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BUILDING SCENARIOS OF ADAPTIVE CAPACITY: A CASE STUDY OF COMMUNITY WATER SYSTEMS IN CENTRAL PENNSYLVANIA

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ABSTRACT

Approximately 83 percent of the estimated 52,000 community water systems (CWS) in the United States serve fewer than 3,300 people. In the Commonwealth of Pennsylvania, about 945,000 people receive their drinking water from smaller CWS, and the CWS of Centre County provide an excellent example of small, rural systems with low human capital, changing regulatory demands, and aging infrastructure. With resources already stretched, it may be difficult for CWS managers to adapt to the impacts of future climate change.

The purpose of this dissertation is to study Centre County CWS managers' perceptions of their systems' capacities to adapt to more frequent floods and droughts. Results from nine interviews with Centre County CWS managers and from managers' social network maps revealed that these managers are limited in their availability to raise funds, comply with water quality regulations, and upgrade system technology. Some managers of small, rural systems compensate for scarce human capital and financial resources by taking advantage of layered social and institutional capital. One of these systems is the Gregg Township Water Authority (GTWA). In a series of mediated modeling focus groups, GTWA members and stakeholders helped to build a scenario generator that allows CWS managers to explore their potential adaptive capacities.

The system dynamics-based Community Water System - Future Adaptive Capacity Scenario (CWS-FACS) generator allows managers to explore how system management variables change under five climate scenarios and three growth rate scenarios. The sample scenarios presented to the GTWA suggested that the system's financial adaptive capacity is low and the stress on the system from a lack of financial resources may be greater than the climate-related stress. Despite this result, managers remained concerned about climate change and found the scenario results to be plausible and consistent. They also valued the model's flexibility and its utility as a learning tool for climate and other influences affecting their system's management. Ultimately, these results indicate that mediated modeling and system dynamics are effective approaches for making climate information relevant to resource managers. The methodology can be transferred to other sectors and regions, making it useful for climate extension and outreach programming.

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Chapter 1

Introduction

Future environmental change will affect billions of people worldwide, but human adaptations will alter the distribution and impact of changes. The water resources sector already faces the task of devising solutions to continue providing water for agriculture, industry, transportation, and drinking despite increasing population and changes in development (Arnell 2004). Most recent drinking water management planning assumes stationarity, the concept that historical patterns of precipitation variability will remain constant in the future (Milly et al. 2008). However, models indicate that climate change may exacerbate traditional water management challenges because of changes in extreme precipitation patterns manifested as more numerous or severe droughts and floods (Arnell et al. 2001; Bates et al. 2008). We often think of these as potential problems in the developing world; however, climate change will affect water management in the United States, where much of the available water is already overallocated (Hurd et al. 2004; Miller and Yates 2005; Bates et al. 2008). For instance, various climate change models and scenarios indicate that climate change in the Mid-Atlantic region, including the Susquehanna River Basin (SRB), may increase or decrease water availability (Thomson et al. 2005) or lead to more frequent flooding (Yarnal 2004).

North American water management as a whole may have a high capacity to adapt to changes in water availability, but closer investigations reveal that this capacity is uneven, with the water supply of indigenous and other socially and economically disadvantaged populations being more vulnerable to damage from floods and droughts (Bates et al. 2008). In small, rural communities with public drinking water systems, smaller populations bear the high costs of producing and delivering drinking water that meets health standards, exacerbating existing economic disadvantages and restricting drinking water system managers' capacities for responding to operational challenges. The United States Environmental Protection Agency (EPA) defines a public water system as "a system for the provision to the public of water for human consumption through pipes or other constructed conveyances, if such system has at least fifteen service connections or regularly serves at least twenty-five individuals" (U.S. Environmental Protection Agency 1998). An estimated 85 percent of the United States population relies on public drinking water systems (U.S. Environmental Protection Agency 2006). Of these public water systems, over 292 million people are served by community water systems (CWS), which are drinking water systems that serve a year-round population (U.S. Environmental Protection Agency 2008). CWS are further classified by size, with CWS serving 25-500 customers and 501-3,300 customers designated as very small and small systems, respectively. In 2007, very small and small systems made up approximately 83 percent of the roughly 52,000 CWS in the United States. These smaller systems served 24.7 million people, or 9 percent of the total population receiving water from CWSs (U.S. EPA Office of Ground Water and Drinking Water 2008). These proportions are similar for the 2,100 systems in the Commonwealth of Pennsylvania, where approximately 945,000 residents use small and very small CWSs as their drinking water suppliers (Pennsylvania Department of Environmental Protection 2007). Although state and federal agencies provide some variances, small and very small CWSs must still comply with the water quality regulations in the Safe Drinking Water Act (SDWA). The costs of compliance are high compared to these systems' size because customer bases are small relative to the minimum costs of treating water to SDWA standards (Jocoy 2000; U.S. EPA Office of Ground Water and Drinking Water 2002; Cotruvo 2003; U.S. EPA Office of Ground Water and Drinking Water 2003). Already faced with the low availability of human capital, aging infrastructure, and changing regulatory demands, very small and small CWS managers may have few resources remaining to confront the impacts of climate change.

