationships between themes (Bernard 2006). Using queries, I identified overlapping and proximal themes – particularly those that overlap between the two overarching groups in order to see how models and management intersect with one another. I used these intersections as the basis for further data analysis to examine the different contexts in which these intersections take place and how models and management affect one another (Bernard 2006). The results of these analyses form the basis for the interpretations presented in the three articles that make up the body of this dissertation with "exemplars" used to demonstrate the underlying findings (Bernard 2006).

Table 3.1 Qualitative Data Analysis Codes and Definitions

Code	Definition
Models-Scientific	Construction of models within a scientific (i.e. academic) context.
Models-Management	Construction of models within a management context.
Models-Resources	Resources such as data, computational needs, etc. that are needed to construct and/or use a model.
Models-Relationships	Social relationships formed in the process of constructing and/or using a model.
Models-Building	The process of constructing a model.
Models-Use	The process of using a model.
Models-Methods	Different modeling methods and techniques.
Models-Env	Effects of models on understanding of environmental systems/processes.
Models-Content	The content of models - what the model simulates or represents.
Mgmt-Issues	Issues that management attempts to address.
Mgmt-Models	The use of models in a management context.
Mgmt-Regs	Regulations that are used for management (e.g. TMDL).
Mgmt-Partnership	Partnerships that form around management (e.g. the CBP partnership, the USC).
Mgmt-Controversy	Controversies that emerge in the process of management.
Mgmt-County	County level management practices.
Mgmt-State	State level management practices.
Mgmt-Federal	Federal level management practices.

Informed Consent and Data Management

This research conformed with the standards for research with human subjects set out by the University of Maryland Internal Review Board (IRB). Informed consent was obtained from all key informants prior to conducting interviews. One informed consent document (Appendix 3) was signed by the informant and returned to me. Another unsigned form was provided to the informants for their records. Paper copies of the signed forms were scanned and destroyed. PDF copies of the forms were stored on a password-protected hard disk kept by me in a secure location.

In order to adequately preserve the data while protecting the identities of my key informants, two sets of data were kept. The first set consisted of raw data with full names and identifying information intact. This was maintained on a password protected external hard disk kept by me in a secure location. The second set was stored on a password protected cloud-based account (box.net) with names and identifying information removed. In place of names, codes were used for identification and a key was produced linking the codes to informant names. This document was stored on the same password protected hard disk as the raw data. Interview recordings were maintained only on the password protected hard disk.

Altogether the data provided me with a substantive understanding of the processes of computational modeling and management and the intersections between them. In the following sections, I examine this data in order to answer the overarching research question, “What is the role of computational models within the broader socioecological contexts in which they are produced and used?” Each section approaches the question in a different way, and answers one of the sub-questions: first, how are modeling practices affected by the environmental management institutions in which they take place; second, how are the models themselves affected by the environmental management institutions in which they are developed and used; and third, how are the social relationships that constitute environmental management institutions affected by the production and use of computational environmental models?

Chapter 4: Navigating Institutional Constraints in the Process of Computational Environmental Modeling

(For the journal Coastal Management)

Computational models are powerful tools, and, in the last few decades, they have become an increasingly essential component of environmental science and management (Edwards 2010; Paolisso et al. 2013; NRC 2007; Paolisso and Trombley 2017). According to the National Research Council's (2007) report on the use of computational models for environmental regulation, they serve a number of important functions (NRC 2007). They allow scientists to simplify complex environmental systems in order to understand the underlying processes affecting ecosystems. For environmental managers, they provide a way to identify, track, and predict the causes and consequences of human activity on the natural environment. In many cases, computational models are more cost-effective than traditional field methods, and there are environmental processes that cannot be easily monitored without the use of models (NRC 2007). However, the practice of constructing and using computational models is not simply a question of their scientific and practical benefits – there are social factors that play an important role as well (Paolisso et. al 2013; Paolisso and Trombley 2017). As a result, modeling must be considered as a socioecological process, and understanding the role of computational models in both our conception of and relationship to the ecological systems they represent is an increasingly important area of research for environmental anthropology.

Knuutilla (2005) points out that there is a tendency to conceptualize computational environmental modeling as a purely scientific or computational process – a way of representing environmental systems in both the epistemological sense of "presenting again" and the political sense of "standing in for" those systems. However, there is a significant amount of research that shows that these representations are also mediated by the social conditions in which they are developed and deployed. For example, Edwards (2010) explores the history of climate modeling as a "knowledge infrastructure" with many social consequences. Lahsen (2005) examines the way that different social incentives affect modelers' appreciation for uncertainty. Sundberg (2009) investigates model parameterization and suggests that there are two "cultures" of modeling – those who want simpler but less representative models and those who want models to accurately represent physical processes regardless of their complexity. Similarly, Shackley (2001) describes different modeling cultures that exist between the US and the European Union. Altogether, these studies help us to understand the social dimensions of computational environmental modeling.

The above studies tend to focus on modeling as a *scientific* process, and there has been little interest paid to the ways in which modeling practices are affected by the social conditions of environmental *management*. Given that environmental management is one of the most significant uses of modeling (NRC 2007) and also an important part of our collective relationship to the ecological systems in which we live (Bodin et al. 2011), it is important to investigate how modeling as a practice is shaped within those management institutions. This article explores the question, how is the process of building and maintaining computational environmental models affected by the management institutions in which they are constructed and used?

I examine this question through ethnographic research with computational environmental modelers in the Chesapeake Bay watershed. This region provides a unique context to investigate this question because, for the past few decades, environmental management on the Chesapeake Bay watershed has been organized by a collaborative partnership institution. Known as the Chesapeake Bay Program (CBP), this partnership includes the federal government, six watershed states, the District of Columbia, and several academic, nonprofit and private institutions. As part of their effort to manage the watershed, the CBP has built and maintained a complex computational environmental model of the watershed known as the Chesapeake Bay Modeling System (CBMS). The CBMS informs decision-making at every level of the watershed's management process such as determining nutrient load reductions and helping to track pollution throughout the landscape.

I argue that the process of building and implementing the CBMS is shaped by the institutional needs and requirements of the partnership in many ways, requiring the CBP's modelers to navigate social relationships and institutional structures in addition to their modeling effort. In this article, I illustrate three of these effects that I have encountered in my research. First, I have found that because the CBP's management approach must be "believable," the CBP modelers must engage extensively with the broader scientific community in order to build a model that has their support. Second, accessing data from the various partner organizations presents a challenge because of the different rules and requirements for access to such data across agency boundaries. This means that the CBP's modelers must find ways to work around these rules and requirements in order to access these data for use in the CBMS. Finally, the different incentive structures – the types of activities that are encouraged among employees – of the various institutions involved in the CBP partnership present a challenge for generating research that is necessary to inform the model. As a result, the modelers must work with these incentive structures in order to encourage individuals within these institutions to produce the necessary information and other knowledge resources. Despite these challenges, the modelers have become adept at navigating these institutional structures in order to access the resources necessary to build the CBMS.

In the following sections, I start by examining the literature on the relationship between environmental modeling and the social conditions in which they are developed and deployed. I then turn to three examples drawn from my research demonstrating the ways that the process of environmental modeling has changed as a result of the needs and constraints of environmental management institutions. Finally, I conclude by arguing that investigating the effects of management institutions on the process of modeling will allow us to understand the broader role of science and technology within these institutions.

The Social Processes of Modeling

The common conception of computational models among scientists, policy makers, and management staff is that they serve as imperfect representations of environmental systems that we seek to understand and manage (Canham et al. 2003; NRC 2007). This conception suggests that models effectively re-present these systems in an epistemological sense of "presenting again," but also that they represent these systems in the political sense of "standing in" – since, presumably, environmental systems cannot effectively represent themselves (Knuuttila 2011). The modeler's job, then, is to accurately and appropriately depict the ecological system and the processes that shape it, which means gathering data and constructing simplified computational simulations of the processes. In other words, the process of modeling is primarily scientific, and only becomes social after the accurate representation has been made and as it gets integrated into decision-making processes. This relationship between computational modeling and decision-making is evident in the way that the process of constructing a model is separated from the process of decision-making – as in, for example, the National Research Council's guide to modeling for regulatory decision-making (NRC 2007).

There are good reasons for this separation of computational modeling from environmental decision-making and management, not the least of which are concerns about stakeholders inflecting models with biased information (NRC 2007). However, this does not mean that the process of computational environmental modeling is entirely removed from social processes, and there have been a number of studies that demonstrate that modeling processes are affected by the social conditions in which they are developed and deployed. It is important to note that this does not mean that models are not scientifically valid or useful representations of ecological systems, only that we must be attentive to the relationship between social contexts and modeling practices if we are to understand their role within broader socioecological processes (Paolisso et al. 2013; Paolisso and Trombley 2017). Below I provide a brief overview of the literature on the social dynamics of computational modeling and why they are relevant to our understanding of models and management.

Edwards (2010) explores the history of climate science as a "knowledge infrastructure." This infrastructure consists of tools and technologies for data collection, scientific researchers, funding agencies, and knowledge institutions like universities and research centers that allow for an understanding of the state of the global climate. Edwards describes the many social factors that contributed to the construction of this infrastructure, which drove some of the early adoption of climate models such as debates about uncertainty in modeling and the political urgency of nuclear fallout and supersonic air transport.

In addition to these drivers for model adoption, Lahsen (2005) examines the way that different social factors affect modelers' appreciation for uncertainty. She revisits the concept of the "certainty trough" which suggests that those closest to scientific practices (i.e. the scientists) will embrace a large amount of uncertainty in their models, while those who are somewhat distant from the process will have a lower degree of uncertainty (and thus more confidence) in the models. She argues that this is not the case, and that modelers can be overconfident about their models as a result of social pressures to sell their models as more effective and accurate than others.

Similarly, some researchers have found different cultural perspectives within the scientific community that shape the process of modeling and their structure. Sundberg (2009) investigates model parameterization – the process of representing processes that cannot be captured accurately in the model. She suggests that there are two “cultures” of modeling – those who want simpler models that use parameterizations to more efficiently simulate processes versus those who want models that use fewer parameters in order to more accurately represent physical processes. Similarly, Shackley (2001) describes different “epistemic lifestyles” for modeling that exist in different social conditions. He describes these two lifestyles as “climate seers” and “climate model constructors” – the former are more inclined towards understanding climate change with models, whereas the latter are interested in understanding broader climatological processes. As a result, the seers use more parameterization in their models, whereas the model constructors tend to use fewer. He argues that these are complementary positions and that social incentives within climate research organizations can foster more or less mixed cultures.

Meanwhile, other researchers have investigated the political dimensions of computational modeling. Knox (2014) examines the way that climate models affect political subjectivities, arguing that scientific conceptions of “population” that emerge from computer modeling get translated into more conventional “biopolitical” understandings through the process of implementing management. The scientific politics of population in climate models, she argues, do not fit with the more conventional notions of “good living” that must be grappled with in project implementation. As a result, management projects must draw upon biopolitical conceptions – the economic benefits of energy efficiency, quality of life improvements for the poor, etc. – in order to carry out their goals with respect to climate change (Knox 2014).

In a more critical vein, Hulme (2010) explores the ways that computational models impose colonial technologies and knowledges upon indigenous populations and artificially universalize knowledge and obscure localized contexts and processes. Hulme (2010) suggests that the "global knowledge" that climate models produce might appear stable, but is, in fact, very "brittle" – meaning that it loses efficacy in a "plural and turbulent world" (562) and potentially distorts reality and reduces local agency. He suggests a "spectral" and "cosmopolitan" approach that focuses on the full range of expert beliefs and allowing knowledge to flow freely rather than fitting it into globalized frameworks (Hulme 2010).

The above studies tend to focus on the computational models within scientific contexts and how scientific models ultimately come to influence policy and decision-making. However, there are an increasing number of models being developed specifically within natural resource management institutions for the explicit purpose of informing ecological management practices (NRC 2007). This presents three interesting areas of research: 1) the effect that computer modeling has on management institutions; 2) the effect of ecological management on the content of the models; 3) the effect of management on the social process of developing and implementing a computer model. The third is the focus of this article.

In the following sections, I explore some ways that the needs and constraints of management institutions affect the process of building a computational model including: the need to engage with a broader scientific community in order to build model "believability;" the process of navigating institutional boundaries to gain access to data; and the importance of managing different incentive structures across institutions in order to help and encourage others to do the research necessary for the model. My research demonstrates that computational modelers, in the context of ecological management, need to be capable not only of collecting data and representing systems and processes in computational code, but they must also be adept at navigating these institutional structures. This is especially complex in the Chesapeake Bay region and working with multiple different agency partners in the watershed.

The Chesapeake Bay Watershed

The Chesapeake Bay watershed is produced from the intersections of many different physical, biological, and social dynamics. At its core, the watershed is a hydrological unit, also known as a drainage basin – a region in which water flows towards a common confluence before draining into an ocean or lake (USGS 2016). The central feature of the watershed is the Chesapeake Bay, a tidal estuary where the various rivers and streams converge before flowing into the Atlantic Ocean (Wennersten 2000).

The Chesapeake Bay is the largest estuary in the US, extending 200 miles north-to-south (Wennersten 2000). It is a complex ecological system that supports a diverse array of organisms, many of which are harvested as resources by the local population – most prominently, Chesapeake Bay blue crabs (*Callinectes sapidus*), oysters (*Crassostrea virginica*), and striped bass (*Morone saxatilis*), also known as rockfish (Wennersten 2000). Since the 1930s, scienitists have documented low-oxygen conditions in the Chesapeake Bay resulting from eutrophication (Newcombe 1936). The excessive flow of nutrients – primarily nitrogen, phosphorous and sediment – into the bay is the primary cause of eutrophication. These low-oxygen conditions threaten to disrupt the ecological balance of the estuary and deplete the resources upon which the regional economy depends (Kemp et. al 2005).

Nutrients primarily flow into the Chesapeake Bay from its watershed – the landscape whose water drains into the estuary (Wennersten 2000). The Chesapeake Bay's watershed covers over 64,000 mi^2, giving it the largest land-to-water ratio of any coastal water body (Kemp et al. 2005). This landscape drains more the 51 billion gallons of water per day into the estuary (CBP 2017). As a result, it is significantly impacted by activities on its landscape. Humans have been a part of the watershed since before the Chesapeake Bay formed approximately 10,000 years ago, and in that time they have played a significant role in shaping the landscape (Miller 2001). However, it has only been in the last few centuries that the landscape has been changed in a way that would contribute to the eutrophication of the estuary. Precipitated by the arrival of Europeans to the watershed, the increased erosion of the landscape, along with intensified agriculture and a larger population has dramatically increased the quantity of nutrients flowing into the bay (Wennersten 2000; Mancall 1991). Addressing these problems has proven to be a significant challenge.

Watershed Management

The Chesapeake Bay Program (CBP) was created in 1983 through an agreement between the federal government and the seven watershed jurisdictions (Maryland, Virginia, Delaware, Pennsylvania, West Virginia, New York, and the District of Columbia) in order to curb the eutrophication of the Chesapeake Bay (CBP 1983). The original agreement was a simple one-page document that committed the signatories (originally only the federal government, Maryland, Virginia, Pennsylvania and the District of Columbia) to a voluntary nutrient management effort. A follow-up agreement in 1987 established a 40% nutrient reduction goal to be achieved by 2000, however, the agreement was also voluntary and the goal was not met (Ernst 2003).

In 2000, as a result of the failure to meet the 1987 goal, a new agreement was signed by the original signatories, but also included the other watershed states (New York, Delaware, and West Virginia) as "partners" under a memorandum of understanding (CBP 2000). The goals in the Chesapeake 2000 agreement were more diverse and included detailed management strategies, however, the agreement continued to be voluntary, and so the goals were again not met by the 2010 deadline. At that point, a number of lawsuits along with a whitepaper released by President Barack Obama forced the EPA to impose a total maximum daily load (TMDL) nutrient pollution diet using its authority under the Clean Water Act (CWA). The Chesapeake Bay TMDL is the largest ever imposed by the federal government (CBP 2010).

Under the CWA, the authority of the EPA is limited to regulating "point sources" of pollution – those that can be traced to a single outlet such as a pipe. Since nutrient pollution is generally attributed to "nonpoint sources" such as farm runoff and storm water, the EPA's authority in the TMDL is limited. As a result, the partnership with the states in the form of the CBP continues to be important, since the states have the authority to regulate nonpoint sources of pollution. In this context, the CBP serves as a form of "cooperative federalism" (Fischman 2005).

Implementing the TMDL has been carried out in several stages. First, the CBP set the nutrient reduction necessary to achieve the management goals and allocated these reductions to the watershed jurisdictions. After that, each jurisdiction was required to submit a plan to achieve the nutrient load reductions. These plans were known as Phase I watershed implementation plans or WIPs. Once these plans had been reviewed and approved by the CBP, the counties in the watershed were required to submit more detailed WIPs, known as Phase II WIPs. These plans were once again evaluated and approved by the CBP and then implementation began. Currently, the CBP is in the process of evaluating the progress that has been made as part of its mid-point assessment. Once the assessment has been completed, the jurisdictions will submit revised Phase III WIPs that will guide management through the 2025 timeline (CBP 2010).

In addition to the federal government and the watershed jurisdictions, the CBP partnership also includes many non-governmental partners. Academic institutions, private firms, and non-profits are among the additional contributors to the CBP management process. Today there are 98 partner organizations listed on the CBP website (CBP 2017c). Organizing all of these partners is a challenging task, but the CBP benefits from this collaborative approach. For example, with the introduction of the TMDL, the American Farm Bureau and other organizations sued the EPA for overstepping its authority. In September of 2013, federal district court judges in Pennsylvania ruled in favor of the EPA, affirming that the partnership meets the requirements of cooperative federalism (CBF 2016).

With the CBP in place, watershed-scale management became feasible for the Chesapeake Bay region. However, there were still limits to our understanding of the problems facing the estuary, and this is where computational modeling has played a significant role.

Watershed Modeling

Addressing nutrient pollution in the Chesapeake Bay watershed has taken more than the creation of a collaborative governance institution in the CBP. It also required developing a scientific understanding of the Chesapeake Bay's eutrophication problems and how to resolve them. This has been accomplished through extensive empirical research on the estuary and the watershed including the creation of a network of monitoring stations, but also through the use of computational modeling (Ernst 2003).

While there was a long history of scientific study of the causes and effects of nutrient pollution on the Chesapeake Bay (Newcombe 1936), it took several decades for scientific understanding to consolidate enough to inform the management process. Two federally funded studies proved critical for this consolidation to take place. The first, authorized by the US Congress under the 1965 River and Harbors Act resulted in a several volume report that found significant deterioration of the Chesapeake Bay ecosystem as a result of nutrient pollution (US ACE 1973). The second study was commissioned in 1976, and the result was very much the same. However, this study also brought about a number of scientific and technological advancements for the watershed. The first was the creation of an extensive monitoring network throughout the estuary (CBP 2017b). The second was the development of a watershed-scale computational model to identify and track the sources of nutrient pollution on the landscape (Hartigan 1983).

The original computational model only simulated the watershed – the flow of water across the landscape – but was quickly expanded to incorporate more components of the system (Hartigan 1983). In 1987, a new iteration of the model was released that increased its resolution and also included a linked model of the Chesapeake Bay estuary (Linker et al. 2002). The next few iterations further increased the resolution of the model and added a added a land use change model to provide high-temporal-resolution land use data, and an atmospheric deposition model to simulate the deposition of nitrates from the burning of fossil fuels (Linker et al. 2002). In 2010, in order to meet the needs of the TMDL management process, a new version of the model was released, called the Phase 5 model. This version added a scenario builder model, which translates county-level data such as zoning, land use, and best management practice implementation into quantitative nutrient loads that can be used by the watershed model (Shenk and Linker 2013). Together this suite of models is known as the Chesapeake Bay Modeling System (CBMS), and is used to set the overarching nutrient reduction goals in the TMDL, to evaluate the WIPs, and to track progress towards achieving the management goals (CBP 2010).

The CBMS is produced through multiple levels of interaction. Within the CBP, a group of approximately 12 modelers makes up what is known as the modeling team. These modelers are employed by a number of agency and academic partners including the US Geological Survey, Environmental Protection Agency, Johns Hopkins University, and University of Pennsylvania. The modeling team works on the day-to-day aspects of building and implementing the CBMS. In addition to the modeling team, the CBP has also assembled a modeling workgroup composed of approximately 25 members from various partner organizations. The modeling workgroup's purpose is "...to provide state-of-the-art decision-support modeling tools that are built through community and participatory principles" (CBP 2017a). It is overseen by the water quality goal implementation team (WQGIT), which is another group of partner organization representatives that makes decisions about the water quality goals and management processes of the partnership (CBP 2010). Together the modeling team, modeling workgroup, and WQGIT collaborate to build and implement the CBMS for watershed management.

With the combination of the CBP and the TMDL management process along with the CBMS, the Chesapeake Bay watershed makes an interesting case to understand the intersections of computational modeling and environmental management. Conducting ethnographic research on these processes allows me to discuss the ways that the CBP's unique management system has shaped the process of building and implementing a computational model like the CBMS.