Current water management structures encourage decentralized reactive responses to floods and droughts, and managers of CWS in rural areas that already find it difficult to address hydroclimatic stresses will be even less prepared for the changes and uncertainties introduced by a changing climate. Some efforts are underway to educate water managers about the effects climate change may have on drinking water provision (Miller and Yates 2005), but the message is slow to enter mainstream communities of practice. For example, in a trade publication that water managers are more likely to read than academic journal articles, climate change merits only a small side comment in an article about the key drivers and trends in water management (Maxwell 2005). Studies of water managers indicate that they tend to use more traditional planning methods, thereby limiting their climate forecast use (Carbone and Dow 2005; Rayner, Lach, and Ingram 2005; Yarnal et al. 2006). Managers whose systems recently experienced meteorological or climatic events are more likely to be concerned, but operational and management issues still take precedence in their perception of potential problems (O'Connor, Bord, and Fisher 1999; O'Connor et al. 2005; Dow et al. 2007). Nonetheless, climate change may affect their systems, and in addition to determining appropriate responses to operational and management changes, managers of CWS will find themselves debating their systems’ ability to adapt to hydroclimatic changes, i.e., their adaptive capacity. Managers need assistance to understand these combined problems and inherent uncertainties so they can begin to address flexible adaptive strategies.

One strategy to approach this problem is to focus on particular adaptations and their impact on the system. Obviously, there are practical limitations to this adaptation-based approach. Researchers must know enough information about the processes shaping how and when adaptations occur to make assumptions about the variety of possible adaptation strategies (Smit et al. 2000), and they must attempt to identify and evaluate all particular adaptation measures to minimize the number of possible surprises. Smit and Skinner (2002) suggest that a practical alternative is to shift the focus from evaluating specific adaptations to enhancing adaptive capacity. Adaptive capacity is generally considered to be the ability of systems or processes to make adjustments that minimize the negative impact or maximize any positive benefits from a given change (Schneider, Easterling, and Mearns 2000; Adger et al. 2004; Smit and Wandel 2006; Adger et al. 2007). The concept of adaptive capacity is not unique to the global environmental change literature; Staber and Sydow (2002) note that organizations can be too well adapted to specific situations and that adaptive capacity enhancement can give organizations more freedom to pursue novel solutions to unanticipated problems. In the context of climate change, adaptive capacity-centered analyses allow for local and individual assessments of options, provide an opportunity to incorporate adaptation into existing management processes, recognize the distinct roles of the public and private sectors, and facilitate the dissemination of information to stakeholders on climate change risk and vulnerability and available adaptations (Smit and Skinner 2002). There are many analyses of current adaptive capacity (Yohe and Tol 2002; O'Brien et al. 2004), but there is a need for more studies that attempt to assess future adaptive capacity (Lorenzoni, Jordan, Hulme et al. 2000; O'Brien et al. 2004).

Tools that incorporate the context of CWS managers' needs may help to communicate the relevance of climate forecast information more effectively (Carbone and Dow 2005; Rayner, Lach, and Ingram 2005; Yarnal et al. 2006). A similar context-specific tool could also be used to address processes shaping adaptive capacity and to communicate its relevance to water managers. Scenarios of community water systems' adaptive capacity may be appropriate tools to help managers learn about the importance of climate change and incorporate it into their existing plans. For example, a small CWS located near an interchange on a new interstate highway may be concerned about development and aging system infrastructure over the next 10 years without perceiving the additional constraint of more frequent floods and droughts possible as a result of global climate change. Scenario-building allows CWS managers to experiment by varying the magnitude of interacting system pressures over time and examining that scenario's cumulative effect on their system's ability to adapt to changing situations – specifically, their future ability to take any action that minimizes the negative effects of and maximizes possible benefits from more frequent floods and droughts.