Methods

The research for this project addresses the question, "how is the process of developing and implementing a computational environmental model affected by the management institutions in which it takes place?" In order to answer this, I draw upon ethnographic research conducted with computational modelers and environmental management staff in the Chesapeake Bay watershed. The research covers a period of three years from 2013 through 2016, which includes the implementation period after the Phase II WIPs and the development of the Phase 6 CBMS. Participant-observation and semi-structured key informant interviews were the primary methods involved, and allowed me to develop a first-hand understanding of the processes involved in building and implementing a computational model for environmental management (Bernard 2006; Whitehead 2005).

Participant-observation involved working with modelers at the CBP in the process of developing the Phase 6 computational model. Primarily, this involved attending 25 meetings of the modeling team and the modeling workgroup as well as other modeling projects in the region. In addition, I attended the Chesapeake Environmental Modeling Symposium (CHEMS) in June of 2016 and spent a two-week period observing the modeling process at the CBP headquarters in Annapolis, MD. The primary focus of my research was the meetings of the CBP modeling workgroup because it was during these meetings that many of the details of the models were discussed and hashed out among the partnership participants. They provided an excellent insight into the process of building the model within the institutional context of the CBP partnership, and the kinds of social relationships that are necessary for that process to take place.

Twenty-five semi-structured interviews were conducted with computational modelers and environmental management staff in the region in order to elaborate upon the social processes involved in the process of building and implementing a computational model. I selected these informants based on their participation in different modeling projects that were taking place during the time of my research, and

I designed the interview questions to elicit information about the social process of computational modeling and how it intersects with the management process.

Ethnographic data was transcribed and coded for themes using an inductive coding method (Bernard 2006). In particular, I sought to analyze the data to understand the process of building and implementing a computational model, the kinds of resources that are necessary in that process, and the ways that modeling intersects with the management process.

"Believability"

The CBP, as part of its commitment to "science based" adaptive management, requires its management process to be scientifically defensible. In addition, this helps to reduce contention by the States and citizens, but also makes it defensible in court. The CBMS is the primary scientific resource and informs much of the management process of the CBP. It is used to set nutrient reduction limits for the TMDL, evaluate watershed implementation plans (WIPs), and track progress towards management goals. As a result, the CBMS itself must also be scientifically defensible. How does this demand for scientific defensibility affect the process of modeling at the CBP, and how do the CBP's modelers go about ensuring the CBMS's credibility? In the common conception of modeling described above, in which computational modeling is predominantly a scientific and computational process of accurately representing processes in order to understand them, the only consideration is the CBMS's validity and ability to withstand peer review. However, my research suggests that, within the CBP, the model's credibility rests on social aspects as well, and the CBP modelers have developed a number of techniques to build this social credibility using workshops, meetings, and other resources to build relationships with the broader scientific community.

As many of my informants pointed out, models are considered "integrators of information." This means that the practice of building a model is a process of assembling different information from various sources and finding ways to integrate it into the model. This fits with descriptions of the role of modeling in science in general, as Edwards (2010) describes the ways that models help to compile a global view of the world's climate by integrating different data sets to make the larger image. Since the information needed to assemble a model is distributed among many different scientists and institutions, integrating information often entails building and maintaining social and institutional relationships that make the sharing of data possible. This is a particular challenge for modelers within management institutions since their primary task is not research, but building effective modeling tools for management.

The CBP has its own modeling team composed of approximately twelve staff members with backgrounds in hydrology, engineering, and computer science. However, since the CBP is not primarily a research institution, the modeling team has to collect the information that they need to create the model from a variety of external sources. There are two ways that this could be done – either by assembling the data internally, or by recruiting other scientists and researchers to contribute to the process through meetings, workshops, and reports. One of my informants described these methods as follows:

> "...we've got all of these different studies that exist and they need to be summarized. So one way to do it would be just one person sit in an office and summarize them and they're putting their own perspective on that summary. But with a workshop you bring everyone together who's done the work and then you have a discussion about how they agree or disagree or fit together or don't fit together and you arrive at some conclusions that these studies are all pointing in the same direction, or this one was different and we don't know why or this one's different and we do know why."

So, on the one hand, there is a process that might be faster and easier – having one person or a team of people summarizing information from the literature and making decisions about how to include it all in the model. On the other hand, there is a process that is, perhaps, slower and more cumbersome – gathering the scientists themselves for meetings and workshops in order to get their input and insight directly and making a group decision about how to include the information in the model.

One example of a workshop that took place during my research project was organized around understanding the infill of the Conowingo Dam. The Conowingo Dam sits at the northernmost part of the Chesapeake Bay where the Susquehanna River drains into the estuary. All of the water that flows from the Susquehanna watershed into the Chesapeake – about 19 million gallons per minute – must make its way through the reservoir and the dam (CBP 2017). Because dams slow the flow of water, they provide an opportunity for nutrients and sediment to settle out of the water column, creating massive deposits at the head of the reservoir. This effectively makes the Conowingo a sediment trap that keeps large quantities of nutrients out of the Chesapeake Bay. However, over time, the bottom of a reservoir fills up and reaches a state of “dynamic equilibrium” where the quantity of sediment deposited is equal to the amount of sediment that is scoured due to water flowing through the reservoir (Cerco 2016). In other words, new sediment is still deposited, but an equal amount of existing sediment is scoured by the flow of water, and, at this point, the dam no longer functions as a nutrient trap.

The Conowingo Dam has been a significant concern in the Chesapeake modeling community over the course of my fieldwork (Zhang, Hirsch, and Ball 2016; Hirsch 2012; Cerco 2016). The dam has served as a nutrient trap since its construction in 1926. It was anticipated that, at some point in the future, the reservoir would reach dynamic equilibrium, but the best estimate was that this would not take place until after 2025 - which is the target year for the nutrient reductions under the TMDL. All of this changed in the late 2000s due to a series of studies that demonstrated that the Conowingo reservoir had already reached its nutrient and sediment trapping capacity (Hirsch 2012).

The nutrient trapping capacity of the Conowingo was not included in the TMDL plans, nor was it incorporated into the CBMS (Cerco 2016). This raised a number of scientific and policy questions that the CBP was not ready to deal with at the time. Since the additional loads coming from the Conowingo have not been allocated in the TMDL, then they will eventually have to be allocate in order to meet the water quality goals by 2025 otherwise the TMDL will fall short. Politically, allocating these loads is challenging: some want the company that owns the dam, Exelon, to pay for it, others want to distribute the load evenly throughout the watershed, and others want to distribute the load only to the Susquehanna basin. In addition to these policy concerns, the problem has generated a flurry of research and discussion to understand the effects of the Conowingo infill as well as negotiations with the jurisdictions to decide how to address it in the TMDL (CBP 2013).

For the modelers, there was a clear set of scientific and technical questions that needed to be answered. First, they need to know how the Conowingo's infill affects the flow of nutrients through the reservoir. Second, they need to find out how the additional sediment would affect water quality in the Chesapeake Bay, which is the result of both the quantity of sediment and the type of sediment that are flowing through and whether the nutrients in the sediment are more or less available to be dissolved in the water column. Some sediments include large materials like sticks and leaves, which carry nutrients, but the nutrients are not easily dissolved in water, whereas smaller sediments like soil erosion can easily release their nutrients into the water, making them available for phytoplankton growth and eutrophication. The modelers needed to know how much of each type of sediment was being allowed to flow through the dam.

In addition, there was an abundance of new data available to answer these questions emerging from research done by the USGS and Exelon. One of my modeler informants described the issues as follows:

> "... we're looking at the effect of the Conowingo reservoir and the filling of it and how that affects the delivery of nutrients and sediment, so that's one thing, and then another part is looking at the estuary and

seeing how that affects the attainment of water quality standards and there are different science questions involved in that. So the first is, for a given flow, what's the sediment coming through the dam either from, more or less, deposition or, more or less, scour and that can be answered by the Bob Hirsch and Qin Ziang studies using just collected data and statistical methods.[1] And then it can also be answered by process based models and so Exelon has some process based models that have given us a map of what we're looking at now, it can also be answered by looking at changes in the bathymetry over time, so we're looking at how all of those things come together to give us a complete story, so we're using all of those multiple lines of evidence to tell us how the behavior of the Conowingo is changing.

So once we get that behavior in terms of the total amount of sediment and nitrogen and phosphorous that comes out for a given flow we also, there's this idea of the ability of the nitrogen and phosphorous that is scoured to be taken up is different for scoured material than for non-scoured material. So the way to think about that is that a lot of the nutrients that come out of treatment plants or off the land are pretty easily eaten by a phytoplankton, pretty easily taken up. But if it's been sitting at the bottom of a reservoir for a while it becomes really stale so

[1] Zhang et. al. (2016) used a statistical model known as Weighted Regressions on Time, Discharge, and Season (WRTDS), which allows researchers to accurately interpolate past flow rates from existing data where those data are lacking. Using this method, they were able to determine the flow of nutrients through the Conowingo reservoir and dam. Their research showed that nutrient flow in the reservoir had reached equilibrium.

it's not very easily used and maybe it just kind of settle once it gets to the bay. So you may have heard in the modeling subcommittee, g1 g2 and g3, organic phosphorous. And so those are organic phosphorous that are pretty available, not so available, and hardly available and so there's a study of how available everything is. And then there's just the modeling of what happens when everything gets into the bay..."

Organizing a workshop allowed the CBP modelers to bring together 68 modelers, scientists, and management staff working on the issue. They represented dozens of organizations including the various state agency partners, academic institutions in the region, private contracting firms involved in the research, the owners of the Conowingo Dam, federal agency staff, non-profits, and the news media (Table 4.1) (Linker et al. 2016). Together, these participants agreed that the Conowingo Reservoir had achieved a state of dynamic equilibrium, that the nutrient loads to the estuary would increase as a result, and that the current approach of modeling all of the nutrients flowing through the dam as fully available was appropriate until additional knowledge proves otherwise (Linker 2016).

Table 4.1 Workshop Participant Roles and Affiliations (Linker 2016)

Role	Affiliations

Federal Agency	USGS, EPA, Sea Grant, US Army Corps
State Agency	MDE, MD DNR, PA DEP, WV DEP
Academic Institution	Johns Hopkins, UMCES, UPenn, VIMS, U of Delaware
Private Contractors	AECOM, Gomez and Sullivan, WEST Consultants, HDR, inc.
Dam Owner	Exelon
Non-Profits	CBF, Riverkeepers
News Media	Bay Journal

The Conowingo workshop is generally considered a very successful example of a workshop, in which the researchers assembled were able to draw conclusions and agree on a path forward for the CBP. However, the workshop process can often include a substantial amount of controversy between different groups of scientists, as well as between the CBP modelers and the scientific community. In some cases, the scientists involved can feel co-opted by the CBP modeling process.

For example, one workshop that I attended (and at which I presented on the social factors to consider in implementing multiple models) was on the inclusion of multiple models in the management process rather than focusing attention on a single CBP-constructed model. The scientists involved contended that multiple models provide better results and a more informed decision-making process. Using multiple models rather than a single model allows researchers to compare the models in order to understand the potential shortcomings of each, and average the models, which has been shown to provide a more accurate result than single models alone (Boomer et al. 2013).

The CBP modelers, on the other hand, argued that using multiple models would create uncertainty in the eyes of the public when and if the models disagree. This was an issue not long before the workshop took place when LimnoTech, an engineering firm, produced a comparison of the CBMS with a similar USDA nutrient model (LimnoTech 2010; CBP STAC 2011). LimnoTech determined that the results of the two models were significantly different and that the CBMS should be reviewed more thoroughly (Limnotech 2010). A later workshop and report by the CBP Science and Technology Advisory Committee (STAC) determined that the results were within reasonable boundaries of one another and that the differences had more to do with different uses of the model than the scientific accuracy of either (CBP STAC 2011). This case was brought up at the multiple models meeting as evidence that it would be challenging to convince the public of the benefits of model discrepancies. After the workshop, the CBP continues to use a single-model approach in their management process, though they have made attempts to integrate multiple models in other ways – primarily for comparison and calibration of the CBMS. This remains a contentious issue for the scientific community.

Despite these disagreements within the scientific community and between the CBP modelers and the scientists, there is a general feeling that the CBP modelers are attentive to scientific concerns. Most of the academic modelers that I spoke with who attended the multiple models workshop believe that it was successful at getting the

CBP modelers to recognize the value of multiple models. As one informant described:

> "The workshop we held on multiple models was a big success, so they came on board with their own version of multiple models. It's not quite what we all have in mind, but it's a first step, and there is a project now going on shallow water modeling that is truly compares and a three to four shallow water models that would give some range of confidence for the bay program model which is one of them. So it's a first attempt and, so I think it's gone, it went very well."

In that sense, the approach of using workshops and meetings instead of assembling information internally has created a better relationship between the CBP and the scientific community. This relationship, despite being contentious at times, provides the CBP with the scientific credibility that it needs to carry out its management goals. One of my informants describes the results of the process:

> "...there are conclusions generated and then when we've got to model it, we've got not just our opinion on how those disparate pieces of information fit together, but we've got the [scientific] community weighing in and saying this his how they fit together. <u>And therefore when we model we've got 'believability' essentially. And we've got the backing of the scientific community to do it in that particular way</u>" (underline added).

In other words, the credibility of the model is not simply a function of its accuracy or validity, since those could be developed in the context of an internal process as well. Rather, credibility comes from having a relationship with the broader scientific community. It requires the modelers to reach out to the scientific community, involve them in the process more, and work through contentions between themselves and the scientists. The examples of the Conowingo Dam and other workshops and meetings demonstrate that working with other modelers and scientists further enhances the CBMS by lending it the credibility and authority it requires to legitimize management decisions despite disagreements within the scientific community.

Accessing Data

Accessing data across institutional boundaries is another challenge that CBP modelers face in the process of building the CBMS. Over time, models must be expanded and updated to keep up with new information and research. In a management context, this process is driven in large part by the management needs of the organization. As new policy questions emerge, the models must be augmented to answer the questions (NRC 2017). This requires modelers to find access to new data in order to calibrate and validate the model, and, in general, accessing data requires negotiating agreements with different organizations, and fellow researchers. But within a management organization like the CBP, there are additional concerns about data sharing that the modelers must navigate. Rules and requirements that limit the free sharing of information between state and federal agencies and research institutions sometimes prevent access to data that the modelers need. In these cases, they must find a way to work around the restrictions, often transforming the data in the process. The question is, how do the different rules and requirements for accessing data across institutional boundaries affect the process of building the CBMS?

One example of this challenge was the case of the USDA agricultural census data. Every five years, the USDA collects information about the nation's farms, including crops grown, employment, and income (USDA 2014). One type of data that is of interest to the CBP is the kinds of environmental management practices that the farms use. Knowing exactly what farmers are doing to reduce nutrient and sediment runoff on their farms would be an extremely valuable set of data for the CBP and would help the modelers improve the tracking of nutrient pollution sources. But the USDA cannot simply turn the data over to the CBP because they are bound by rules regarding data sharing in the government, concerns about confidentiality, and their own mission of working with the farming community. One of my informants on the CBP modeling team described the issue:

> "...[A] lot of the partners would like us to be able to get finer scale or have access to more agricultural data, and the USDA has access to those agricultural data. So a lot of the partnership is demanding of the USDA to give the Bay Program office information on implementation of BMPs and things like that. And their argument against that is, 'well, we go to the farmers and ask them for this information and if they knew it was going toward regulation rather than science, they wouldn't give it to us, and that would be the last survey we would have.'

> Specifically if we gave… well and that's not the only reason, the other reason is privacy. So if their farming neighbors knew what they were doing then they would, then essentially their business competitors would have information on them and so they want to protect that as well. So those are two very legitimate reasons for us not getting the data that would make our modeling better."

In other words, the data that the modelers need to improve agricultural modeling exists, but is inaccessible to the CBP modelers due the differing interests and goals of the federal agencies that make up the partnership. In order to work around this obstacle, the CBP modelers had to figure out a way to transform the data into a format that would not breach the privacy concerns of the USDA. They struck upon a solution that utilizes the network of institutional relationships within the CBP partnership to gain access to the data in a modified form. Instead of acquiring the data directly from the USDA, the CBP established a data pipeline that goes first from the USDA to the USGS. These two agencies are non-regulatory and, as a result, have an agreement to share data between them. USGS, then, has the ability to transform the data using geographic information systems (GIS) into a spatial scale that obscures the individual identifiers. However, these data often intersect with data that the states provide to the CBP already. In order to account for this overlap, but also to remove themselves from liability, USGS sends the data to the states, who are already required to submit data to the CBP. The states combine the data with their own, filtering out any repetitive figures, and then send it to the CBP for use in the CBMS. My informant described the process:

> "... to navigate that we talk to them about what we can possibly get ... a lot of it can be used if it can be dumbed down spatially, so if we can aggregate up to a high enough level then they can give us some of that information. There's actually an agreement that was pretty successful that you take the data that the USDA has, send it to USGS, who was able to sign a non-disclosure agreement, and then they do all the GIS that is necessary to give it to us at a level… actually, they give it back to the states at a level that protects those different things that people are concerned about, so that means that some information is at county, some information is at state if it's a rare BMP, and then the state gives it to the Bay Program, and all that's understood. It's not someone giving away information they're not supposed to be giving away. That's completely worked out and understood by all parties.
>
> ...the states are responsible for reporting on the BMPs and the data that they have, some of it is the same data that USDA has, so to deal with double counting and just to make the data responsible, so it's not really the USDA's issue, or USGS issue, that the data go through the states, it's Bay Program standard procedure."

It is a brilliant solution to the problem of accessing data that is otherwise inaccessible. In a purely scientific context, the concern about privacy would not be as significant, but it becomes a major obstacle for the CBP and other management organizations.

In addition to privacy concerns and other rules regarding the exchange of information between agencies, there are also issues with managing funding between organizations. For example, a persistent problem the CBP modelers had during my research was acquiring atmospheric deposition data from a researcher at Pennsylvania State University (Penn State). Nutrients – primarily nitrates like ammonia - are introduced into the atmosphere through emissions from fossil fuel combustion in automobiles and power plants. These nutrients can dissolve in water as it forms into clouds and rain, fall to the ground, and enter the water. Data on atmospheric deposition is collected by the National Atmospheric Deposition Program (NADP), but the form of the data is not usable in the CBMS – a lot of statistical analysis must be done to make it useful, such as calculating distances from smokestacks. One researcher at Penn State has been doing this type of analysis, and the CBP modelers wanted to have the Chesapeake Bay watershed's data analyzed in the same way. There were a couple of ways that they could accomplish this: 1) put out a request for proposals (RFP) and select someone to do the analysis, or 2) find a way to fund the Penn State researcher to do it through existing agreements. They opted for the second because they believed it would take less time. However, the funds had to be provided by the Commonwealth of Pennsylvania since there is an existing agreement between Pennsylvania and Penn State that allows for funding to be provided for research.

Ultimately, the process took longer than expected because there were a number of negotiations that had to be done in order to provide funding for the research. EPA had to negotiate with Pennsylvania, Pennsylvania had to negotiate with Penn State, and each partner along the way received a share of the funding for its part in providing the data. The negotiation process began in 2015 and was still pending when I completed my research in 2016. I have since checked in with the CBP modelers and learned that the data analysis has been completed. However, this illustrates some of the social complexities that come with sharing and accessing data across organizational boundaries.

As these examples illustrate, expanding and updating the CBMS to meet management needs is not simply a scientific process of producing and accessing data, but is dependent upon the ability of the modelers to negotiate data sharing agreements like the one described above. In this particular case, the CBP modelers are fortunate to have access to the network of institutional relationships that make up the CBP – without these the agreement might not have been possible and the data would have remained inaccessible.

Managing Incentives

Computational environmental modeling often entails some degree of collaboration between researchers in different organizations (NRC 2017). In general, this involves some degree of negotiating between the different organizational structures (Edwards 2010). But when incentive structures differ between the disparate organizations, collaboration can be more challenging. This is especially the case, perhaps, for researchers in management organizations like the CBP that prioritize informing decision-making and management processes – in other words, providing information in line with management schedules. Trying to coordinate research with individuals in organizations that incentivize peer-reviewed research publications and scientific practices can be challenging due to the different timelines for these activities. The question, in this case, is: how do the different needs and incentives among the various institutions involved affect the process of building a model at the CBP?

The CBP partnership consists of different federal and state agencies, academic partners, NGOs, and private firms, and each of these has a different approach and reason for conducting research and participating in the restoration process. As a result, there are times when the needs and interests of the individuals working in the various institutions do not align with the goals and needs of CBP, and this can make it difficult to make progress on model development. One of my informants describes these challenges in the following way:

> "Bay Program employees are essential[ly] paid to help the managers make informed decisions, so we create decision tools for that purpose. The USGS researchers that we work with to get better information for our models, they are incentivized by publications so they sit down for their annual review and the question is: how many publications did you write? Did you publish them in peer reviewed journals? And what's your plan for publishing next year?"

In addition, there are different requirements that the researchers at these organizations need to meet in order to meet scientific standards. In this case, the USGS is guided by "fundamental science practices" or FSPs, which determine every aspect of how data is collected, peer review processes, the release of information products, safeguarding data, data management, preservation requirements and more

(USGS 2015). This means that the information obtained from USGS employees is reliable information, but also means that it is difficult to get a concrete answer in a short amount of time. One of my informants described the pros and cons of this process:

> “So anything that takes time to do that doesn’t lead toward publication is really difficult to get from them and also as you’re doing those publications did you follow fundamental scientific principles… fundamental scientific [practices], or “FSPs” as they’re called, is a written document that the USGS has that says this is exactly how you do science and what you follow. So we have trouble getting any kind of guesses from people who work for the USGS, ... They will not guess, they will only give us information that is backed by FSPs and that’s great. I know that anything I get from them is not a guess but citable and we just try to figure out how to exploit that here.”

The difference between the need to provide timely information for management and the need to produce peer-reviewed research makes collaboration across these institutions challenging. The USGS researchers need time to be able to do a full analysis of the evidence and literature, which is needed contribute to a peer-reviewed publication. For the CBP modelers, this means working with the different timelines for producing information, and planning far enough in advance that their collaborators – USGS or otherwise – will be able to do the work that they need to meet their institutional requirements. My informant provided an example:

> "...we all have information in a particular place about lag times, we don't have information for the western shore, and I asked well what do you think and they said 'well you can't use this, you can't use this, and you can't use this.' Our current guess in the phase 0 through phase 5 watershed model is no lag time at all, and their like 'you can't do that, and you can't do that.' …
>
> So we wanted [a USGS employee] to run Sparrow[2]... and he could answer the questions in a day, but he's not willing to do that unless it results in a publication, which if it's going to result in a publication then you've got to find out who else has tried to do this. So it's a month and a half of work for a day's worth of analysis. Where he's correct is that if he did that analysis in a day and he didn't do all that other stuff, then maybe he made a mistake and maybe some other people have looked at this and found the opposite. You know, that could be a really big detriment to his career if he just ran off kind of half-cocked and gave us this information quickly. So that's kind of a struggle for us to plan for what we want and plan far enough ahead so that we can get to their publication schedule…"

This is not only the case with the USGS and other federal agencies, but also with academic partnerships. Managing these disparate social relations requires working with the differing incentive structures among the partner institutions in order

---

[2] Sparrow is another computational model that can track water quality, which is built and maintained by the USGS.

to motivate the kind of research that is necessary for the CBMS as well as organizing timelines for producing the data in a way that satisfies those different incentives. My informant explained it:

> "And in the same way, academics need to publish in order to get tenure, they also have to get grants and write proposals to get tenure… our understanding of those incentives is what allows that process to take place…"

This is much more of a day-to-day process than the previous examples, and requires a detailed knowledge of the different incentives and goals of the various agencies and partners. In fact, this knowledge is not widespread even in the CBP. One of my informants describes transitioning from a position with the EPA to one with the USGS and having to learn about FSPs and the USGS's aversion to policy-making despite having worked at the CBP alongside staff from the USGS for many years. In addition to adjusting and managing timelines, however, the CBP modelers can attempt to incentivize specific kinds of work in other ways as well. Using their position with the CBP, they can help researchers to secure grants and provide data for specific types of research, which benefits academic researchers whose careers depend on securing funding and getting peer-reviewed publications. My CBP informant described how this works in more detail:

> "...the other way that we interact with the academic community is, as you well know, to get anything done, you've gotta go get a grant from somebody. And we've got tiny little bits that we give out from time to

> time. It's insignificant, so the way that we do interact is that people go to NSF or some other funding agency and say, you know, we want to do this research and it will benefit the Bay Program partnership in this particular way. And so we'll write them a letter of recommendation saying, yes, this exact thing that they're going to do, we are going to stick into our watershed model or estuary model in this specific way, and we're going to require them to write this, you know, we'll give them all of this information from our model so that they can do their research and then feed it back to us in this certain way. And we've been very successful in those kinds of partnerships recently, and there are some really big NSF grants that Hopkins, Virginia Tech, Penn State have, uh, had these really big, with multiple universities and multiple PIs, multiple years, millions of dollars that all kind of work that way."

Navigating these different incentive structures means that the process of collaboration is more complicated in a management organization than in other modeling contexts. Modelers at the CBP not only have to be able to work with other researchers across institutional contexts, but must also be adept at managing the many different incentives and requirements involved in the process. This means planning much farther in advance than usual in order to meet their management deadlines and helping others with the funding and publications that they need to meet their institutional requirements.

Conclusion

The examples above illustrate the ways that the management context affects the process of building a computational environmental model. It differs significantly from the scientific process in that the CBP modelers must be not only effective modelers and scientists, but also adept at navigating the institutional relationships that make environmental management possible.

I began the article by examining some of the research that shows how the process of modeling is shaped and informed by social processes. Importantly, this does not mean that models or modelers are "biased," simply that there are always social considerations involved and that understanding those considerations helps us to recognize the role of these models within their broader socioecological contexts. Existing research, however, focuses on the scientific context of ecological modeling, and little has been done to examine the relationship between computational environmental modeling and institutions in which they are produced and used for decision-making and environmental management.

With this in mind, I presented three examples, drawn from my research with modelers in the Chesapeake Bay watershed, that demonstrate how the process of computational environmental modeling is affected by the needs and constraints of management institutions. First, I looked at the way that CBP modelers ensure the scientific credibility of the CBMS by including other researchers in the broader scientific community in the process through meetings and workshops. This suggests that the credibility of the CBMS has to do with more than simply its scientific validity – it is also, in part, a function of the positive relationships that the CBP develops with the scientific community as a result of these meetings and workshops. Second, I examined the constraints imposed on the CBP modelers to access data across institutional boundaries. Accessing these data is more than simply a process of negotiating a data sharing agreement – it requires utilizing institutional networks to translate the data into a useable form before the CBP modelers can gain access to it. Finally, I explored the ways that different institutional incentive structures can impede the process of conducting research for management. This is beneficial because it means that modelers can trust the information they get from their collaborators, but it also means managing timelines to work with the longer processes of publication and obtaining funding. At the same time, the CBP modelers can help others achieve their institutional requirements by assisting with the processes of obtaining funding and writing peer reviewed publications.

Altogether, these examples suggest that there is a significant difference between scientific modeling processes and management modeling processes. As management institutions increasingly adopt the practices of computational environmental modeling to achieve their goals, understanding the relationship between these institutions and the modeling process will become more important. Using an ethnographic approach helps to shed light on the range of social and environmental factors affecting computational environmental modeling and management. Furthermore, scientists, including social scientists, modelers, and managers will benefit from a better understanding of the role that scientific practices in general and computational modeling in particular play in the socioecological process of environmental management.

This article only touches the surface of these issues, and many questions remain. There is considerable potential for future ethnographic research to answer some of the following questions: how do alternative management practices such as the self-governing institutions described by Ostrom (1990) affect the process of modeling differently? How does the *content* of modeling change as a result of its inclusion in a management process? And, what effects does the process of computational modeling have on the management institutions in which it takes place? Answering these questions would require an interdisciplinary approach working with computational environmental modelers, natural scientists, and environmental managers and would help to inform future modeling and management practices.

Finally, the value of this research for computational environmental modelers and environmental management staff is that it will help to identify some of the constraints to modeling for management as well as some effective ways to work around and through these constraints. The CBP modelers that I spoke with are very adept at navigating these institutional frameworks, but they have been doing it for over three decades and have learned through trial and error. In some ways, they are still learning and changing as management conditions and modeling methods change. Management institutions that are attempting to adopt computational modeling or those that have only adopted modeling more recently might benefit from the CBP's experience, but also from a better awareness of institutional constraints in general. This will help them to plan for their own unique constraints and identify ways to address them in advance. Recognizing institutional opportunities and constraints that make modeling and management possible is essential in a world of increasingly complex social and environmental challenges.

Chapter 5: Models for Management and Science: Comparing the effect of social context on computational models

(For the journal Science, Technology, and Human Values)

The proliferation of computational models for understanding complex environmental systems has increased dramatically in recent decades (Edwards 2010; Oreskes 2003). In addition, they have become important tools for environmental management (NRC 2007). As a result, understanding their role in both environmental science and management is an important field of inquiry for an environmental anthropology interested in examining human-environment interactions and relationships (Paolisso et al. 2013; Paolisso and Trombley 2016). In previous research (Chapter 4), I have examined the ways that the *process* of building and implementing computational models is affected by the socioecological management institutions in which those activities take place. In this article, I document some of the social factors that affect the models *themselves* – what and how they represent ecological process. Doing so, I argue, will offer a better understanding of their role within the socioecological contexts in which they are developed and used and inform future implementation of computational modeling in environmental science and management.

Many scholars have examined the epistemological aspects of computational modeling from a scientific perspective Oreskes (1998), for example, shows that models do not behave in the same way that empirical sciences do because they rely upon past empirical data for calibration. As a result, they cannot be “validated” in the usual sense, but instead can be "evaluated" for their ability to potentially predict outcomes from existing states. In a similar vein, Knuutilla (2011) argues that models, rather than being representational of ecological systems, should be considered as "epistemic artifacts" that play a performative role in our understanding of those systems. By manipulating and working with the models, researchers come to know more about the ecological dynamics they represent as well as the limits of their understanding.

Meanwhile, others have investigated the effects that different social contexts have on the process of modeling. Shackley (2001) and Sundberg (2009), for example, show that the process of parameterization – in which complex processes are represented in simplified form within the model – depends upon the social context of modelers. Modelers who are more interested in understanding all of the processes within an ecological system are more likely to use fewer parameterizations in order to more accurately represent the system. On the other hand, those who are more concerned with specific issues such as climate change are more likely to parameterize those processes that are not immediately relevant to the problem.

Landstrom et al. (2013) further explore the social context of modeling by looking at the way that modelers draw upon different affordances and obstacles depending on the social context in which they work. The authors examine two contexts – a "post-normal" project in which stakeholders are involved in the process of developing a flood model, and a "normal" context in which institutional modelers attempt to develop a large-scale coastal flood model internally. They find that these contexts affect the models substantially. The "post-normal" model is developed using a much simpler graphical user interface in order to accommodate the needs of the stakeholders, whereas the "normal" model uses a highly technical software in order to maintain connections to existing coastal flood modeling projects and management institutions.

While all of this research contributes to our understanding of the role of modeling within the broader socioecological contexts in which they operate, the work of these scholars generally focus on the scientific context of modeling. Given that models are increasingly central to the socioecological process of environmental management (NRC 2007), it is important to understand the effects that different social contexts – i.e. scientific and management – have on the structure and content of the models themselves.

In this article, I examine these social effects on models through ethnographic research with computational modelers and environmental managers in the Chesapeake Bay watershed. This region offers two primary social contexts for modeling. The first is the development of scientific models that are used to understand complex environmental processes, primarily in academic settings. The Chesapeake Bay region has a vibrant environmental modeling community among the various academic institutions in the region. In this context, modelers are motivated to understand environmental complexity, and so the models themselves are part of a continual feedback process between the simulation and the reality. As a result, the models tend to be very complex and are continually being expanded and improved to include more of the system.

The second context is the use of computational models by environmental management staff in order to inform decision-making. For the last few decades, the Chesapeake Bay watershed has been the subject of a large-scale effort to reduce the quantity of nutrient pollution flowing into the estuary. This effort is led by the Chesapeake Bay Program (CBP), a multi-state and federal partnership that encompasses the Chesapeake Bay watershed. Since 2010, the watershed has also been subject to the largest total maximum daily load (TMDL) "nutrient pollution diet" ever implemented in the US (CBP 2010). In order to coordinate these activities at the federal, state, and county levels, the CBP has produced a complex computational model known as the Chesapeake Bay Modeling System (CBMS) along with other modeling tools. These modeling tools are used to identify, track, and predict the effects of management practices on the nutrient loads in the region. In this context, the environmental management staff are primarily concerned with the costs and benefits of different management practices. As a result, the model, despite being very complex, is primarily used as a nutrient "accounting tool" in order to determine compliance with the TMDL.

In the following sections, I start with a detailed description of the Chesapeake Bay watershed and the management and modeling approaches taking place within it. I suggest that, in scientific contexts, the modelers are motivated to understand the broader system and the many processes that shape it. As a result, the models are involved in a continual feedback process between simulation and empirical data, and the models themselves are continually expanded to account for new information and to represent more processes. Management staff, on the other hand, are motivated by a cost-benefit analysis of different management practices. As a result, the models developed in these contexts are "accounting tools" that help them to determine the most cost-effective management options in their region. Furthermore, scientific models that are utilized within a management context can be reduced in complexity to accommodate management needs.

The Chesapeake Bay Watershed

I have chosen to focus my research on the Chesapeake Bay watershed because it is the site of a significant management and modeling effort. The Chesapeake Bay is a unique ecological system that extends approximately 200 miles north to south from Havre de Grace, Maryland to Virginia Beach, Virginia (Wennersten 2000). It is an estuarine system – a mix of fresh and tidal waters up to the fall line, which is the geological boundary between the Atlantic Coastal Plain to the east and the Piedmont Plateau to the west visible as a series of waterfalls as the tributaries flow across it. As a result of the varying salinities north-to-south, the Chesapeake Bay supports an abundance of different species, including 348 species of finfish and 173 species of shellfish (CBP 2017). Many migratory birds and fish also make their way to or through the estuary at different times of the year for spawning and/or wintering (Steadman 2001; Miller 2001). All of these features make the Chesapeake Bay a very productive ecosystem and a substantial contributor to economic activity in the region in the form of seafood harvesting as well as tourism. However, in the last few centuries, the ecosystem of the Chesapeake has come under threat as a result of eutrophication caused by excessive nutrient pollution flowing into the estuary from its watershed.

The Chesapeake Bay watershed is a diverse geological and ecological region. It covers 64,000 square miles from the Atlantic Coastal Plain across the Piedmont Plateau, over the Blue Ridge, and into the Appalachian range to the west and north (Wennersten 2000). The land-to-water ratio is the largest of any coastal water body in the world (Kemp et al. 2005), and drains more than 51 billion gallons per day into the estuary (CBP 2017). Five major rivers – the James, the York, the Potomac, the Susquehanna, and the Choptank – contribute most of the fresh water to the estuary with the Susquehanna alone accounting for more than half (CBP 2017).

Since the arrival of Europeans in the watershed, it has become depleted as a result of deforestation, soil depletion caused by farming, overharvesting of resources such as oysters, growing population, and other factors (Wennersten 2000; Mancall 1991). It is as a result of these changes to the landscape that nutrient pollution has become a significant problem for the Chesapeake Bay. Since the 1930s, scientists have documented low-oxygen conditions in the Bay that threaten the stability of the ecosystem (Newcombe 1936). Managing the problem has presented a unique challenge for both environmental management and science.

Watershed Management

The Chesapeake Bay watershed includes portions of six states - Maryland, Virginia, Delaware, West Virginia, Pennsylvania, and New York – and the District of Columbia. This presents a challenge for addressing nutrient pollution on the landscape since doing so requires the participation of all of the watershed jurisdictions. Fortunately, the states and the federal government found a unique solution to the problem in the creation of the Chesapeake Bay Program – a federalist collaborative watershed management organization.

The Chesapeake Bay Program (CBP) was created in 1983 (CBP 1983). However, it was not originally a full watershed management organization. The first Chesapeake Bay Agreement was a one-page document signed by the governors of Maryland, Virginia, and Pennsylvania, the Mayor of the District of Columbia, the head of the Chesapeake Bay Commission, and the Administrator of the US Environmental Protection Agency (CBP 1983). The agreement was voluntary and simply acknowledged the need for a cooperative approach between the various jurisdictions involved. In 1987, a follow-up agreement was signed and was the first to set a specific goal to reduce nutrient loads by 40% by 2000 (CBP 1987). However, this agreement was also voluntary and ultimately the required reductions were not met (Ernst 2003). Furthermore, the upper-watershed states – West Virginia, New York, and Delaware – were not included.

In 2000, as a result of the failure to meet the 1987 goals, a new agreement was signed, known as Chesapeake 2000 (CBP 2000). For the first time, the upper-watershed states were included as “partners” on a memorandum of understanding. Still, these goals and practices were voluntary, and when it became clear that the nutrient reductions would not be achieved by the 2010 deadline, and as a result of lawsuits filed by activist groups and the watershed states, the EPA was required to implement a total maximum daily load (TMDL) nutrient pollution diet for the Chesapeake Bay and its tributaries before 2011. As a result, in 2010, a TMDL was set for the entire watershed – the largest TMDL ever implemented by the EPA (CBP

2010). In 2014, a new watershed agreement was signed, this time including all of the watershed states as signatories (CBP 2014).

The TMDL is authorized under the Clean Water Act (CWA) of 1972, which grants the federal government regulatory authority to manage interstate waters for water quality issues (CBP 2010). The TMDL sets a watershed-wide limit on the quantity of nutrients that can be introduced into its waters and then sets a load reduction that must be achieved to meet the limit. The CBP then distributes these load reductions to each of the watershed's jurisdictions, and the jurisdictions must develop a watershed implementation plan (WIP) describing management practices they will implement in order to achieve the nutrient reductions assigned to them. If the jurisdictions fail to implement the practices outlined in their WIPs, the EPA can use its regulatory authority to penalize them.

Nevertheless, the federal government's regulatory authority under the CWA is limited to the management of point sources (Malone 1993). Since nutrient pollution comes largely from non-point sources such as runoff from farms and other distributed effects, managing it under the CWA is challenging and limited primarily to addressing deficiencies in wastewater treatment. However, the states may still regulate non-point sources if they choose to do so under a TMDL. As a result, the nutrient management process on the Chesapeake Bay watershed must continue to be a partnership, despite the regulatory authority of the EPA – what is known as "cooperative federalism" in legal terminology (Fischman 2005). The CBP provides a unique approach to implementing this cooperative federalist form of governance for the watershed. With the CBP in place, watershed-scale management became feasible for the Chesapeake Bay region. However, there were still limits to our understanding of the problems facing the estuary, and this has posed a challenge for environmental science in the region – a challenge that could only be addressed through the use of computational modeling.

Watershed Modeling

Addressing nutrient pollution in the Chesapeake Bay watershed has taken more than the creation of a collaborative governance institution in the CBP. It also required developing a scientific understanding of the Chesapeake Bay's eutrophication problems and how to resolve them. This has been accomplished through extensive empirical research on the estuary and the watershed including the creation of a network of monitoring stations, but also through the use of computational modeling (Ernst 2003).

Two studied commissioned by the US Congress drove the process of understanding the problems facing the Chesapeake Bay. The first began in 1965 and resulted in an extensive report by the US Army Corps of Engineers published in 1973 (US ACE 1973). This report found the much of the Chesapeake Bay's waters were impaired by eutrophication. A subsequent study was commissioned in 1976 and resulted in a similar finding, however this study also led to a number of scientific and technological changes to our understanding of the watershed (Ernst 2003). Primarily among these was the development of the first computational model of the Chesapeake Bay watershed, which was released at the same time that the CBP was created (Hartigan 1983).

The first model only simulated the watershed and the flow of water across the landscape (Hartigan 1983; Linker et al. 2002). However, the modelers quickly expanded it to include more aspects of the watershed ecological system. The next iteration of the model was released in 1987. It increased its resolution and also included a linked model of the Chesapeake Bay estuary – a three-dimensional hydrodynamic model of the bay itself (Linker et al. 2002). It was developed further over time and additional components were added including a model of the airshed for the region. Finally, in 2010, a Phase 5 model was developed specifically for use in the TMDL. This model added a Scenario Builder model, which converts county data such as zoning, best management practice (BMP) implementation, and acres of cropland into pounds of nitrogen, phosphorous, and sediment that can then be used by the watershed model. It also increased the resolution of the watershed and estuarine models even further (Shenk and Linker 2013). Together, this suite of models is known as the Chesapeake Bay Modeling System (CBMS). The overarching purpose of the CBMS is to provide answers to resource management questions and, ultimately, for setting regulatory TMDL limits on nutrient and sediment runoff (CBP 2010).

The CBMS is considered state-of-the art, and helps to inform decision-making on the watershed by allowing the CBP to identify and track nutrient pollution on the landscape and predict its effects on the estuary (Shenk and Linker 2013). It was used to determine the initial 40% load reduction goal in the 1987 agreement, and was then used to establish the nutrient reduction goals in Chesapeake 2000 agreement and evaluate the tributary strategies (Linker et al. 2002; Ernst 2003). In the TMDL, it serves the same purpose – establishing the TMDL limit and evaluating the WIPs (CBP 2010). The CBMS is also used to track progress towards the TMDL goal during its midpoint assessment in 2017 and 2018.

In addition to the CBMS, there are other models that have been developed either by or in collaboration with the CBP, the most important of which, for the present article, are the Assessment Scenario Tool (AST) suite of models: Chesapeake Assessment Scenario Tool (CAST), Maryland Assessment Scenario Tool (MAST), Virginia Assessment Scenario Tool (VAST), and the Bay Facilities Assessment Scenario Tool (BayFAST). These tools help management staff to determine the costs and benefits of different management practices without having to consult the CBMS, which is a lengthy process.