There is a precedent for using scenarios to facilitate interaction with stakeholders. Lorenzoni, Jordan, and Hulme et al. (2000) use linked scenarios to examine the co-evolution of socioeconomic and climate systems despite considerable uncertainties in the future. Stakeholders analyzed multiple scenarios and incorporated their own knowledge to develop critical analyses of their own adaptive capacity under each scenario. Soliciting the managers' responses about the pressures they experience will not only make the process more salient to them, but it will also provide information on the feedbacks between the indicators of adaptive capacity across systems and scales. By participating in a collaborative researcher-manager effort to create several plausible storylines that demonstrate how changes in hydroclimate, operational practice, and management may affect their systems, these managers may begin to understand the scope of the forces shaping their systems' adaptive capacity.

Accordingly, this dissertation will investigate:

1. The perceptions CWS managers have regarding their systems' capacity to adapt to hydroclimatic change and variation
2. The processes shaping CWS managers' current adaptive capacity
3. The interactions of these processes to produce possibilities of CWS managers' future adaptive capacity
4. The difficulties of integrating CWS managers into the research design

This dissertation presents a scenario construction process for CWS capacity to adapt to hydroclimatic variation[1] – namely, changes in precipitation and in the frequency and intensity of floods and droughts. The combination of a mediated modeling approach and a system dynamics perspective results in a scenario construction process that is sufficiently flexible to allow managers to prioritize indicators as appropriate for their systems. It also imposes enough structure on the construction process to ensure that managers and researchers constructed adaptive capacity scenarios in a consistent manner. This scenario construction process is demonstrated through a case study of a small rural CWS in Centre County, Pennsylvania. As a result of participating in the model-building exercise, managers and other stakeholders in the Gregg Township Water Authority (GTWA) learned from the scenario-building process and reflected on how this process highlighted necessary changes in their CWS's management structure.

This dissertation consists of three manuscripts ready for submission to peer-reviewed journals. Because each manuscript focuses on a discrete portion of the research, the remainder of this chapter provides an integrated overview of the research process. First, I summarize the previous research on CWSs in Centre County and discuss how this history informed the dissertation. Second, I present the purpose of the work and the research questions that guided it. Third, I include a brief summary of the methods to assist the reader in placing the following manuscripts within the overall research context. Finally, I summarize the remaining dissertation structure.

[1] In this dissertation, references to CWS adaptations and other actions, are understood to be metonyms for the CWS managers' and other decision-makers' actions taken to preserve the CWS's operation.

Previous Central Pennsylvania CWS Research

For at least a decade, various researchers from the Pennsylvania State University have conducted qualitative and quantitative studies on Centre County CWS (Figure 1-1). Some of the earliest relevant research emerges from Pascale's thesis on Centre County CWS, drinking water regulations, and vulnerability to drought (Pascale 1997). This research inspired a broader survey of CWS in the Susquehanna River Basin (SRB) on managers' perceptions of their systems' sensitivities to weather and climate change that found experienced managers are more likely to include weather and climate information in their planning (O'Connor et al. 1999). Additional research by Jocoy (2000) examined the relationship between CWS size and success in applying for and receiving grants from the PENNVEST construction loan and grant program. A 1999 grant from NOAA's Human Dimensions of Global Change Research (HDGCR) program (Yarnal et al. 2003) supported research that contributes to knowledge on both CWS managers' use of climate forecasts and CWS vulnerability to hydroclimatic events. Researchers used the results of focus groups with managers of medium and large CWS and with managers of small CWS to construct a survey administered in summer 2000 to CWS managers in the Pennsylvania portion of the SRB and in South Carolina (O'Connor et al. 2005; Yarnal et al. 2006; Dow et al. 2007). The research also involved constructing Bayesian networks to explore managers' decision-making processes for coping with weather- and climate-related risks (Pike 2001). Semi-structured interviews and archival research conducted through the Human Environment Research Observatory (HERO) network Research for Undergraduates (REU) program further investigate the survey results and how they relate to vulnerability (Windram et al. 2003). In subsequent years HERO REU students expanded their qualitative inquiry to other sectors, but their work still includes important assessments of CWS and their current capacity to adapt to hydroclimatic variation and change (Hamilton, Daley, and Hulett 2004; Booher et al. 2005). In other HERO-