Together the CBMS and the various AST tools, along with empirical research and other modeling projects, have helped us to understand the causes and effects of eutrophication in the Chesapeake Bay. Combined with the CBP's management approach and the TMDL, these tools are also part of a broader effort to reduce nutrient pollution throughout the watershed. Understanding how these two processes – one scientific and one management – affect the structure and content of the models will help to plan better modeling and management practices in the future.

Methods

This project attempts to answer the question, "how are computational models affected by the different social contexts in which they are developed and utilized?" For this purpose, I conducted participant observation and semi-structured key informant interviews with environmental modelers and scientists involved in modeling in the Chesapeake Bay watershed (Bernard 2006). This included working with modelers at the CBP itself to understand the process of modeling within an environmental management institution, but also working with modelers in academic and scientific settings. This combination provided me with a substantial amount of data on the process of producing computational environmental models in different circumstances, and enables me to draw some comparisons between the scientific context and the management context of modeling. Much of the research took place over the course of three years from 2014 to 2016, which was the "build year" for the Phase 6 version of the CBMS.

In order to observe and experience the development of computational models first-hand, I conducted participant observation with modelers at the CBP and in various academic settings. This included spending time at the CBP office in Annapolis Maryland observing the modeling team there, and observing at the University of Maryland for Environmental Science (UMCES) with academic modelers. I also attended several meetings of modelers and management staff in the region including the Chesapeake Environmental Modeling Symposium (CHEMS) in June of 2016. These meetings provided a rich source of data on the model development process since they are sites where modelers discuss the progress that has been made and the various obstacles that have been encountered.

In addition to participant observation, I conducted twenty-five semi-structured interviews with modelers and other scientists, as well as management staff working on environmental issues in the region. I selected these informants based on their participation in modeling projects that were taking place during my research. My questions revolved around the development of computational models and their application to management and scientific understanding of ecological systems and processes. The interviews augmented my participant-observation experience (Whitehead 2005) and provided me with insight into the process of modeling and its role within the CBP management institution as well as different perspectives on the management and modeling process.

All of the data was coded using an inductive coding method, in which key themes were identified from the data themselves (Bernard 2006). In particular, I sought out information about the relationship between computational modeling and environmental management. The following sections examine the data for computational modeling in the watershed in order to understand how models are affected by the scientific and management contexts in which they are produced and used. I start with modeling in the scientific context arguing that a continual feedback between models and empirical data results in more complex and nuanced models and an appreciation for their limitations. Afterwards, I discuss models in a management setting suggesting that the needs and concerns of management staff often result in simplified "accounting" models that focus on a few key processes needed for cost-based decision-making.

Modeling as a Scientific Practice

> "…well the limitations are [the model is] wrong, because all models are wrong."

This sentiment, frequently expressed with the maxim “All models are wrong, some models are useful” (Box 1976) was a common refrain throughout my research with computational modelers. In other words, there is recognition among modelers that their simulations can never fully capture the reality of a system, and that it is unreasonable to try. For example, climate models struggle to capture the effects of cloud cover because the clouds are too small to fit into the grids. As a result, these processes must be “parameterized” or represented in different ways that are not directly representative of the processes (Sundberg 2009). However, even if the clouds and other factors could be represented effectively, there is a sense that there are always aspects of the ecological systems that we do not understand well enough or cannot effectively represent in the models, and so they will never completely match up to the full complexity of the system.

This is sometimes considered a limitation of computational modeling, but in terms of scientific understanding, it can be an asset in that it is in the discrepancy between the model and reality can expose the limits of our understanding and new scientific avenues to pursue. For example, one academic modeler described to me his approach, which is to look at calibrated models, which have been finely tuned using empirical data to accurately represent particular ecological systems or processes, and uncalibrated models, which are not finely tuned but simulate the processes more accurately in terms of our theoretical understanding. By comparing two models in this way, he argues that we can get a better sense for where our theoretical understanding is lacking, and what processes are not being captured without calibration:

> "…all models are wrong, ... isn't that the saying? But some are useful? ...my approach to modeling, is trying to minimize unconstrained model calibration. … One thing we're also looking at for this project is using that methodology but then going with the full model calibration and looking at the difference, that difference between the uncalibrated and calibrated basically tells us what we don't understand about the system. Where we need to improve our input data. Where we need to improve our process understanding."

This shows that if there is a continual feedback between models and empirical data as well as between different types of models, then it enables scientists to recognize the limitations of their understanding, which then drives further modeling efforts and further data collection. This can be seen clearly in the work of the modelers who develop the CBMS, as they are continually attempting to improve the model and expand it to incorporate additional processes. For example, during the time that I was conducting my research, the CBP modelers were working with academic scientists and modelers to improve various components of the model including the lag time between nutrient application on the landscape and its introduction to streams and rivers (STAC 2013), the infill of the Conowingo dam (Linker 2016), and the simulation of shallow waters in the estuary (Tian et al. 2014). Each of these new components was being added as a result of new data that had been collected and had shown the CBMS to be deficient in some way. When these factors are incorporated into the model, it may show new areas that need further study. The effects of climate change or variations in the placement of wetlands, for example, are some of the areas I heard discussed as possible areas of future research.

Among many of the modelers I spoke with, this drive for exploration and understanding is exciting and one of the primary rewards of the modeling process. In the below quote, one academic modeler I spoke with discusses the importance of knowing the distribution of how long water has been in an ecosystem. Currently, the CBMS and many other models do not account for the lag between the time water falls on the ground and the time when it enters a river or stream. My informant approaches this as a research question that cannot be answered easily with empirical methods, but proposes a modeling method – transit time distribution – that might be able to capture some of the processes involved more effectively than is being done in the current models:

> "So imagine that you stand next to a stream that has some catchment above it, the water is draining out of that catchment into the stream. And you can take a sample of water in that stream and ask every molecule of water in that sample - when did you arrive as rain? How long ago? And some of it arrived in the last storm, some of it arrived a decade ago. But there is this distribution of ages and you can think of this as like a histogram, this is like the probability, actually the probability density. None of it was this age, quite a lot of it was this age, a little bit was this age. So we have this distribution. …If I know the water that fell this long ago had a certain amount of some solute in it, it had a certain concentration of that, and I know that for all the ages

going back in time, if I assume that all the water that is this age still has the same concentration, then I can predict what the concentration of the water in the stream is right now. Because it's this much of water that has that concentration, this much water that has that, whatever that concentration was back then. So this is how the idea of using a transit time distribution, and if you can combine a transit time distribution with a plot of concentration [Nitrogen] as a function of time, … you can predict concentration [coming] out as a function of time. Um, the problem is, how do you represent, how do you know what [the age of the water] is? Because you can't ask every molecule of water, how old are you, and you can't do that every time that you need it in sort of a record."

This modeler's excitement about the problem is palpable. The question – how do you represent differently aged water moving through the ground in a computer model? – is compelling for him not only because it is relevant to the CBP's environmental management, but simply because it is an interesting math problem and a fascinating environmental process:

"I wasn't motivated initially by, you know, the Chesapeake Bay Program needs us. But, having started thinking about, here's some really cool math and a really interesting sort of very pure science hydrology question, I guess I thought, is this, it's an interesting question, but is it an important question?"

Another informant similarly describes her and her student's work simulating seagrass meadows and how the plants reproduce. Seagrass is a rhizomatic plant, which means that it spreads by branching out new nodes and colonizing new areas of the meadow. Existing models that simulate seagrass growth as an increase in carbon did not take this biological aspect into account. As a result, she developed an "individual based" model that simulates individual ramets, or clones, in order to represent their movement through space. She describes her approach in the following quote:

> "So the big model that is mine in this is an individual-based model of a seagrass meadow. And we can't yet simulate entire, so I simulate individual ramets of seagrass. And those ramets grow in response to all the things that you think plants grow in response to. Light, temperature, nutrients, and they also get affected negatively by those things. And as opposed to a traditional model where we typically grow seagrass as grams carbon per meter squared, so we just lump it into a black box of carbon, the individual-based model we're actually thinking about the botanical structure of this plant and the fact that it essentially moves through space. So as seagrass lays down new nodes and new rhizomes, it's actually colonizing and moving across the sediment surface, and so the idea is just simulating grams carbon per meter squared we've always felt neglected that aspect of seagrass biology, and especially in a restoration or expansion context, which is certainly the case for many of the coastal bays where we're hoping to

simulate what will happen if you reduce nutrients and increase light, we want to have a model that's able to emulate that process."

In other words, her individual-based model is better able to capture the full biological reality of the seagrasses, but there are still aspects of seagrass reproduction that her model does not capture. In her model, for example, the reproduction of the plant was only simulated by having each plant clone itself rhizomatically. However, the actual seagrass that she is attempting to simulate also reproduces itself sexually under certain conditions. Her student is working on adding a sexual reproduction component to the model, which will help management staff who are attempting seagrass restoration using seeds. Since sexual reproduction in these plants is temperature dependent, it might be affected by temperature changes resulting from climate change.

These examples show that, in a scientific context in which the motivation is to understand complex ecological processes, computational modelers recognize the shortcomings of their models. Rather than being a limitation, however, these shortcomings are considered an asset in that they point to areas for future research and modeling. Furthermore, the models do not exist in isolation – they are part of a continual feedback process between empirical data and other models that augments the drive for further research. As a result, the models are continually expanding to add new components and to represent ecological systems and processes more effectively. I have provided only a few examples, but this was true for other scientific models that I observed as well. Some additional examples of this feedback process include: incorporating new and emerging data about oyster habitat into estuarine models

(Theuerkauf and Lipcius 2016), developing predictions about the effects of climate change on the watershed and estuary (Hinson 2016), simulating conditions in shallow water as compared with the deeper portions of the bay (Tian et al. 2014), and simulating the effects of dam infill on nutrient pollution in the bay (Hirsch 2012). It is clear that this continual feedback is an important part of the scientific practice in general, and computational models provide an additional tool to augment the process.

Although some of these models become incorporated into management modeling tools and the CBMS itself is informed by scientific modeling processes, there is, nevertheless, a significant change that takes place in models as they become incorporated into a management context. In these instances, they become simplified and focused on the essential features in order to function as “accounting tools” for management decision-making. In the following section, I will explore how this transition takes place and how it affects the models themselves.

Management Modeling

Modeling for management is very different from that of scientific modeling, and is shaped by the needs of the environmental managers themselves (NRC 2017; Canham et al. 2003). Much of the concern for the managers I spoke with was oriented around getting “the biggest bang for our buck,” as one of my informants likes to say. That is, which projects will cost the least and get the largest nutrient load reduction? For example, in terms of lower cost and larger nutrient reduction, is it better to plant a riparian buffer or restore a wetland? These are the kinds of questions that occupy the manager’s minds, rather than understanding all of the complex processes that take place within an ecological system.

Also, managers often do not fully understand the models. This is in part because they do not have the training to make sense of them, but also because they do not have the time to learn because they are more occupied with other kinds of work. For example, the soil and water district staff in New York that I talked to are not only tasked with addressing nutrient pollution for the Chesapeake Bay, but are also supposed to help farmers be more profitable and sustainable. As a result, they are engaged in helping to build barnyards, deconstructing gravel berms and replacing them with restored stream banks to prevent flooding, and constructing wetlands. One of my informants from the region explained that all of this work took priority over learning the ins-and-outs of the CBP's models:

> "...you know the scenario builder, I have not gotten into all of that. I don't have time to learn it, I just want to do work, do my covered barnyards, do my grazing work..."

As a result, the models are often made simpler, easier to understand, and more practical to use. Instead of representing the full complexity of the ecological system, they are reduced to the primary factors that must be considered in their decision-making: the nutrient load reduction that will come from a given management practice, and its cost. As a result, many of my informants described the models as "accounting tools" that can convey those costs and benefits simply and straightforwardly. In the context of management, the CBMS, despite being a large and complex model, is effectively one of these "accounting tools." One of my modeler informants at the CBP even described it as such to me, recognizing the role that the model plays in the management process does not include the full complexity of the ecological system that they try to incorporate into the models:

> "…it's an accounting model…so most academic models are models for understanding...We are saying that we're understanding the process based on other people's work…using multiple lines of evidence, agreeing what the process is, and then putting it into an accounting tool, which is not trying to understand anything, it's trying to take understanding and agree on it and then use it for accounting."

Another informant explains further that the CBMS, despite its complexity, is less a tool for understanding the complexity of ecological processes and predicting potential outcomes, and more oriented towards tracking the effects of different practices on the watershed.

> "[One modeler] argues that the watershed model, at least, is an accounting tool. It's no longer a prediction or forecast, it is just, you know 'I've done a hundred acres of riparian buffer, here's what that would mean in water quality improvement.' So all he's doing is now he's saying that by doing that you're tallying what the load should be to the creek river or bay. So they're getting away from the thought that this is a model to predict or forecast, they're getting to basically being a spreadsheet approach. I mean it's not, it's still a very complex model, but it's just an accounting tool to say if Pennsylvania does this and Virginia does this and Maryland does this, by doing those individual

> things, you sum them up and here's what you get. So in that sense, you know I agree with him it is an accounting tool."

In other words, rather than being a tool for understanding the ecological system, as an accounting tool the model is used to allocate and track nutrient loads throughout the watershed. This is done with the help of an additional model known as the Scenario Builder, which:

> "...generates information that is used to simulate loads related to animal production areas, manure storage, application of manure and fertilizers, septic inputs, plant growth/uptake, and best management practice (BMP) implementation" (CBP 2010).

The Scenario Builder model compiles data submitted by the states and counties including zoning, permits, and best management practice (BMP) implementation and translates it into a quantitative load – pounds of nitrogen, sediment, and phosphorous. The data produced by Scenario Builder can then be fed into the CBMS watershed model to evaluate the effect of those practices on the quantity of nutrients and sediment in the water.

In addition to scenario builder, there is another set of models, known collectively as assessment scenario tools (AST): Chesapeake Assessment Scenario Tool (CAST), Maryland Assessment Scenario Tool (MAST), Virginia Assessment Scenario Tool (VAST) and Bay Facilities Assessment Scenario Tool (BayFAST). These models allow management staff and the CBP to quickly and easily explore different options for management, including costs of different management practices.

All of these tools were developed specifically to help state and county level management staff plan for the TMDL. The AST suite, for example, started in Maryland after the TMDL had been set and the states were required to submit their WIPs. The first phase of WIPs was difficult for Maryland and the other states because they had to first submit their plan for evaluation using the CBMS. This process took a long time – they did not fully understand how the model worked, so it took multiple tries to get the appropriate set of practices that would reduce their allotted loads. As a result, Maryland wanted a tool that would be able to give them the response faster and without the hassle of running it through the CBP and the CBMS:

> "...what happened with, initially it was MAST, is, MDE had approached [my student] and me and asked if we could develop something that would approximate the watershed model so that they could better develop their watershed implementation plan, and at that time it was the phase one plan. No, I take that back, it was the phase two plan, because they had done their phase one, it had been really difficult because they would submit a scenario to the bay program, it would take two weeks or sometimes more to get those results back, and they weren't understanding how the model worked, which essentially was trial and error: 'what do we need to do?' and they try this, they try that, and they weren't getting what they needed in terms of loading reductions. And so they needed a rapid way to do that sort of scenario development for the phase two WIPs."

As a result, what the AST tools do is to model the model. Instead of trying to develop a simplified representation of the watershed that would parallel the CBMS, they developed a simulation of the CBMS itself that would estimate the load reductions of management practices as they would be represented in the watershed model. This approach has been so effective for the TMDL process that the CBP has been working on reconfiguring the CBMS watershed model to run the same calculation that CAST does, so the results from CAST for managers will be exactly the same as those for the watershed model. The only thing that the watershed model adds is a higher temporal resolution necessary for running the estuary model, which is used to predict the impacts of management activities on the Chesapeake Bay itself.

I encountered other simplifications of models for management purposes in my research. In addition to working with the CBP, I also followed a participatory modeling project on the coastal side of the Eastern Shore. The purpose of the project was to develop a model that could be used by county-level management to address water quality problems in the coastal bays of Maryland, Delaware, and Virginia. They were faced with a similar problem to that of MDE – the turnaround for results from the CBMS was lengthy, and so they wanted a simpler model that could be run quickly in order to make management decisions. The modelers on the participatory project worked with the coastal management staff to develop a simple spreadsheet-based model of the watershed along with a "box model" of the coastal bays, which simulates the bays as a single unit rather than breaking them into segments and including three-dimensional changes, and an agent-based model of seagrass beds (described above). This simpler approach was embraced by the management staff who attended the meetings, but even so, the model was still more complex than they needed. The primary interest was in the watershed spreadsheet model, because it would allow the managers to test scenarios and evaluate nutrient load reductions for management practices in the same way that the AST tools do. The seagrass model, in particular, was a hard sell, as one informant explains:

> "...the project [the student is] doing right now is incredibly geeky, you know, where she's really interested in this kind of fundamental question of whether sexual reproduction will shift the way these seagrass meadows work under climate change. And even thinking, you know, at a higher level of what is the purpose of sexual reproduction in a rhizomatic plant. And why do these plants have either clonal or sexual reproductive strategies. So those questions, I mean I guess a manager might occasionally ponder on them, but they're not really gonna directly influence their day to day operation."

These examples show that when modeling enters a management context where the focus is on reducing loads and finding the most cost-effective ways to do so, the models may be very complex in themselves, but they become simplified to the basic functions necessary for management. Rather than engaging in a continual feedback between simulation and empirical data or other models, as in the case of scientific modeling, these models are simply reduced to "accounting tools" that can provide cost-benefit analysis in order to help management staff get "the biggest bang for their buck." This suggests that, within the socioecological context of environmental management, models do not require the full complexity of the system in order to be useful. However, by focusing on nutrient loads reductions and costs, the models also help to reinforce the cost-benefit management process.

Conclusions

The purpose of this article has been to examine the effect that different social contexts have on computational environmental models through ethnographic research in the Chesapeake Bay watershed socioecological system. The Chesapeake Bay watershed offers two contexts for modeling: 1) the scientific process of building a model in order to understand the ecological processes that shape it, and 2) the process of environmental management in which computational models are used to identify goals and track progress towards their completion. While there has been a great deal of research on the social factors that affect computational modeling, the focus tends to be on modeling within a scientific context. As a result, this comparative approach will help to understand the different roles that models play within socioecological contexts and how these tools contribute to both our understanding of and our relationship with ecological systems.

I first set out to describe the two contexts for modeling within the Chesapeake watershed. These contexts are in many ways difficult to separate given that much of the computational modeling in the region contributes to the scientific understanding that underlies the management process. However, there are clear differences that make it possible to draw comparisons. Computational models, within a scientific context, are used to understand complex ecological processes. To some extent, all of the models that I studied, including the CBMS, meet this basic requirement.

However, a transformation takes place once the models are being used primarily for management purposes. In this context, the models set management goals and identify effective management practices in order to meet those goals. In other words, their primary purpose is no longer understanding the processes affecting the system; those are assumed to be incorporated into the model. Instead they become “accounting” tools for quantifying costs and benefits of certain management practices.

With these two contexts in mind, I set out to examine their effects on the computer models. Within the scientific context for modeling, I found that the modelers were well aware of the limitations of their models. Rather than seeing these limitations as a detriment, however, they view them as a benefit. By comparing models with empirical data and with each other, the researchers who I spoke to were able to identify the limits of our understanding of ecological processes. This encourages further empirical research to study those processes we do not yet fully understand, followed by further modeling to attempt to capture those processes in our simulations. This continual feedback process between the models and empirical data is motivated by an interest in understanding ecological systems, while recognizing that we may never fully be able to do so. The models augment this motivation by providing a tool for comparison that helps to continue the feedback process. In other words, models, in this context, can augment an existing curiosity and interest in understanding complex ecological systems and processes.

I then set out to discuss the management context for modeling. This is a very different social context with a different set of motivations and concerns. The managers I spoke with are primarily interested in identifying management practices that get them the "biggest bang for their buck" – that is, they want to know which practices will give them the largest nutrient load reduction for the lowest cost. Models can help to identify these practices by simulating their effects on the landscape. However, in order to address these concerns, the models must be understandable to the management staff, and they must be practical and efficient for them to use, since, in the case of the TMDL, they are on a constrained timeline to achieve their goals. This means that using a model that represents the full complexity of the ecological system is not practical (it takes too long) and is not necessary (all of the ecological processes are not relevant to the cost-benefit analysis of management). As a result, the models become simplified into "accounting tools" that identify and track the most effective management practices and, in many cases, provide a cost estimate for implementing them. Even a complex model like the CBMS can be reduced in this way to provide only the most relevant information, but other models have been created in addition to the CBMS to serve these management functions. The models, therefore, augment the cost-benefit analysis of management decision-making by reducing complex systems to the basic relevant functions for management.

This evidence suggests that models take on multiple forms in the socioecological processes of understanding and managing complex ecological systems. They can be used to push the limits of our understanding of those systems, or they can be tools for identifying and tracking management processes. They can help to expand our conception of the ecological systems, or they can augment a more quantitative approach to management. As a result, computational models may not only change depending on their social conditions, but might further augment existing conceptions of ecological systems, not allowing us to recognize their full complexity.