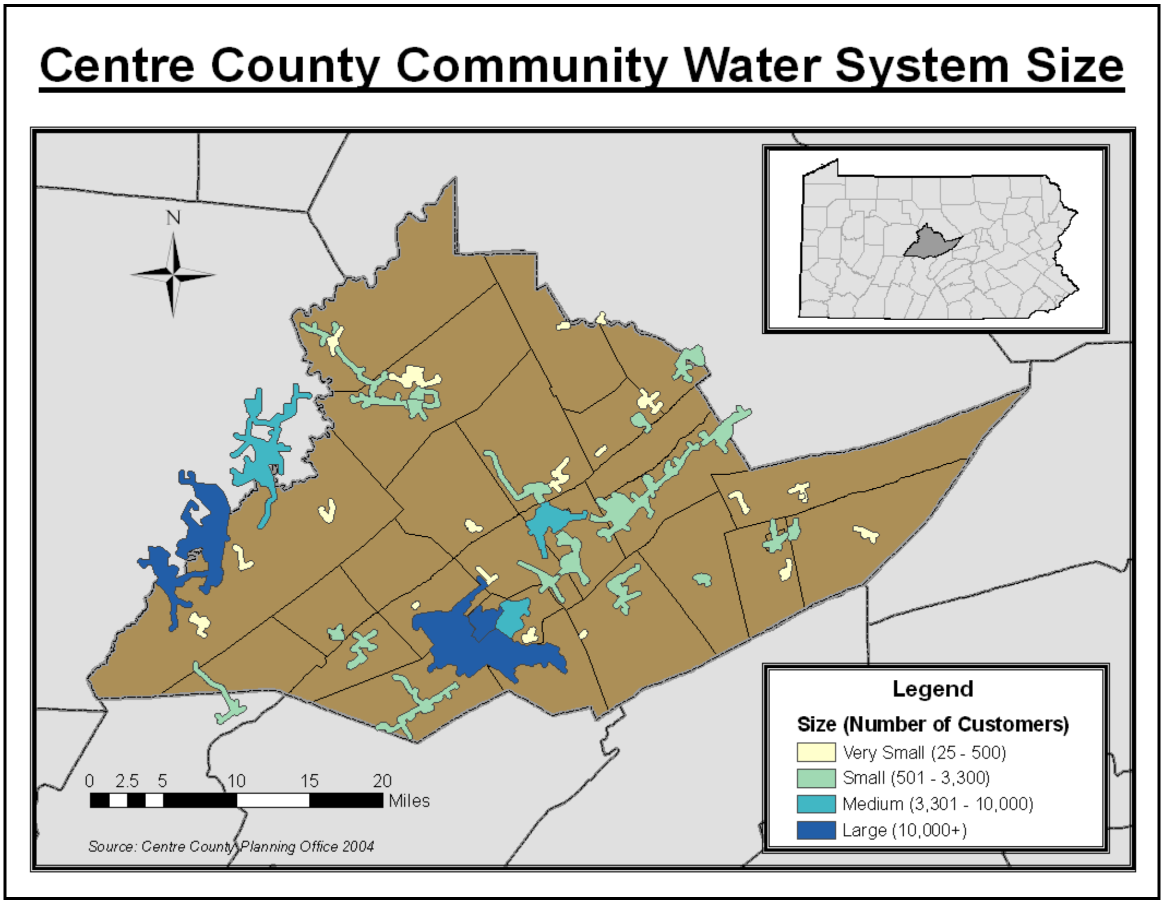

Figure 1-1: CWS in Centre County, Pennsylvania, classified by size.

sponsored research, Yu used regulatory requirements and CWS managers' reported behaviors to construct an agent-based model of Centre County CWS managers' responses to drought emergencies (Yu et al. in press). These studies all provide valuable information on the role of Central Pennsylvania CWS managers' perceptions of weather- and climate-related risk in using forecasts, on their perceptions of their systems' vulnerability to such risk-related problems, and on the sensitivities and adaptive capacities of their systems.

CWS Managers and Climate Forecasts

The role of CWS managers' perceptions of weather- and climate-related risk became apparent in the NOAA HDGCR survey (Yarnal et al. 2006). There were 405 valid survey responses from CWS managers in the SRB, representing 53 percent of the managers in the basin (O'Connor et al. 2005). A response bias toward managers of larger CWS may have led to an overestimation of forecast use, but separating the analysis into smaller and larger systems yielded similar response patterns for risk perception and forecast reliability. Surprisingly, perceived forecast reliability matters little in explaining whether managers use these forecasts (*Ibid*). Instead, the results indicate that only managers' perceptions of risk from weather and climate events accounts for statistically significant forecast use variance. Most managers do not use forecasts because they do not perceive any risk to their systems from weather- or climate-related problems.

Perceived CWS Vulnerability

The NOAA HDGCR survey results indicate the importance of CWS managers' perceptions of their systems' vulnerability to problems resulting from weather and climate events (Dow et al.