This suggests that working with multiple different approaches to modeling and using participatory and collaborative methods might help to offer different perspectives and provide opportunities to develop new and innovative solutions to difficult problems. By including different models – some that are more complex and others that are less so – management projects could avoid getting locked into a narrow cost-benefit understanding of the ecological system. Including more people in the modeling process, even on a smaller scale than the watershed, would help to foster a better appreciation for the complexity of ecological systems and the limitations of the computational models.

Further research might examine the additional roles that models can play within the socioecological systems in which they are developed and deployed, since scientific and management processes are not monolithic – there may be other ways that these contexts might influence the models. Additionally, further research could examine the effects that these models, in turn, have on the social contexts in which they are produced and used. I have shown how models can augment existing social dynamics, but perhaps there are ways that they generate new motivations and interests that had not existed before the computational models were developed. As models become increasingly influential in our environmental decision-making processes, understanding how they are shaped by and, in turn, shape the social contexts in which they operate is essential for developing better environmental management practices.

Chapter 6: Assembling Watershed Management Using Computational Models

(For the journal Cultural Anthropology)

Large-scale environmental management increasingly depends upon the use of computational models to inform decision-making and track progress towards management goals (NRC 2007, Canham et al. 2003). However, in addition to their informational capacity, there is an abundance of research that shows that modeling also plays a relational role within the socioecological contexts in which they are constructed and used. Edwards's (2010) far-reaching analysis of climate science as a "knowledge infrastructure," for example, shows that the development of climate models has depended upon an array of institutional and international relationships that make it possible to assemble global data. In addition, Landstrom et al. (2013) show that, in addition to the knowledge embodied in computer models themselves, modelers and others within different social contexts gain "experience based" knowledge from the performative practice of building models and navigating various "obstacles and affordances" – the constraints and resources that are encountered in the modeling process. These studies suggest that computer models might play more than an informational role within an environmental management context as well.

In this article, I argue that computational environmental models play multiple roles in the management process depending on the specific conditions in which the models are being used. I further suggest that by serving multiple roles, models help to organize the management process at various levels and keep everyone involved working towards a common set of management goals. Without these functions, environmental management at large scales would be challenging. Examining these multiple roles can help us to understand not only the process of computational modeling, but also the process of management and how different organizations coordinate with one another through the use of modeling.

I approach this issue through ethnographic research with computational environmental modelers and environmental management staff in the Chesapeake Bay watershed. The Chesapeake region is an excellent place to examine these questions for many reasons. First, for the past few decades, the Chesapeake watershed has been the focus of a large-scale effort to reduce nutrient pollution flowing into the estuary. This effort has been led by the Chesapeake Bay Program (CBP), a partnership between the federal government, the six watershed states, the District of Columbia and several academic, private, and nonprofit organizations. As a result, the process involves many different kinds of activities at many different scales.

The second reason this region is well suited to these questions is that, in order to coordinate nutrient pollution reductions, the CBP has been developing and implementing a complex ecological model known as the Chesapeake Bay Modeling System (CBMS). The CBMS is a state-of-the-art and well-respected model that helps to inform decision-making by identifying, tracking, and predicting the effects of ecological management practices on nutrient loads (CBP 2010). It plays a role at every level of management, and so is an interesting case study to explore the many roles of computational modeling in the management process.

My research shows that the CBMS plays different roles depending on the specific context in which it is being used. For the modelers, it is a tool that must be assembled from bits of code and data by people in different institutions in the partnership. For the CBP staff who work to coordinate the various institutions that make up the CBP management process, the model provides information that helps to keep all of the various institutional actors oriented towards a common management goal. Finally, for the county-level management staff who implement management practices on-the-ground, the model prioritizes certain projects over others and directs their work towards specific watershed goals. Altogether, the model helps to organize the various people and organizations involved in the management process and directs their work towards the CBP management goals.

In the following sections, I develop this argument by first examining the existing research that discusses the different roles of computational modeling in scientific and management contexts, in terms of both its informational and its relational dimensions. I then turn to a description of the Chesapeake Bay watershed as a socioecological system, with particular focus on the watershed-scale management and modeling efforts of the CBP. After this, I examine three ethnographic examples that illustrate the different roles that the CBMS plays in the process of building and maintaining the social, institutional, and environmental relationships that organize the CBP management process.

In the first example, I discuss the CBMS as a scientific instrument that must be assembled from various data resources and bits of code. This process of assembling helps to bring together the researchers and modelers in the region and direct their efforts towards understanding the causes and effects of nutrient pollution in the watershed. The second example analyzes the use of the CBMS to organize the collaborative management effort led by the CBP. In this context, the model helps to keep all of the disparate institutional “partners” oriented towards a common set of management goals, but also serves as a reminder that all of the institutions are participants in the process by providing resources and information. The third example looks at the on-the-ground process of managing the landscape at the county-level. In this case, the model helps to set priorities and identify potential management practices that help to organize their activities on the landscape. I conclude with some thoughts about how this research helps to inform our understanding of the socioecological process of environmental management as well as suggestions for further research.

The Social Roles of Computational Environmental Modeling

Computational environmental models are primarily considered informational tools that help to inform our understanding and management of complex ecological systems (NRC 2007; Canham et al. 2003). In this context, they serve multiple roles: synthesizing relevant information into a unified format, identifying the causes of environmental problems, setting management goals, and tracking progress towards those goals (NRC 2007). These are all important roles that models can play, but, in addition to these informational roles, additional research suggests that models can also play a number of roles in the social relationships that form around understanding and managing ecological systems.

Edwards (2010) provides a thorough history of the field of climate science and its development through the 20th century. He describes climate science as “knowledge infrastructures” which “... comprise robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds” (Edwards 2010, 17). Computational modeling plays an essential role in all of these processes because it allows researchers to overcome “data frictions” such as differences between data collected using different instruments and methods across space and over time. In that sense, models bring together all of the heterogeneous components of the global knowledge infrastructure to form a unified image of the globe. However, doing so has required not only scientific processes of data collection, but also the negotiation of various institutional relationships that have made it possible to assemble the necessary data and material resources to conceptualize the global climate. This has resulted in the creation of international organizations dedicated to integrating these scientific practices such as the International Panel on Climate Change (IPCC).

In another case, Landström et al. (2013) describe the process of constructing a model in two different social contexts – one they describe as “normal,” or taking place within an established and uncontroversial institution, and another they describe as “postnormal,” or taking place within a contested social context. The normal modeling example they provide is the development of a coastal flooding model within a consultancy firm in the UK, while the postnormal example involved a flood management “competency group” organized in rural England to address localized flooding issues in the region. The authors describe the ways that these two groups “improvise” certain aspects of model construction, drawing upon “affordances” in order to overcome “obstacles.” They discuss this process as a kind of learning that does not necessarily produce new information, but nevertheless generates new knowledge by pushing the limits of the modelers' skills with the software and modeling processes. In the normal context, the modelers were obliged to use a specific modeling software called TUFLOW in order to maintain institutional relationships, and, as a result, had to navigate the limitations of the software and the existing datasets. As a result, they developed new knowledge about using the software in different contexts. In the postnormal context, the learning process involved integrating non-scientific understandings of flooding into the modeling process, which required the scientific researchers to adapt by being more flexible about the tools and modeling techniques that they used. This demonstrates that modeling can play different roles in different social circumstances, serving as both a constraint on the learning process as well as an affordance that can foster flexibility.

These studies, despite extending beyond the informational capacities of computational models, still focus on the models as knowledge tools within a broader social context. However, environmental management requires more than knowledge – it also requires the organization of effort towards a set of common management goals. Ostrom (1990) argues that communities can avoid the "tragedy of the commons" by organizing common pool management regimes that coordinate collective management of a resource. I argue that computational models, in addition to informing management processes, can play a variety of roles in the process of building and maintaining such regimes, especially those organized at large scales and involving many different institutional actors. In the following section, I describe how the CBP manages the Chesapeake Bay watershed using computational modeling in order to reduce the introduction of excessive nutrients into the estuary. I then turn to three ethnographic examples of the various roles that computational modeling plays in the process of building and maintaining the CBP's watershed management structure and orienting its partners towards the common management goals it has set out to achieve.

Watershed Management of the Chesapeake Bay

When Europeans first arrived in the Chesapeake Bay region, they described the rich abundance of the estuary, the pristine environment that supported large populations of fish, oysters, crabs, birds, and other forms of life. The indigenous peoples living in the area at the time – the Powhatans and Piscataways – were thriving on the resources that the bay provided (Wennersten 2000). However, the quality of the water began to decline rapidly after European arrival, which had a detrimental impact on the ecology of the estuarine system (Rick et al. 2016). By the 19th century, the Chesapeake Bay and many of its tributaries were severely depleted (Black et al. 2017), and by the early 20th century, scientists had documented low-oxygen conditions in many parts of the estuary (Newcombe 1936).

Much of this decline was due to overharvest of resources in the Chesapeake Bay itself (Wennersten 2000), but it also was caused in large part by ecological decline in the greater watershed. The primary factor affecting the bay's water quality was the excessive load of sediment and nutrients such as nitrogen and phosphorous entering the estuary. These nutrients cause eutrophication – an overgrowth of microalgae that transforms the ecological balance of the system (Kemp et al. 2005). Larger populations, deforestation, and intensification of agriculture in the watershed all contributed to these processes. More people combined with poor sanitation meant that higher quantities of human waste were being dumped into the rivers and streams of the region. Deforestation to clear land for agriculture and development resulted in more erosion on the landscape. Intensification of agriculture resulted in the application of external fertilizers such as manure and synthetic fertilizer. Combined with higher quantities of farm animals, especially chickens, this resulted in additional nutrient runoff from farms. With the bay's ecosystem already depleted – due in large part to the overharvest of oysters from its waters – it had no way to recover and process the additional loads being introduced. As a result, the water became increasingly murky, oxygen levels in the water declined, and fish and other macroorganisms began to die in large quantities. For decades, the problem was recognized but the political means to address it were not in place. Cleaning the Chesapeake Bay required participation from the full watershed to reduce nutrient loads into the system, and state and local boundaries prevented such a large-scale program. This changed in the 1980s with the creation of the CBP.

The CBP, as a watershed-scale environmental management program, is a unique organization in the United States (Horton 1991). The purpose of the CBP is to support an "...environmentally and economically sustainable Chesapeake Bay watershed with clean water, abundant life, conserved lands and access to the water, a vibrant cultural heritage, and a diversity of engaged citizens and stakeholders" (CBP 2014). One of the primary goals of the CBP, however, is to improve the quality of water within the estuary by reducing the introduction of nutrients and sediment into its waters.

Because of its unique structure, the CBP is an interesting context to understand the roles that computational modeling can play in building and maintaining an environmental management institution. Due in part to restrictions on the ability of the federal government to regulate water quality under the Clean Water Act (CWA) – primarily, regulation of pollution that runs off of farms (Malone 1993) – the CBP has been organized as a partnership between the federal government, represented primarily by the Environmental Protection Agency (EPA), and the seven jurisdictions whose boundaries encompass a portion of the watershed: Maryland, Virginia, Delaware, New York, Pennsylvania, West Virginia, and the District of Columbia. In addition to these governmental partners, the CBP has included a number of academic institutions, nonprofits, and private firms who help contribute to the management process in different ways. Organizing all of these various institutional partners is a challenging task, but the CBP has been successful over the past few decades, at expanding and maintaining these connections despite an, at times, hostile political environment (CBF 2016).

Since its beginning, computational modeling has played an important role in the CBP's management process (Linker et al. 2002; Shenk and Linker 2013). Over the past 34 years, researchers at the CBP have been developing a computational model of the Chesapeake Bay watershed. At first, the model only represented the flow of water on the landscape, but over time more components have been added to make it one of the most sophisticated water quality models in existence (Linker et al. 2002; Shenk and Linker 2013). The model includes a watershed model, an estuarine model, an airshed model, and multiple other models and tools that help to manage the data and simulate watershed processes. Together, these components are known as the Chesapeake Bay Modeling System (CBMS). It serves many informational functions in the CBP including identifying the major sources of nutrient pollution on the watershed, setting nutrient reduction goals, allotting nutrient reductions to the various jurisdictions involved, and evaluating progress towards the management goals (CBP 2010). These roles have become especially important since 2010 due to the establishment of a total maximum daily load (TMDL) nutrient pollution diet for the entire watershed (CBP 2010).

However, I argue that these are not the only roles that the CBMS plays in the CBP's watershed management process. It also serves many roles in the process of building and maintaining the CBP's partnership structure and organizing the efforts of the disparate institutional actors towards a common set of management goals. Understanding these roles is essential to future modeling and management projects.

Methods

The goal of this project was to use ethnographic methods to investigate the ways that computational models are used in the environmental management process. The research covered three years starting in 2014 and ending in 2016. The preponderance of data was collected in 2015, which was the "build year" for the Phase 6 version of the CBMS. The methods utilized consisted of participant-observation and semi-structured key informant interviews (Bernard 2006). These methods have enabled me to develop a first-hand understanding of the processes and practices involved in building and implementing a computational model for environmental management and provide a rich and detailed understanding of the management conditions in which computational modeling takes place (Whitehead 2005).

I conducted participant observation and semi-structured key informant interviews with environmental modelers and scientists involved in modeling in the Chesapeake Bay watershed. This included working with modelers at the CBP itself to understand the process of modeling within an environmental management institution, but also working with modelers in academic settings. This combination provided me with a substantial amount of data on the process of producing computational environmental models in different circumstances, and enables me to draw some comparisons between the scientific context and the management context.

Participant-observation included spending two weeks each working at the CBP office in Annapolis Maryland with the computational modeling staff and at the University of Maryland Center for Environmental Sciences (UMCES) in Solomons, Maryland. I attended 25 meetings of the CBP's modeling workgroup, modeling team, and other scientific and modeling projects. I also participated in the biannual Chesapeake Environmental Modeling Symposium (CHEMS) in June of 2016, and attended meetings of management staff at the CBP and throughout the watershed. These meetings are the primary focus on my research because they highlight the social interactions involved in the management process and enabled me to understand the various ways that the CBMS is used in these different management contexts.

In addition to participant observation, I conducted twenty-five semi-structured interviews with modelers and other scientists, as well as management staff working on environmental issues in the region. I selected these informants based on their participation in modeling and management in the watershed. I focused particularly on those who could provide a unique perspective on the modeling and management process and the social relationships involved. My questions were designed to elicit information about how computer models are utilized in the management process, and to engage my informants in a broader discussion about the social dynamics of modeling and management. All of the data was transcribed and coded using an inductive coding method, in which key themes were identified from the data themselves (Bernard 2006). In particular, I selected themes that would highlight the intersections of computational modeling and environmental management.

In the following sections, I use the data collected from my research to examine three ethnographic examples that show the different roles that the CBMS plays in the management process beyond the informational role described above. First, I start with the construction of the model itself and the way that it is used to bring together computational modelers and other scientists in the region to work towards understanding the physical processes that affect the watershed and the estuary. Second, I discuss the way that the CBP staff uses the model to organize the various institutions that make up the partnership and keep them oriented towards a common set of management goals. Finally, I look at the role that the model plays in local-level decision-making and prioritizing certain kinds of landscape modification. In this sense, it helps to organize the effort of local management towards the watershed goals. All of these are important roles for the model in the watershed, and help to contribute to the management process in more than simply an informational way.

Assembling the Watershed

It is June 2016, and I am at the CBP office in Annapolis in the room that houses the modeling team. I sit in a cubicle recently left open by a team member who has moved on to another job. For the most part it is quiet except for the sound of tapping on keyboards and the click of computer mice. It is a claustrophobic space with little in the way of adornment. I learn later that the headaches that grow on me throughout the day – which I have attributed to staring at a computer screen for hours on end – might be the result of a high concentration of CO2 in the office air due to a lack of air circulation. One of the team members keeps a CO2 monitor on his desk to track it throughout the day. In such close quarters, there is very little privacy even with the cubicles, and every phone conversation or visit from an outsider is a matter of public knowledge. Allan sometimes calls it "the monastery."

In the cubicles around me, there are people from several different institutions: the Environmental Protection Agency (EPA), the US Geological Survey (USGS), University of Pennsylvania (UPenn), and Johns Hopkins University (JHU). They are here to work on developing the next generation of the CBMS watershed model, a Phase 6 that will allow them to carry out the 2017 and 2018 mid-point assessment. They are the core of the modeling team at the CBP, but they are not the only ones working on the model. I know there is another group of modelers across from this room who work on the Scenario Builder. Far away at the US Army Corps Engineer Research and Development Center office in Mississippi, I know that Don[3] and his team are also working on the estuary modeling. I know, too, that there are many academics at the University of Maryland Center for Environmental Studies

[3] I have changed the names of my informants to protect their identities

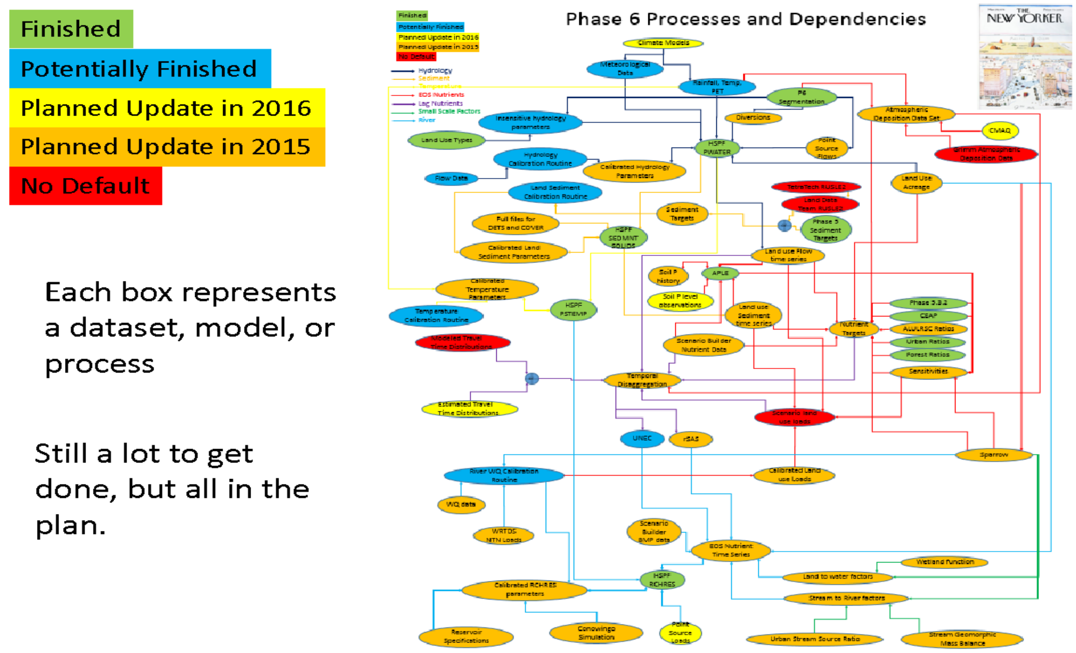
(UMCES), UPenn, JHU, and the Virginia Institute of Marine Sciences (VIMS) who are also working on components that may eventually make their way into the finished model.

Much of the work of the CBP modelers – particularly Allan and Stephen – involves assembling all of these components together: figuring out what features the model will need, finding people to work on the code, tracking down data sources for calibration and validation, and, ultimately, making sure that everything fits together. This generally means spending a lot of time on phone calls and in meetings. I have attended some of the meetings, phoned in to the conference calls and observed the labor of assembling all of these pieces together. The following is a composite description of several of the meetings that I have attended. It illustrates the way that people from a variety of institutions work together to assemble the pieces that make up the model.

The quarterly meetings of the modeling workgroup take place in a room with a large wall-length window overlooking the Severn River, a tributary to the Chesapeake Bay. A large table takes up most of the room, but a podium and presentation screen occupy one end and several chairs line the outer wall. The room is in a small building known at the CBP as the “Fish Shack,” which sits at the edge of a dock in the parking lot of the office building that houses the CBP. Several boats rock listlessly by the docks outside. The meeting is led by representatives, Charles and Matt, from two of the watershed states who introduce the program and attempt, but often fail, to keep all of the presentations on schedule. Stephen and Allan are at the meetings as are most of the members of the CBP modeling team. The rest of the attendance varies each time, but often there are academic partners, federal and state agency staff, and staff from private firms. All have an interest in or play an active role in the work of building the model.

The meetings usually take two days. The first is generally devoted to the watershed modeling and the second to the estuary model, with other aspects of the model coming up as necessary. Stephen often gives the first presentation of the day to update everyone on the status of the watershed model. Frequently, his presentation opens with the slide shown in Figure 6.1. It is an illustration of the many different "processes and dependencies" of the watershed model, color-coded to show the status of each piece. It strikes me not only how many different processes and components go into the model, but also that each of these ovals represents someone doing work to produce some component of the model. This might mean working directly on the model itself, devising new modeling methods, conducting research that will help inform the models, or assembling data that will contribute to the model calibration or validation. As the image illustrates, it is a remarkable amount of collaboration and effort, but Stephen and the modeling team seem to manage it well.

Figure 6.1: Processes and Dependencies of the Phase 6 Watershed Model -



After Stephen gives his presentation, others stand up to present their own contributions to the work of modeling. One agenda from a meeting that I attended included: a discussion of model calibration, recommendations on the simulation of climate change and sea level rise, an approach to evaluate ammonia emissions for atmospheric deposition, and concerns about how the model represents best management practices. These meetings help to organize the work of modeling, ensuring that all of the necessary parts are on track and that everything will eventually fit together.

In this context, the model must be assembled from various constituent parts: bits of code, and data representing the structure of the landscape and the physical processes on the watershed. Assembling the model in this way organizes various scientists and modelers dispersed among many different institutions in the partnership. Together they work to build the model, and in the process, contribute their research, ideas, and effort to the process of understanding the estuary and its watershed for the purpose of management. However, organizing scientists and modelers is not the only function that models can play in the watershed management process. The data that they produce also allow the CBP to organize the various state, local, and federal agencies in the partnership and ensure that everyone is working towards the same management goals. These processes are discussed in the following section.

Maintaining the Watershed

I am now in a large banquet room in the Doubletree Hotel in Williamsburg, Virginia. Several large circular tables are placed methodically around the room on tiers and set with white tablecloths, pitchers of water, and glasses. At the front of the room is a small stage in front of which is a portable projector screen and a projector on a cart. The room is slightly too large for the quantity of people assembled, and so they sit in clusters around the tables with many empty spaces between them. At the front of the room is Bill, who is giving a talk about the CBP's management process, showing the progress that has been achieved over the years, and explaining what is needed as we continue into the future with the TMDL. He is enthusiastic and optimistic, and the modelers in the audience are listening with interest.

This event took place at the Chesapeake Environmental Modeling Symposium (CHEMS) in June of 2016. Bill was one of the three keynote speakers who gave a talk that morning. He works for the CBP where his job is to oversee the scientific aspects of the management process, but his actual work entails much more than that. He is also partially responsible for communicating the management progress to diverse audiences and getting their feedback, but also convincing them to take part in the process. I have heard Bill give this talk a few times in a few different contexts – to county and state-level management staff, and to the scientific community. The content is always different depending on the audience – for example, with modelers he emphasizes the modeling, while with county-level managers he emphasizes monitoring data – but the form of the talk is almost always the same. It is clear that he has given this talk or similar ones dozens, possibly hundreds of times before, in many different circumstances and to many different audiences.

Bill starts his presentation explaining the progress that has been made towards reducing nutrient pollution in the watershed (always start with something positive) and then moves on to the work that still needs to be done. He talks in circles at times, redirecting (or, perhaps, misdirecting) the audience away from the conflicts and back to the progress and the benefits that will accrue from taking part in the process. He mixes the details with anecdotes about walking into large auditoria full of farmers and trying to convince them to trust the models – these generate knowing laughs. He frequently cracks jokes, often about the people in the room, but just as often about himself, poking fun at his age and consequent inability to fully understand all of the fancy new gadgets, theories, and modeling methods that everyone else seems to know so well. Again, generating laughter from the crowd.

The audience is often skeptical: Is the progress real or is it just an artifact of the modeling? Does it have more to do with success on point sources or is there progress on non-point sources? Why are their management practices not showing up in the model? How much is it all going to cost? How do they convince their farmers to do something that costs them money when they are dumping out loads of milk because the price is too low? Bill's talk becomes a catalyst for all of these concerns and more. He responds by bringing attention back to the progress, he tells another anecdote, or maybe cracks a joke to break the tension. At the end of the talk, there is a palpable sense of hesitant optimism among the group – a sense that maybe it is all actually worthwhile, but that remains to be seen.

Bill's talk is part of the process of holding the watershed management partnership together despite the different interests and goals of the institutions involved. All of the partners have their own interests and priorities that, in many cases, do not coincide with the management goals of the CBP partnership. The states and counties are concerned with management issues outside of the watershed and with priorities that have no effect on the CBP. The nonprofits involved are often driven to endorse more stringent management goals than the CBP. Academic institutions are interested in furthering scientific understanding, but also finding sources of funding and other resources. In order to keep all of these institutions involved in the CBP's management process, the CBP staff must continually remind them of the goals and their role in watershed management.

Without the model, this process of assembling all of these organizations together would be far more difficult. In an interview, Bill explained the importance of modeling for the partnership by comparison with the Gulf of Mexico/Mississippi River watershed. The Gulf of Mexico watershed is much larger than that of the Chesapeake Bay and includes many more jurisdictions. Instead of using a complex watershed model like the CBMS, they have worked with a simpler statistical model.

Bill claims that the lack of a complex model has prevented the Gulf of Mexico Program from getting participation from the various states in the watershed, and points towards the CBP's successes as evidence of the value of computational modeling:

> "The gulf of Mexico has gone for a very simplistic [modeling] approach. Almost like a linear regression model …I said, yeah, …show me where you've convinced the Iowa farmers they need to do it. Yes there's a difference between a 6-state watershed and a 37-state watershed, I agree with that. But… you guys haven't been able to, and you've been doing it since '85, the same as us. …But they said, oh we've gotten away with a simpler [model], but no one's taking responsibility. They have not allocated, they have not gotten the agreement to the levels that we've done. I said, show me where you've got 450 wastewater treatment plants that have gone close to limited technology, or within a reasonable piece of that. I can show you 6, 7 billion dollars worth of investments right here. And I can show you cleaner water!"

It is, of course, debatable whether the Gulf of Mexico watershed is comparable to the Chesapeake Bay watershed, but Bill's statement reflects his perception of the important role that modeling plays in keeping the partnership together. The modeling is not always front-and-center in this process – Bill, for example, likes to downplay the role of the model when talking to stakeholders and county managers – but it is always there in the backs of the minds of many of people involved. It provides the guidance about what needs to be done, and is a point of frustration for many people involved in the process. When it comes up – and it always does – Bill reminds those present that the model is not the "EPA's model," it is a "partnership model." Everyone in the room has had a hand in its construction and/or application – they have provided data, code, feedback, and other resources that have contributed to the modeling process. This does not always allay concerns, but it reminds the people in the audience that they are an important part of the broader management process.

When I talk to state and county-level staff, they do not always speak fondly of the CBMS, as I will discuss in the following section, but they do point to their own advancements as indicated by the model and empirical data. As a result, they feel in part responsible for the progress that has been achieved in the watershed as a whole. The model data help to foster that sense of collaboration and collective effort, and help to further organize management activities and keep them involved in the partnership and working towards the watershed goals. In addition to bringing all of these state, local, and federal partners together and keeping them oriented towards the same management goals, the model also affects on-the-ground decision-making and implementation by helping to prioritize certain efforts over others. This makes it possible to organize the work of altering the landscape in order to achieve the watershed management goals. I discuss this process in the following section.

Making the Watershed

I am sitting in another conference room. This one is very different from the Fish Shack at the CBP office. It is located in Owego, New York in the basement of the Tioga County Sheriff's office. The only two windows are obscured by blinds, and the many tables have been arranged into a large square. The people in attendance are also very different from those who were at the meetings in Annapolis. In some cases, their hands show signs of physical labor, as if they have spent hours outside working with heavy machinery or digging in the dirt. They wear jeans and flannel shirts in place of the slacks and dress shirts I see in Annapolis. They have hats that say "Caterpillar" or "John Deere."

This is the Upper Susquehanna Coalition (USC), a group of county-level management staff from the Southern Tier of New York and a few of the counties in northern Pennsylvania. They gather bi-monthly to discuss the work that they have done to address nutrient pollution, wetland depletion, and other pressing concerns in the watershed. A few of the members give presentations that talk about specific projects. There are some success stories: the initiative that brought in volunteers to plant trees in depleted areas, for example, or the construction of a wetland on a golf course in the northern watershed. There are also some failures like the copse of trees planted on a farmer's land that were trampled by cows who had knocked over a fence.

However, the majority of the labor discussed at these meetings involves obtaining permits for management projects, seeking out and writing grants to fund the projects, and communicating with state and federal agencies about the on-the-ground activities that have been implemented. Most of the discussion is very tedious and bureaucratic – it pains me to listen to the litany of red tape that must be managed on a day-to-day basis in order to carry out the projects that they want to implement. Is a permit needed to lay gravel on a road if the gravel comes from the same farm? What is the status of reporting on stream restoration efforts to the state? Can funds from this grant be used for a grazing workshop? And so on. All of these bureaucratic procedures direct their efforts in particular ways - steering them away from those that are too difficult or cost-prohibitive, and towards easier, cheaper, and more effective management practices.

When the CBMS comes up, it is usually to voice frustration over the way that certain management practices are represented. In some cases, they feel that the model inaccurately represents the landscape – too many cows, more beef cows than dairy cows, the amount of manure applied to certain land uses, the amount of phosphorous being applied to the land, projections for population change, and so on. These factors all affect the estimated nutrient loads in the model, which, in many cases, means more work for them to reduce those loads. In other cases, these inaccuracies potentially work in their favor and there are discussions about whether to "game the model" in order to get better results, but, in the end, they agree that it is better for them and for their relationship with the CBP to provide accurate data to improve the model.

Speaking with the members separately, they tell me repeatedly that they simply want to do the work of implementing projects. But in order to do so, they first have to navigate all of the permits, regulations, and funding, and the computer model simply adds another obstacle that must be navigated.

In order to comply with the TMDL, for example, they have to get credit for the work that they do in the model. An example one of my informants described to me was work on stormwater, which is one of the major concerns in the watershed, aside from agriculture. Large flows of water that result from storms can cause erosion and accelerate the flow of nutrients towards the estuary. Furthermore, the additional water can overload wastewater treatment systems causing overflows of sewage into the waterways. This problem is exacerbated when there are a large amount of impervious surfaces in an area such as roads, buildings, and parking lots. These prevent the water from being absorbed into the ground, which would slow the flow of water into the rivers and streams. The USC has made significant progress on reducing stormwater in the region by constructing and restoring wetlands, improving road ditches, and other projects. However, it is the responsibility of the state to report these activities to the CBP. The USC argued that their progress in this area was not being accounted for in the model because the New York State Department of Environmental Conservation (DEC) was not submitting the information to the CBP. As a result, they have been trying to work with DEC to get accurate data to send to the CBP. These negotiations would not be necessary if not for the model and the TMDL process.

Another informant discussed the trouble she and her staff had keeping up with different best management practice (BMP) definitions and their load reductions. She explained to me that the CBP had changed the definitions of several of the BMPs over the years, and each time they have to learn the new definitions, determine how it affects their existing loads according to the model, and finally, change their work on the ground to fit the new BMP definitions. All of the work they do to keep up with the changes to the model, get credit for their on-the-ground work, and verify existing

BMPs could be an additional job in her office, but they are already understaffed and underfunded.

One of the county management people I spoke with expressed this frustration explaining that he would rather work on projects that have a direct impact on the economic and environmental sustainability of farms in his county like covered barnyards and educating farmers about grazing practices:

> "I think it's always difficult when we try to figure out what work we're going to do and how it's going to impact the model… you know the scenario builder, I have not gotten into all of that. I don't have time to learn it, I just want to do work, do my covered barnyards, do my grazing work."

Later I asked him if there was any way that the model helped his work. He responded that being part of a TMDL helped to make them more competitive for grants, but then turned the question back on me:

> "I don't know it's hard, I think it's a tough question to answer yes or no, I just think it's there, it's something that we look at, and you know, to think about it in the grand scheme, how would it help us? How would the bay model really help us, and … could you think of a way that the bay model would actually help us?"

I responded that it might help them to identify priority projects, but he responded that they already had those tools in place before the model. He said,

"…[A]ll the model has done … is given us headaches, but not migraines." However, immediately following that, he told me that the model has made them focus more heavily on stream buffers, which are forested areas between the streams and farmlands that help to reduce nutrient runoff from the farms. This means working on restoring existing buffers that have been depleted, but also means working with farmers to rebuild buffers that have been destroyed and replaced with cropland. He explained:

> "They were trained for years to cut the trees down, and plant right up to the edge of the stream. And now we're saying 'No, no, no we need the woods back, we need fifty feet or whatever… that's definitely been driven by the bay program model."

In this situation, the model is largely a constraint on their labor, similar to t the permitting processes and the search for funding for projects. It pulls their effort in certain directions and pushes back in other directions. It determines what kinds of work are useful and beneficial and which projects are easier or more difficult – and perhaps not worth the effort. Instead of putting time and work into building farm storage, the model says to direct it towards restoring buffers, for example. It is a continual point of frustration for the management staff at this level. They would prefer to simply go about their work than have to deal with the model, but in helping them to identify priorities and cost-effective management practices it aligns their effort with the watershed management goals.

Conclusions

In this article, I have examined the multiple roles that computational models play in the socioecological process of environmental management. Typically, models are recognized as informational tools that can help identify goals and track progress, but I argue that they play other roles as well. I started by discussing some of the literature that shows how models play more than an informational role in our relationship to environmental concerns. This literature suggests that they can play an important part in the development of "knowledge infrastructures" that help to inform our understanding of and relationship to ecological systems (Edwards 2010), and they can play a role in institutional learning processes beyond the informational content that they provide (Landström et al. 2013). These roles are significant, but still focus primarily on the knowledge that models provide. I argue that models can also be seen to play an important role in helping to build and maintain the social and institutional relationships that enable collective management of natural resources (Ostrom 1990).

In order to illustrate the various roles that computational modeling plays in building and maintaining socioecological relationships, I drew from ethnographic research with the Chesapeake Bay watershed socioecological system. The Chesapeake Bay watershed has, over the last few decades, been the subject of a watershed-scale effort to reduce the nutrient pollution entering the Chesapeake Bay. This has led to the creation of the CBP, a partnership of the federal government, the seven watershed jurisdictions, and several additional organizations. In order to inform and track watershed management goals, the CBP has also created a watershed-scale computational model known as the CBMS. However, in addition to its informational role, I argue that the CBMS also helps to organize the partnership and orient all of the disparate partners towards a common set of management goals.

I then provided three examples of how the CBMS helps to organize the partnership's social and institutional relationships. First, I described the process of constructing the CBMS with the participation of various scientists and modelers in the CBP partnership. The model must be assembled from various pieces of data and code. By including the partnership scientists in the process of assembling the model, it helps to organize their effort towards the scientific and technical needs of the CBP watershed. Second, I examined process of communicating progress and keeping the various partners on track towards the management goals. This involves sharing model results and empirical data that demonstrate the progress that has been made as well as the work that remains to be done. Although the CBMS remains a point of contention in the watershed, providing this information and reminding the partners that they have participated in providing data and other resources for the model makes them feel part of the process and part of the progress that has been made in the watershed. Finally, I described the role that modeling plays in organizing activity on-the-ground at the county level. The county management staff I spoke with were frustrated by the model because it seems to simply add to their already large, bureaucratic burden. They would rather be doing work that has a direct impact on the landscape and the farms in the region rather than navigating the modeling tools. However, the model does ultimately help them to determine priority management practices and obtain funding to implement them. They may not appreciate the additional burden, but the model helps to direct their effort towards watershed management goals.

These examples show that computer models can play many roles within the socioecological context of environmental management beyond their informational role. It is their ability to serve these many different roles that makes computational models an effective tool for organizing collective environmental management. Models not only provide informational guidance for management, they also contribute to the organization of the social relationships and activities that make management possible. Evaluating whether the CBP management process is effective is not within the scope of this research. However, it is arguable, given these findings, that without the CBMS and other models, the watershed partnership and the management process would not be possible. Furthermore, this research suggests that other approaches to modeling, such as collaborative modeling methods, could contribute to alternative management processes by fostering new forms of partnership and implementation. These are all areas for future research.

Chapter 7: Conclusion

This dissertation has attempted to answer the question, "What is the role of computational models within the broader socioecological contexts in which they are produced and used?" drawing upon ethnographic research with computational modelers and management staff in the Chesapeake Bay watershed. In order to answer this overarching question, I have pursued three sub-questions:

1. How are modeling practices affected by the environmental management institutions in which they take place?
2. How are the models themselves affected by the environmental management institutions in which they take place?
3. How are the social relationships that constitute environmental management institutions affected by the production and use of computational environmental models?

Although these may not be exhaustive of the ways that computational models affect and are affected by their socioecological contexts, addressing these questions has helped to advance our understanding of these processes, and, hopefully, will be useful for informing future research and future computational modeling and management projects. In this conclusion, I provide a brief summary of the findings presented in this dissertation, offer some broader conclusions that help to inform the field of environmental anthropology, suggest some ways that computational modelers and environmental management staff might find this research useful, and propose additional research that would help to elaborate some of the findings and conclusions in this dissertation.

Dissertation Summary

Each of the research sub-questions was addressed separately in one of the three chapters written as articles for publication in a peer-reviewed journal. The first article addressed the question, "How are modeling practices affected by the environmental management institutions in which they take place?" I found that computational modelers within environmental management institutions must learn to navigate organizational needs, rules, and incentives. First, in order to meet the scientific needs of the CBP, the modelers must be able to assemble and organize a community of scientists and modelers to provide data and other resources, as well as review of the model and its components. This not only helps to provide the scientific knowledge and expertise required to develop the CBMS, but also gives the model a degree of "believability" or credibility, which extends beyond its scientific validity. This credibility legitimizes the CBP's management activities and fosters support for the model from the scientific community.

Second, accessing data within an environmental management institution like the CBP presents a number of challenges including the rules for sharing data across institutional boundaries. In order to work around these rules, the modelers have found ways to negotiate data-sharing pipelines that make use of the network of partnerships that make up the CBP. Third, modelers must often collaborate with other researchers in other government agencies and academic institutions. However, doing so can be challenging because of the different incentives and requirements by which individuals in these organizations must operate. As a management organization, the CBP requires timely access to information and resources. But in order to meet their needs, individuals in research organizations must achieve basic scientific requirements such as peer-review. The modelers at the CBP, as a result, must work with these researchers in order to manage timelines to get the necessary information, and also help to incentivize specific kinds of research by contributing to publications and obtaining funding. This, in turn, helps to build further relationships with the scientific community, which augments the CBP's management process. Altogether, these practices demonstrate that computational modeling is more than simply a scientific or computational process, it is also a social process that is shaped by the institutions in which it takes place. As a result, management modelers must have a different set of social skills and knowledge than scientific modelers.

In the second article, I addressed the question, "How are the models themselves affected by the environmental management institutions in which they take place?" In order to do this, I examined two contexts for modeling within the watershed: the scientific context in which models are constructed primarily to understand ecological processes, and the management context in which they are used as tools for decision-making processes. In the scientific context, I found that computational models are part of a continual feedback with empirical data and other models. The goal of this feedback is to understand more about the processes that take place within ecological systems - models help us to understand these processes, but also show us the areas where our understanding is lacking. This augments the existing curiosity and interest in the nuances of ecological systems. On the other hand, the management context was focused on getting "the biggest bang for our buck" – the most nutrient load reductions for the lowest cost. This is because management staff are primarily concerned with achieving their management goals, and so they do not have time to fully engage with the modeling in the way that scientists do. As a result, the models themselves – even those that emerge from a more scientific context – can be reduced in size and complexity. Management models tend to only represent the environmental processes that are relevant to the management process. This further augments the cost-benefit analysis process of management decision-making. Altogether, this suggests that models take on different forms in different social contexts and can end up reinforcing specific conceptions of ecological systems.

The third article addressed the question, "How are the social relationships that constitute environmental management institutions affected by the production and use of computational environmental models?" I offer three examples of ways that computational models are used in environmental management organizations like the CBP in addition to their informative roles. First, models must be constructed, and this process involves organizing environmental scientists and modelers to contribute data, code, methods, and other resources to the model. Doing so helps to bring together the scientific community to work towards understanding the ecological processes that are affected by management. Second, models and the data that they produce are used to organize the institutional partnerships involved in the management process by keeping everyone on track and by reminding them that they are part of the process in terms of providing data. Third, the models are used by local environmental management staff to prioritize certain projects and guide their efforts on the landscape. This helps to orient their work on the landscape towards watershed management goals. Altogether, this suggests that models play many roles within environmental management institutions beyond their informational capacities, and can shape the management process in many ways. It is this capacity to take on different roles that makes them useful to the environmental management institutions in which they are used.

Broader conclusions

This research makes contributions to the field of environmental anthropology and our broader understanding of human-environment interactions and to the body of research on the social dimensions of computational environmental modeling. In particular, it helps to understand the role that science and technology play in socioecological contexts like the Chesapeake Bay watershed. More specifically, it addresses this question within the context of environmental management institutions.

Most fundamentally, this research suggests that computational environmental modeling, whether it is used to understand or manage environmental systems, cannot be easily separated from the social contexts in which it takes place. This affirms earlier research that underscores the social dimensions of science in general and of computational environmental modeling in particular. For example, as Shackley (2001) and Sundberg (2009) point out, the complexity of models is influenced by a number of social factors including the needs of management versus those of scientific research. Additionally it reinforces research that suggests that the *processes* of constructing and implementing models is shaped by social factors including the types of scientific processes in which models are used (Landström et al. 2013).

However, this research elaborates on these studies by investigating computational environmental modeling specifically within a management context. Given that management institutions are essential components of our relationship to ecological systems (Ostrom 1990), and computational models play an increasingly important role within them (NRC 2007), understanding how models both affect and are affected by these management contexts is an important area of inquiry for an environmental anthropology concerned with human-environment interactions.

We tend to think of computational modeling as simply a representational process – simulating environmental systems and processes in order to stand in for them (Knuutilla 2006). This impression suggests that the primary skillset of modeling is scientific and computational – that is, using computers to describe and predict environmental systems and processes. However, this research shows that modeling practices are, in many ways, mediated by their social contexts. In particular, management modelers must not only represent the systems accurately, they must also meet the needs of the management institutions in which they work. This means that they must be able to navigate the organizational structures of management in order to access data and other resources necessary for constructing a computational model, but also for building relationships between organizations and with the broader scientific community in order to legitimize and reinforce the management process. As a result, modeling must be seen within not only within the context of a scientific and technical interaction with the environment, but as a socioecological process of navigating both environmental and social contexts.

Modeling as a general practice – the construction of simplified representations of complex systems whether through computation or other means – is an important part of our shared understanding of ecological systems and processes (Paolisso 2002, 2010). This research also augments this area of study by investigating the ways that social processes mediate our models of the environment and the ways that science and technology can shape our understanding as well. My findings suggest that computational models take on different characteristics depending on the social context in which they are produced and used. In that sense, they often reflect the conceptual understanding of the people involved. Scientific modelers recognize the limits of our understanding of ecological systems and use models as tools to plumb deeper to learn more about the processes that shape the landscape. Their models tend to be more complex, as a result. Management staff, on the other hand, are focused on the costs and benefits of certain management practices in order to meet their goals in a cost-effective way. Management models, as a result, tend to be less complex and more focused on the specific processes involved in management. In that sense, models might augment and reinforce these conceptions of ecological systems - promoting a more nuanced and complex understanding among scientists, and a more cost-benefit understanding among management staff.

Finally, computational models are not only informational tools that allow us to understand and manage complex ecological systems. They are also "artifacts" (Knuutilla 2011) that play a role in shaping our relationships to those systems through our interactions with them. This research has focused on the context of environmental management institutions and how models are used, not only to inform management processes, but to build and maintain the relationships that underlie these institutions. By using computational models as tools to assemble different actors and activities, the modelers and management are able to orient their efforts towards a common set of management goals. Without these aspects of modeling, it is possible that large-scale management, like that which takes place in the Chesapeake Bay watershed, would not be possible.

Altogether, this suggests that further ethnographic research on computational environmental modeling and environmental management institutions is warranted. Ethnography can highlight the social dimensions of computational environmental modeling, and illuminate the nuances of their role in mediating the socioecological process of environmental management. Furthermore, interdisciplinary research with computational modelers and other natural scientists would allow for greater coordination between social scientists, natural scientists, and environmental managers. The result could be more effective modeling and management approaches and a better understanding of human-environment interactions.

Applied Outcomes

In addition to informing the field of environmental anthropology, this research will help computational modelers, scientists, and environmental management staff to understand how the production and use of computational models affects the social relationships that contribute to environmental management. This information will help these groups to more effectively plan the implementation of computational environmental models and address issues with modeling and management as they arise.

This research can help modelers think about ways to navigate institutional constraints to accessing data and other resources. For example, it shows that having a robust network of organizational connects can help negotiate access to data that would otherwise be inaccessible. This kind of information might be useful for existing modeling and management projects that struggle with assembling information as well as for new projects that must think through various possible strategies for implementation. Starting to build those organizational connections early will help them to avoid complicated and challenging negotiation processes. This might, for example, mean engaging in collaborative methods that include a wide array of modeling, management, and research participants. Incorporating a diverse array of partners will help by providing connections that can be used to transmit data and other resources across institutional boundaries.

In addition, this research can help modelers and management staff reflect on the ways that models might reinforce certain perspectives or conceptions of environmental systems and problems. Both a nuanced view of ecological processes and a straightforward cost-benefit analysis can be useful at times, but it is important not to be constrained to one or the other. Breaking out of these conceptions might require developing multiple models that simulate the processes in different ways, or engaging in participatory or collaborative modeling projects that include participants who understand the systems and processes differently. However it is done, it is important for modelers and management staff to plan ahead and think about new ways to incorporate a broader understanding and generate alternate perspectives. This will help not only to make better models, but also to come up with different approaches to management that do not fit the traditional regulatory framework.

Another way this research could help modelers and management staff is by allowing them to think about the kinds of social relationships that are necessary in order to carry out their management practices, and consider the ways that models could be used to build and maintain those relationships and organize collective effort towards management goals. The scale of a management project may not be as large as the Chesapeake Bay watershed, and might not incorporate as wide a range of organizational partners as the CBP partnership, but they will always encounter different people and organizations with conflicting interests. By incorporating more of these individuals and organizations in the modeling process, it is possible to foster more collective effort and agreement about management goals and practices. Again, this might include using collaborative modeling methods or other approaches that involve people more directly in the process.

Finally, this research can help modelers and environmental management staff think about how modeling affects the management institutions in which it takes place. If models affect our understanding of environmental systems, are shaped by the social contexts in which they take place, and in turn shape social relationships involved in science and management, then it is important to take all of these effects into consideration when developing a computational model for management purposes. It is important to consider what kind of management process is necessary for addressing the particular problems at hand, and decide whether different approaches to modeling might be more effective at fostering the kinds of social relationships and ecological knowledge that would be necessary for carrying out the goals of the project. For example, participatory or collaborative modeling methods might be more conducive to implementing collaborative management, whereas more technical and specialized approaches could be best for regulatory management.

Within the Chesapeake Bay watershed itself, the research in this dissertation augments prior calls from the scientific community to implement multiple models and participatory modeling approaches. A multiple models approach, which is already underway to a limited degree, could foster multiple perspectives on the Chesapeake Bay and potentially help to generate new management approaches. Similarly, using a collaborative approach in which a diverse array of stakeholders are involved in the process of developing and implementing a computational model, perhaps on smaller scales, could allow for more exchange of ideas and information between different groups. Finally, integrating a more ethnographic approach to the use of models and the implementation of management practices could provide a necessary social perspective that would help track the ways that human-environment interactions are mediated by computational environmental models.

Alternative Modeling and Management Practices

The applied outcomes described above suggest a number of ways that watershed management and modeling might be done differently in the Chesapeake Bay region. Briefly, I would like to comment on some potential scenarios drawing from my ethnographic research to discuss how conditions might change and what resources might be necessary in order for these alternatives to be implemented.

First, the prospect of participatory and collaborative approaches to computational modeling has been suggested not only in this dissertation, but in a broad body of literature (cf. Gray et al. 2016). These approaches come with a number of benefits as well as challenges that will often vary depending on the specific conditions in which the collaboration takes place (Paolisso and Trombley 2016). My research suggests that collaborative approaches cannot be thought of as techniques for convincing recalcitrant participants of the value of management efforts – in other words, as communication efforts. This would deny the social conditions of computational modeling and the ways that modeling and models affect and are affected by their social contexts. Those involved in such projects should expect the models, the process of modeling, and the management process to change as a result of the collaborative approach.

It is important to remember that collaboration has different meanings in different contexts, and, in some sense, the CBP's modeling and management approach could be considered collaborative since it involves all of the various partners, including industry representatives such as the American Farm Bureau. However, many scholars of collaborative methods would argue that collaboration necessarily entails including members of the public directly in the process rather than relying on representatives (Callon 1999). This, of course, poses a challenge in a watershed of this scale with approximately 18 million people from a diversity of different backgrounds. However, multiple smaller-scale modeling projects throughout the watershed might be more feasible, and could foster social relationships that would contribute to a more polycentric approach to management (Ostrom 2010).

I would also suggest, given the tendency for models to reinforce existing socioecological relationships as described in chapter five, that collaborative modeling efforts should not be exclusively or even primarily oriented towards building practical tools for decision-making. Rather, a significant part of their agenda ought to be engaging in a scientific process using computational modeling as a mediator to develop a more nuanced and detailed understanding of the ecological system and the processes that shape it. This would help to foster a diversity of perspectives on the problem and generate novel solutions to address it.

Another area that has been explored in modeling is the incorporation of "human dimensions" into the models themselves. This would require simulating human behavior, which is a practice that has garnered a great deal of critique among anthropologists (Helmreich 2000). My research reinforces the idea that there is a risk in this form of modeling of reducing human behavior to economistic decision-making rather than appreciating the complexity of choices and the structural elements of human behavior. However, this does not mean that modeling of human behavior should be rejected entirely. A modeling approach that engages with a scientific feedback process could benefit our understanding of these activities and also provide decision-makers with a more nuanced appreciation for human behavior. For this reason, I suggest that incorporating an ethnographic approach into the modeling process would be beneficial because it would provide the detailed account of human-environment interactions that would form the basis for the feedback.

In addition to enabling a greater appreciation for human-environment interactions, an ethnographic approach would also provide a necessary reflexive component to environmental modeling and management projects. As the present research demonstrates, there are significant social causes and effects involved in the process of computational modeling and environmental management. Incorporating ethnographic methods early in the process would help to define some of the social dimensions of modeling and management from the start. Over the course of the project, ethnographic research would provide necessary feedback to help evaluate the process over the long-term. This seems to be a rich area for environmental anthropology as computational modeling becomes increasingly common and essential to the management process.

In addition to collaborative modeling and incorporating ethnographic approaches to modeling and management, it is also important to consider the effects of industry research in environmental management and decision-making. This has already been observed in the case of climate change where the fossil fuel industry has sponsored research that refutes the scientific consensus. It can also been observed in the Chesapeake Bay watershed, where the agriculture industry is attempting to push back on the science of nutrient pollution. The primary example is a case mentioned in Chapter four in which the Agriculture Nutrient Policy Council (ANPC) hired a private firm, Limnotech, to conduct an evaluation of the CBMS through a comparison with the USDA's nutrient model. Limnotech found significant differences between the two models and called for an evaluation of the CBMS (Limnotech 2010). This was shortly after the TMDL had been put in place and threatened to disrupt the management process. The CBP STAC reviewed the results of the Limnotech study and found that the differences between the two models were within the expected range (CBP STAC 2011). This challenge to the CBMS was a politically motivated attack on science in order to upend a management process. These types of attacks are becoming increasingly common, and modelers and management staff must be ready to confront them as they arise. My research suggests that building a robust community of scientists, modelers, management staff, and members of the public helps to reinforce the modeling and management process in order to withstand such attacks. As a result, it benefits the management process to treat computational modeling as a social practice rather than simply considering it as a scientific practice distinct from social and political concerns.

Further Research

There are a number of areas for further research that could expand upon the findings in this dissertation. In particular, further comparative studies would provide a better understanding about how the factors described affect other kinds of modeling and management projects. For example, delving deeper into modeling and management in the Chesapeake watershed might help to shed light on the role of different "data cultures" (Shackley 1999). The present research focused on dominant modes of computational modeling in the watershed, but there are potentially other heterodox approaches that are not captured within the context of the CBP's modeling approach. If such data cultures exist within the watershed, it would be useful to understand the social relationships that lend legitimacy to one approach over another and the different social dynamics that underlie these approaches. Using a comparative approach to examine the different modeling cultures across watersheds – for example, the statistical modeling approach in the Gulf of Mexico watershed – would also provide similar insights.

Comparing the Chesapeake Bay watershed with other watershed-scale management projects that either do or do not make use of computational modeling would indicate the extent to which large-scale environmental management depends upon computational modeling for successful management. In addition it would highlight the different ways that institutions at this scale make use of modeling for both informational purposes and for building and maintaining the social relationships that underlie them.

Another potential comparative study could look at alternative modeling approaches in different socioecological contexts. This would help us to understand further how models and management institutions intersect with one another. For example, an ethnographic study of collaborative modeling for environmental management would allow us to understand whether collaborative methods can foster collective action and a shared understanding of environmental problems and management goals. Furthermore, could these alternative modeling approaches encourage different forms of management as well?

Similarly, a comparative study of alternative management processes would help us to understand the different contexts in which modeling could play a role. For example, research on the use of models within common property regimes described by Ostrom (1990), would help to understand whether modeling could play an effective role in these approaches to addressing environmental challenges. Can models be useful for more collaborative and bottom-up approaches or do they tend to lead to more technical and top-down management approaches regardless of the method of their production?

Another question that can be explored is the ways in which computational models affect our understanding of ecological systems in different social contexts. The research in this dissertation suggests that models can reflect differing socially contextual understandings, and I have suggested that this might reinforce these already existing conceptions. However, additional research could examine the extent to which models shape our conceptions by looking at different models and modeling approaches, examining the knowledge they represent and examining whether it affects the perceptions of environmental problems for those involved. For example, this research could explore whether incorporating more complexity into the models fosters a more complex understanding of environmental systems compared with simpler modeling tools.

Conclusion

As computational modeling becomes increasingly prevalent in the management process, and as management institutions become increasingly complex and large-scale, understanding the interactions between the two will be an important area of inquiry for environmental anthropology – helping to further our understanding of human-environment interactions. This research provides many new insights into the role of computational models in the management contexts in which they are produced and used. It illustrates the ways that computational environmental models and modeling practices are affected by the process of management, and offers some insight into the ways that models, in turn, affect the management institutions in which they are produced and used. However, there is still considerable research to be done in this area. Hopefully, further study will not only help to elaborate our understanding of human-environment interactions, but will also provide information and resources for computational modelers and environmental management staff to improve both modeling and management practices in the future.

I suggest that the CBP and the CBMS have a reciprocal relationship. The CBP depends upon the CBMS to inform the modeling process and keep the partnership working towards the same set of management goals. On the other hand, the CBMS depends upon the CBP partnership for the data, code and other resources that constitute it. Ultimately, it is through this symbiotic relationship that the Chesapeake watershed socioecological system is organized and maintained. Without these two components, the watershed would continue to be largely a function of external forces, but together they help to channel the effort and interest of a heterogeneous assemblage of individuals and institutions towards a common set of management goals (Ostrom 1990). Understanding how this takes place, as well as the benefits and pitfalls of the CBP's management approach, is important if we are to continue to develop similar collaborative environmental management processes in the future.

Appendices

Appendix 1: List of Key Informant Affiliations

Affiliation	Title	Expertise
CBP (USGS)	Hydrologist (Modeler)	Develops CBMS watershed model
CBP (EPA)	Modeling Coordinator (Modeler)	Engineer
CBP (EPA)	WIP Specialist	Coordinates implementation plans with states and counties
CBP (EPA)	CBP Director	Oversees the CBP's day-to-day operations
CBP (EPA)	Associate Director for Partnership and Accountability	Manages partnership relations and governance at the CBP
CBP (EPA)	Associate Director for Science, Analysis and Information	Manages relationships with scientific community at CBP
US ACE	Hydrologist (Modeler)	Develops CBMS estuary model
VIMS	Associate Prof. Marine Science (Modeler)	Coastal systems ecologist
UMCES Solomons Island	Associate Professor, Chesapeake Biological Laboratory (Modeler)	Estuarine ecologist
UMCES Horn Point	Professor, Horn Point Laboratory (Modeler)	Biological oceanographer
CRC (retired)	Former CRC Director	Oceanographer
CRC (JHU)	Professor Current CRC Director (Modeler)	Environmental Engineering

UMCES Solomons Island	Assisstant Professor, Chesapeake Biological Laboratory (Modeler)	Coastal Marine Ecology
UMCES Solomons Island	Professor, Chesapeake Biological Laboratory	Estuarine Ecologist
Devereux Consulting	Devereux Consulting (Modeler)	Developed Scenario Builder, CAST, MAST, VAST, BayFAST
JHU	Assistant Professor (Modeler)	Environmental Engineering
VT	Professor, (Modeler)	Hydrologist
Coastal Bays Program	Chairman, Coastal Advisory Fishery Committee	County-level management
Tioga County S&W (USC)	Director	Natural resource management
Broome County S&W (USC)	Executive Director	Natural resource management
NY DEP	Former Chesapeake Bay coordinator	Engineer
WV DEP	Technical Analyst	Co-Chair of CBP modeling working group, engineer
MDE	Acting Director, Water Management Administration	Co-Chair of CBP modeling working group
VA DEQ	Chesapeake Bay program manager	Chair of CBP water quality goal implementation team
PA DEP	Chesapeake Bay coordinator	Natural resource management

Appendix 2: Semi-Structured Interview Instrument

1) Tell me about your background and how you came to work at ____ .
2) Tell me about how you use computational models in your work.
3) What are some of the benefits of using computational models for environmental science and management?
4) What are some of the drawbacks of using computational models for environmental science and management?
5) How does your work coincide with the CBP management process, if at all?
6) How has your work been affected by the recent TMDL process?
7) How have you made use of or contributed to the CBMS?
8) Tell me about your perspective on the CBP management process.
9) Tell me about your perspective on the CBMS.
10) What do you think environmental management would be like without computational models?
11) Is there anything else you would like to mention that might be relevant to my research?

Appendix 3: Informed Consent Form

Project Title	**Comparing Computational Environmental Modeling Practices**
Purpose of the Study	*This research is being conducted by Michael Paolisso and Jeremy Trombley at the University of Maryland, College Park. We are inviting you to participate in this research project because you are involved in the production or use of computational models or are affected by model-informed policies within the Chesapeake Bay Region. The purpose of this research project is to understand the effects of computational modeling on the social and environmental systems within the Chesapeake Bay Region, and evaluate different methods of modeling in the region.*
Procedures	The procedures involve semi-structured interviews, participant observation, a survey, and a collaborative modeling project. The research will take place in various sites around the Chesapeake Bay Region.
Potential Risks and Discomforts	*There are no known risks associated with participating in this research project*
Potential Benefits	*The benefits to you include compensation for travel and time as a participant in the collaborative modeling project. We hope that, in the future, other people might benefit from this study through improved understanding of the role and effects of computational modeling for environmental management. We hope that this will inform improved modeling practices.*
Confidentiality	*Any potential loss of confidentiality will be minimized by storing data on an encrypted, password protected hard disk accessible to only the researcher and research assistant.* If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.
Compensation	*If you choose to participate in the collaborative modeling project, you will receive $20. You will be responsible for any taxes assessed on the compensation.*

	☐ *Check here if you expect to earn $600 or more as a research participant in UMCP studies in this calendar year. You must provide your name, address and SSN to receive compensation.* ☐ *Check here if you do not expect to earn $600 or more as a research participant in UMCP studies in this calendar year. Your name, address, and SSN will not be collected to receive compensation.*
Right to Withdraw and Questions	Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator: **Michael Paolisso, PhD** 0131 Woods hall College Park, MD 20742 (301) 405-1433 mpaoliss@umd.edu **Jeremy Trombley, MAA** 1111 Woods Hall College Park, MD 20742 jmtrombley@gmail.com
Participant Rights	If you have questions about your rights as a research participant or wish to report a research-related injury, please contact: **University of Maryland College Park** **Institutional Review Board Office** **1204 Marie Mount Hall** **College Park, Maryland, 20742** **E-mail: irb@umd.edu** **Telephone: 301-405-0678**

<table>
<tr><td></td><td colspan="2">This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.</td></tr>
<tr><td>Statement of Consent</td><td colspan="2">Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form.

If you agree to participate, please sign your name below.</td></tr>
<tr><td>Signature and Date</td><td colspan="2">NAME OF PARTICIPANT
[Please Print]</td></tr>
<tr><td rowspan="3">Signature and Date</td><td>SIGNATURE OF PARTICIPANT</td><td></td></tr>
<tr><td>DATE</td><td></td></tr>
<tr><td></td><td></td></tr>
</table>

Bibliography

Agar, Michael H. 1982. "Toward an Ethnographic Language." *American Anthropologist* 84 (4): 779–95.

Anderies, John, and Marco Janssen. 2016. *Sustaining the Commons*. Arizona State University. http://lib.hpu.edu.vn/handle/123456789/21654.

Atran, Scott. 2005. "The Cultural Mind: Environmental Decision Making and Cultural Modeling within and across Populations." *Psychological Review* 112 (4): 744–76.

Bateson, Gregory. 2000. "Ecology and Flexibility in Urban Civilization." In *Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology*, 1st ed., 502–14. University Of Chicago Press.

Beisaw, April M. 2012. "Environmental History of the Susquehanna Valley Around the Time of European Contact." *Pennsylvania History: A Journal of Mid-Atlantic Studies* 79 (4): 366–76.

Bernard, H. Russell. 2006. *Research Methods in Anthropology: Qualitative and Quantitative Approaches*. 4th ed. AltaMira Press.

Black, H. D., C. F. T. Andrus, W. J. Lambert, T. C. Rick, and D. P. Gillikin. 2017. "δ15N Values in Crassostrea Virginica Shells Provides Early Direct Evidence for Nitrogen Loading to Chesapeake Bay." *Scientific Reports* 7 (March).

Bodin, Örjan, Christina Prell, Saudiel Ramirez-Sanchez, and Henrik Ernstson. 2011. "A Social Relational Approach to Natural Resource Governance." In *Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance*, edited by Örjan Bodin and Christina Prell. Cambridge University Press.

Boomer, Kathleen M.B., Donald E. Weller, Thomas E. Jordan, Lewis Linker, Zhi-Jun Liu, James Reilly, Gary Shenk, and Alexey A. Voinov. 2013. "Using Multiple Watershed Models to Predict Water, Nitrogen, and Phosphorus Discharges to the Patuxent Estuary1." *JAWRA Journal of the American Water Resources Association* 49 (1): 15–39.

Box, George E. P. 1976. "Science and Statistics." *Journal of the American Statistical Association* 71 (356): 791–99.

Bruch, Elizabeth, and Jon Atwell. 2015. "Agent-Based Models in Empirical Social Research." *Sociological Methods & Research* 44 (2): 186–221.

Callon, M. 1999. “The Role of Lay People in the Production and Dissemination of Scientific Knowledge.” *Science Technology & Society* 4 (1): 81–94.

Canham, Charles D., Jonathan J. Cole, and William K. Lauenroth, eds. 2003. *Models in Ecosystem Science*. Princeton: Princeton University Press.

Carse, Ashley. 2014. *Beyond the Big Ditch: Politics, Ecology, and Infrastructure at the Panama Canal*. MIT Press.

CBF. 2016. “American Farm Bureau et Al v. EPA - Chesapeake Bay Foundation.” *Chesapeake Bay Foundation*.

CBP. 1983. “1983 Chesapeake Bay Agreement.” Chesapeake Bay Program. http://www.chesapeakebay.net/content/publications/cbp_12512.pdf.

———. 1987. “1987 Chesapeake Bay Agreement.” Chesapeake Bay Program.

———. 2000. “Chesapeake 2000.” Chesapeake Bay Program. http://www.chesapeakebay.net/content/publications/cbp_12081.pdf.

———. 2010. *Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment*. Annapolis MD: Chespeake Bay Program.

———. 2013. “The Conowingo Dam and Chesapeake Bay Water Quality.”

———. 2014. “2014 Chesapeake Bay Agreement.” Chesapeake Bay Program.

———. 2017. “Chesapeake Bay Facts & Figures.” http://www.chesapeakebay.net/discover/bay101/facts.

———. 2017a. “Modeling Workgroup.” Accessed May 24. http://www.chesapeakebay.net/groups/group/modeling_team.

———. 2017b. “Monitoring.” Accessed May 26. http://www.chesapeakebay.net/about/programs/monitoring.

———. 2017c. “Partner Organizations.” Accessed June 2. http://www.chesapeakebay.net/about/partners.

CBP STAC. 2011. “Review of the LimnoTech Report, ‘Comparison of Load Estimates for Cultivated Cropland in the Chesapeake Bay Watershed.’” Edgewater, MD: Chesapeake Bay Program Scientific and Technical Advisory Committee.

Cerco, Carl F. 2016. “Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science.” *Journal of Environmental Quality* 45 (3): 882–886.

CLUI. 1998. “The Chesapeake Bay Hydraulic Model: A Miniaturization of the Largest Estuary in the United States.” Culver City, California.

Cooper, S. R, and G. S Brush. 1993. “A 2,500-Year History of Anoxia and Eutrophication in Chesapeake Bay.” *Estuaries and Coasts* 16 (3): 617–626.

Costelloe-Kuehn, Brandon. 2012. “Environmental Media Systems: Innovations at the U.S. Environmental Protection Agency’s National Exposure Research Laboratory.” Rensselaer Polytechnic Institute.

Crate, Susan. 2009. *Anthropology and Climate Change : From Encounters to Actions*. Walnut Creek CA: Left Coast Press.

Dailey, Mark. 2016. “Cultural Models of Forests and Ecological Change on the Appalachian Plateau, 1750-1840 /.” *ResearchGate*. Accessed June 22.

D’Andrade, Roy. 1995. *The Development of Cognitive Anthropology*. Cambridge ;;New York: Cambridge University Press.

Dean, Jeffrey S., George J. Gumerman, Joshua M. Epstein, Robert L. Axtell, Alan C. Swedlund, Miles T. Parker, and Stephen McCarroll. 2000. “Understanding Anasazi Culture Change through Agent-Based Modeling.” *Dynamics in Human and Primate Societies. Oxford University Press, Oxford*, 179–206.

Dunn, Joel. 2014. “Envision the Susquehanna.” *Bay Jorunal*, January 12 edition. http://www.bayjournal.com/article/envision_the_susquehanna.

Edwards, P. N. 1999. “Global Climate Science, Uncertainty and Politics: Data-Laden Models, Model-Filtered Data.” *Science as Culture* 8 (4).

———. 2010. *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, Mass.: MIT Press.

Egmond, Stans van, and Ragna Zeiss. 2010. “Modeling for Policy.” *Science Studies* 23 (1): 58–78.

Ernst, Howard R. 2003. *Chesapeake Bay Blues: Science, Politics, and the Struggle to Save the Bay*. 1St Edition edition. Lanham: Rowman & Littlefield Publishers.

———. 2009. *Fight for the Bay: Why a Dark Green Environmental Awakening Is Needed to Save the Chesapeake Bay*. Rowman & Littlefield Publishers.

Escobar, Arturo. 2008. *Territories of Difference: Place, Movements, Life, Redes*. Duke University Press.

Fischman, Robert. 2005. "Cooperative Federalism and Natural Resources Law." *14 New York University Environmental Law Journal 179 (2005)*, January.

Fiske, S. J., S. A. Crate, C. L. Crumley, K. Galvin, H. Lazrus, L. Lucero, A. Oliver-Smith, B. Orlove, S. Strauss, and R. Wilk. 2014. "Changing the Atmosphere." *Anthropology and Climate Change. Report of the AAA Global Climate Change Task Force (American Anthropological Association, 2014)*.

Fortun, Kim. 2009. *Advocacy after Bhopal: Environmentalism, Disaster, New Global Orders*. University of Chicago Press.

Gray, Steven, Michael Paolisso, Rebecca Jordan. 2016. *Environmental Modeling with Stakeholders: Theory, Methods, and Applications*. Springer.

Geertz, Clifford. 1977. *The Interpretation Of Cultures*. New York: Basic Books.

Hardin, Garrett. 1968. "The Tragedy of the Commons." *Science* 162 (3859): 1243–48.

Hartigan, John. 1983. "Chesapeake Bay Basin Model Final Report." Chesapeake Bay Program.

Hastrup, Kirsten, and Martin skydstrup, eds. 2013. *The Social Life of Climate Change Models: Anticipating Nature*. New York: Routledge.

Helmreich, Stefan. 1999. "Digitizing 'Development'Balinese Water Temples, Complexity and the Politics of Simulation." *Critique of Anthropology* 19 (3): 249–265.

———. 2000. "Power/Networks: A Rejoinder to Lansing." *Critique of Anthropology* 20 (3): 319–27.

———. 2009. *Alien Ocean: Anthropological Voyages in Microbial Seas*. University of California Press.

Hesed, Christine D. Miller, and David M. Ostergren. 2017. "Promoting Climate Justice in High-Income Countries: Lessons from African American Communities on the Chesapeake Bay." *Climatic Change*, May, 1–16.

Hinson, Kyle. 2016. "Integrating Climate Change into the CBP Watershed Model." In . Williamsburg, VA.

Hirsch, Robert M. 2012. "Flux of Nitrogen, Phosphorus, and Suspended Sediment from the Susquehanna River Basin to the Chesapeake Bay during Tropical

Storm Lee, September 2011, as an Indicator of the Effects of Reservoir Sedimentation on Water Quality." US Geological Survey.

Holland, Dorothy, and Naomi Quinn, eds. 1987. *Cultural Models in Language and Thought*. Cambridge [Cambridgeshire] ;;New York: Cambridge University Press.

Horton, Tom, and Chesapeake Bay Foundation. 2003. *Turning the Tide: Saving the Chesapeake Bay*. Revised edition. Washington, D.C: Island Press.

Hulme, Mike. 2010. "Problems with Making and Governing Global Kinds of Knowledge." *Global Environmental Change*, 20th Anniversary Special Issue, 20 (4): 558–64.

———. 2013. "How Climate Models Gain and Exercise Authority." In *The Social Life of Climate Change Models: Anticipating Nature*, edited by Kirsten Hastrup and Martin skydstrup. New York: Routledge.

Ihde, Don. 2006. "Models, Models Everywhere." In *Simulation: Pragmatic Construction of Reality*, edited by Johannes Lenhard, Günter Küppers, and Terry Shinn. Vol. 25. Springer.

Johnson, KatherineJ, BrianA Needelman, and Michael Paolisso. 2016. "Vulnerability and Resilience to Climate Change in a Rural Coastal Community." In *Responses to Disasters and Climate Change*, 1–14. CRC Press.

Jordan, Thomas E., David L. Correll, and Donald E. Weller. 1997. "Effects of Agriculture on Discharges of Nutrients from Coastal Plain Watersheds of Chesapeake Bay." *Journal of Environmental Quality* 26 (3): 836–48.

Keiner, Christine. 2004. "Modeling Neptune's Garden: The Chesapeake Bay Hydraulic Model, 1965-1984." In *The Machine in Neptune's Garden: Historical Perspectives on Technology and the Marine Environment*, edited by Helen M. Rozwadowski and David K. Van Keuren, 273–314. Watson Pub International.

Kemp, W. M., W. R. Boynton, J. E. Adolf, D. F. Boesch, W. C. Boicourt, G. Brush, J. C. Cornwell, et al. 2005. "Eutrophication of Chesapeake Bay: Historical Trends and Ecological Interactions." *Marine Ecology Progress Series* 303: 1–29.

Kempton, Willett. 1995. *Environmental Values in American Culture*. Cambridge Mass.: MIT Press.

Knox, Hannah. 2014. "Footprints in the City: Models, Materiality, and the Cultural Politics of Climate Change." *Anthropological Quarterly* 87 (2): 405–29.

Knuuttila, Tarja. 2005. "Models as Epistemic Artefacts." *Helskinki: University of Helsinki, Department of Philospphy*.

———. 2006. "From Representation to Production: Parsers and Parsing in Language Technology." In *Simulation*, 41–55. Springer.

———. 2011. "Modelling and Representing: An Artefactual Approach to Model-Based Representation." *Studies In History and Philosophy of Science Part A* 42 (2): 262–271.

Knuuttila, Tarja, and Atro Voutilainen. 2003. "A Parser as an Epistemic Artifact: A Material View on Models." *Philosophy of Science* 70 (5): 1484–1495.

Kottak, Conrad. 1999. "The New Ecological Anthropology." *American Anthropologist* 101 (1): 23.

Lahsen, Myanna. 2005. "Seductive Simulations? Uncertainty Distribution around Climate Models." *Social Studies of Science* 35 (6): 895–922.

Landström, Catharina, Sarah J. Whatmore, and Stuart N. Lane. 2013. "Learning through Computer Model Improvisations." *Science, Technology & Human Values*, April.

Lansing, J. Stephen, and James N. Kremer. 1993. "Emergent Properties of Balinese Water Temple Networks: Coadaptation on a Rugged Fitness Landscape." *American Anthropologist* 95 (1): 97–114.

Lansing, John Stephen. 2006. *Perfect Order: Recognizing Complexity in Bali*. Princeton University Press.

Lansing, Steve. 2000. "Foucault and the Water Temples." *Critique of Anthropology* 20: 3.

Larsen, Curtis E. 1998. "The Chesapeake Bay; Geologic Product of Rising Sea Level." US Dept. of the Interior, US Geological Survey,.

Levine, Naomi M., Ke Zhang, Marcos Longo, Alessandro Baccini, Oliver L. Phillips, Simon L. Lewis, Esteban Alvarez-Dávila, et al. 2016. "Ecosystem Heterogeneity Determines the Ecological Resilience of the Amazon to Climate Change." *Proceedings of the National Academy of Sciences* 113 (3): 793–97.

LimnoTech. 2010. "Comparison of Draft Load Estimates for Cultivated Cropland in the Chesapeake Bay Watershed." Ann Arbor, MI.

Linker, Lewis C., Robert M. Hirsch, William P. Ball, Jeremy Testa, Kathleen Boomer, Jeff Cornwell, Carl Friedrichs, et al. 2016. "Conowingo Reservoir Infill and Its Influence on Chesapeake Bay Water Quality." 16–004. Annapolis MD: STAC.

Linker, Lewis C., Gary W. Shenk, Ping Wang, Katherine J. Hopkins, and Sajan Pokharel. 2002. "A Short History of Chesapeake Bay Modeling and the Next Generation of Watershed and Estuarine Models." *Proceedings of the Water Environment Federation* 2002 (2): 569–82.

Malone, Thomas C., W. R. Boynton, Tom Horton, and Court Stevenson. 1993. "Nutrient Loadings to Surface Waters: Chesapeake Bay Case Study." In *Keeping Pace with Science and Engineering Case Studies in Environmental Regulation.*, edited by Myron F Uman. Washington: National Academies Press.

Mancall, Peter C. 1991. *Valley of Opportunity: Economic Culture along the Upper Susquehanna, 1700-1800*. 1 edition. Ithaca: Cornell University Press.

McCay, Bonnie J., and James M. Acheson. 1990. *The Question of the Commons: The Culture and Ecology of Communal Resources*. University of Arizona Press.

Miller, Henry M. 2001. "Living Along the 'Great Shellfish Bay': The Relationship Between Prehistoric Peoples and the Chesapeake." In *Discovering the Chesapeake: The History of an Ecosystem*, edited by Philip D. Curtin, Grace S. Brush, and George W. Fisher, 109–26. JHU Press.

Morgan, Mary S., and Margaret Morrison. 1999. *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge University Press.

Netting, Robert McC. 1981. *Balancing on an Alp: Ecological Change and Continuity in a Swiss Mountain Community*. CUP Archive.

Newcombe, Curtis L. 1938. "Oxygen-Poor Waters of the Chesapeake Bay." *Oxygen-Poor Waters of the Chesapeake Bay* 88 (2273): 80–81.

NMAH. 2016. "The Norie Atlas." *National Museum of American History*. February 8. http://americanhistory.si.edu/norie-atlas.

NRC. 2007. *Models in Environmental Regulatory Decision Making*. National Academies Press.

Ogden L, Oslender U, Heynen N, West P, Kassam K.-A, and Robbins P. 2013. "Global Assemblages, Resilience, and Earth Stewardship in the

Anthropocene." *Frontiers Ecol. Envir. Frontiers in Ecology and the Environment* 11 (7): 341–47.

Ogden, Laura. 2011. *Swamplife*. Minneapolis: Minnesota University Press.

Oreskes, Naomi. 1998. "Evaluation (Not Validation) of Quantitative Models." *Environmental Health Perspectives* 106 (Suppl 6): 1453.

———. 2003. "The Role of Quantitative Models in Science." In *Models in Ecosystem Science*, edited by William K. Lauenroth. Princeton University Press.

Ostrom, Elinor. 1990. *Governing the Commons : The Evolution of Institutions for Collective Action*. Cambridge ;;New York: Cambridge University Press.

———. 2008. "Institutions and the Environment." *Economic Affairs* 28 (3): 24–31.

———. 2010. "Polycentric Systems for Coping with Collective Action and Global Environmental Change." *Global Environmental Change*, 20th Anniversary Special Issue, 20 (4): 550–57.

Paolisso, Michael. 2002. "Blue Crabs and Controversy on the Chesapeake Bay: A Cultural Model for Understanding Watermen's Reasoning about Blue Crab Management." *Human Organization : Journal of the Society for Applied Anthropology.* 61 (3): 226.

———. 2010. "A Cultural Model Assessment of Oyster Restoration Alternatives for the Chesapeake Bay." *Human Organization : Journal of the Society for Applied Anthropology.* 69 (2): 169.

Paolisso, Michael, and Jeremy Trombley. 2017. "Cognitive, Material and Technological Considerations in Participatory Environmental Modeling." In *Environmental Modeling with Stakeholders*, edited by Steven Gray, Michael Paolisso, Rebecca Jordan, and Stefan Gray, 3–23. Springer International Publishing.

Paolisso, Michael, Jeremy Trombley, R. R. Hood, and K. G. Sellner. 2013. "Environmental Models and Public Stakeholders in the Chesapeake Bay Watershed." *Estuaries and Coasts*, 1–17.

Paulson, Susan, and Lisa L Gezon. 2005. *Political Ecology across Spaces, Scales, and Social Groups*. New Brunswick, NJ: Rutgers University Press.

Poag, C. Wylie. 1996. "Structural Outer Rim of Chesapeake Bay Impact Crater: Seismic and Bore Hole Evidence." *Meteoritics & Planetary Science* 31 (2): 218–26.

Rabinow, Paul, and Gaymon Bennett. 2012. *Designing Human Practices: An Experiment with Synthetic Biology*. University of Chicago Press.

Rappaport, Roy. 1968. *Pigs for the Ancestors Ritual in the Ecology of a New Guinea People,*. New Haven: Yale University Press.

Rick, Torben C., Leslie A. Reeder-Myers, Courtney A. Hofman, Denise Breitburg, Rowan Lockwood, Gregory Henkes, Lisa Kellogg, et al. 2016. "Millennial-Scale Sustainability of the Chesapeake Bay Native American Oyster Fishery." *Proceedings of the National Academy of Sciences* 113 (23): 6568–73.

Shackley, Simon. 2001. "Epistemic Lifestyles in Climate Change Modeling." In *Changing the Atmosphere: Expert Knowledge and Environmental Governance*, edited by Clark A. Miller and Paul N. Edwards. MIT Press.

Shackley, Simon, James Risbey, Peter Stone, and Brian Wynne. 1999. "Adjusting to Policy Expectations in Climate Change Modeling." *Climatic Change* 43 (2): 413–54.

Shaffer, L. Jen. 2014. "Making Sense of Local Climate Change in Rural Tanzania Through Knowledge Co-Production." *Journal of Ethnobiology* 34 (3): 315–334.

Shaffer, L. Jen, and others. 2010. "Indigenous Fire Use to Manage Savanna Landscapes in Southern Mozambique." *Fire Ecology* 6 (2): 43–59.

Shenk, Gary W., and Lewis C. Linker. 2013. "Development and Application of the 2010 Chesapeake Bay Watershed Total Maximum Daily Load Model." *JAWRA Journal of the American Water Resources Association* 49 (5): 1042–1056.

Steadman, David W. 2001. "A Long-Term History of Terrestrial Birds and Mammals in the Chesapeake-Susquehanna Watershed." In *Discovering the Chesapeake: The History of an Ecosystem*, edited by Philip D. Curtin, Grace S. Brush, and George W. Fisher, 83–108. JHU Press.

Steward, Julian Haynes. 1938. *Basin-Plateau Aboriginal Sociopolitical Groups*. Washington: U.S. Govt. Print. Off.

———. 1972. *Theory of Culture Change: The Methodology of Multilinear Evolution*. University of Illinois Press.

Sundberg, Mikaela. 2009. "The Everyday World of Simulation Modeling The Development of Parameterizations in Meteorology." *Science, Technology & Human Values* 34 (2): 162–181.

Theuerkauf, Seth, and Romuald Lipcius. 2016. "Validation of a Habitat Suitability Index for Oyster Restoration." *bioRxiv*, 39875.

Tian, R., P. Wang, and L. C. Linker. 2014. "Shallow-Water System Dynamics in Chesapeake Bay, with Physical-Biological Modeling Application." *AGU Fall Meeting Abstracts* 23 (December).

Tsing, Anna Lowenhaupt. 2011. *Friction: An Ethnography of Global Connection*. Princeton University Press.

———. 2015. *The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins*. Princeton: Princeton University Press.

US ACE. 1973. "Chesapeake Bay Existing Conditions Report." Baltimore, MD.

———. 1977. "Chesapeake Bay Future Conditions Report." Baltimore, MD.

US Congress. 1965. *Rivers and Harbors Act. 89-298*.

US EPA. 1982. "Chesapeake Bay Program Technical Studies: A Synthesis." Chesapeake Bay Program.

USDA. 2014. "2012 Census of Agriculture." Washington D.C.: USDA.

USGS. 2015. "USGS Fundamental Science Practices (FSP)." https://www2.usgs.gov/fsp/default.asp.

———. 2017. "Watersheds and Drainage Basins." *USGS Water Science School*. Accessed May 26. https://water.usgs.gov/edu/watershed.html.

VERBI Software. 2014. "MaxQDA 12 Reference Manual." VERBI Software.

Wennersten, John R. 2000. *The Chesapeake: An Environmental Biography*. 1St Edition edition. Baltimore: The Maryland Historical Society.

Whitehead, Tony L. 2005. "Basic Classical Ethnographic Research Methods." *Ethnographically Informed Community and Cultural Assessment Research Systems*.

Zhang, Qian, Robert M. Hirsch, and William P. Ball. 2016. "Long-Term Changes in Sediment and Nutrient Delivery from Conowingo Dam to Chesapeake Bay: Effects of Reservoir Sedimentation." *Environmental Science & Technology* 50 (4): 1877–1886.