2007). Managers' perceptions of potential weather- or climate-related problems are affected by their experience: 90 percent of managers who experienced such problems in the past five years expected similar problems in the future (*Ibid*). These perceptions do not include streamflow-related events only; lightning strikes also present a concern through the potential for power disruption. Managers tend to be more concerned about financial or water quality problems resulting from droughts and floods than they are about their systems' ability to continue supplying water. There is some relationship between system source type and size – in general surface water-based systems are believed to be more vulnerable than groundwater-based systems (Yarnal et al. 2006; O'Connor et al. 1999) – but the nature of this relationship is event- and problem-dependent (Dow et al. 2007). In particular, system size is not a robust indicator of perceived system vulnerability. Anticipated drought severity is influenced by managers' perceptions of financial impacts and changes in water quality. For floods and lightning strikes in Pennsylvania, managers did express concern over water rationing required because of an inability to meet water quality standards.

In semi-structured interviews, manager perceptions also emerge as important to vulnerability – CWS managers do not perceive risks to their systems from climate change (Windram et al. 2003; Hamilton, Daley, and Hulett 2004). Experienced managers are more likely to have emergency plans in place, reducing their systems' sensitivity to hydroclimatic events (Windram et al. 2003). However, a lack of education about climate change (including its indirect effects on system finances and water quality) and the need for adaptation to hydroclimatic variation and change reduces a system's overall adaptive capacity (Hamilton, Daley, and Hulett 2004).

CWS Sensitivity and Adaptive Capacity

Regulatory structures emerge as important indicators of CWS sensitivity and adaptive capacity. Pascale (1997) uses case studies comparing a historical drought and the 1995 drought in three Centre County CWS to determine that the passage of the Safe Drinking Water Act in 1974 and subsequent amendments are changing the patterns of CWS drought vulnerability in Centre County. A shift to groundwater to avoid strict surface water filtration requirements ultimately reduces drought vulnerability (Pascale 1997); groundwater tables in the region drop in response to drought, but the response rate to reduced precipitation is less pronounced than it is for surface water sources (Windram et al. 2003). CWS adaptations, like switching to groundwater sources or regionalizing multiple small CWS, increase long-term adaptive capacity; however, it should be noted that such requirements place a significant financial burden on some systems, decreasing short-term adaptive capacity. Historically, this burden has been greater for very small CWS because these managers have been less likely than managers of larger CWS to apply for state construction grants and loans through the PENNVEST program, and very small CWS that do apply have a lower chance of winning an award (Jocoy 2000).

Pike (2001) focuses on training Bayesian network models of water quality violations using 10 CWS operator conceptual models and their systems' water quality regulation violation histories. The study includes several important points about the sensitivity of water quality to hydroclimatic events and the role of CWS operator experience. Water quality violations are most likely to occur during extremely high streamflow events (floods or extended periods of intense precipitation) or extremely low streamflow events (droughts). However, the greatest driver of violations is CWS operators' decisions, because operator experience plays a role in the quality of decision-making. For most violation types (those not related primarily to chemical spills or industrial discharges), operators with less than five years of experience in cost-sensitive CWS are more likely to make incorrect decisions that lead to violations.

Other institutional structures, like the effect of drought emergency declarations and local municipal interactions, also contribute to CWS sensitivity and adaptive capacity (Hamilton, Daley, and Hulett 2004; Booher et al. 2005). Funding, often related to system size, emerges as a significant contribution to systems' abilities to update infrastructure (Jocoy 2000; Windram et al. 2003). Many CWS in Centre County are community-run, relying on volunteers and part-time employees, thereby reducing the ability to keep up with emergency planning and response. Finally, population growth and urbanization may change the patterns of contamination and runoff CWS currently experience. Population growth may be a positive contribution to a CWS because of the increased revenue; population decline and the subsequent loss of businesses and services has already contributed to significant financial losses for one CWS in Centre County (Booher et al. 2005).

The rich history of CWS research in central Pennsylvania therefore makes it an ideal study region for examining adaptive capacity in the future. These studies provide important baseline information on managers' perceptions of weather- and climate-related events and their influence on climate forecast use, their perceived system vulnerabilities to problems caused by these events, and other factors affecting CWS sensitivity and adaptive capacity. Additionally, these studies' results also point to the importance of a CWS's operational and regulational context. Some CWS in Centre County may not experience severe resource scarcity as a result of climate change, but they anticipate problems from the combination of resource scarcity and external socioeconomic factors (Yarnal et al. 2006). In addition, current plans and adaptations do not account for cases in which problems occur concurrently or in sequence (Dow et al. 2007). New research in future adaptive capacity assessment under a variety of climatic and socioeconomic conditions will help CWS begin to develop more flexible adaptive strategies.

Purpose

The purpose of this mixed methods action research study is to explore CWS managers' perceptions of their capacity to adapt to hydroclimatic change and variation, and to use this information to develop a framework for constructing local-scale scenarios of their CWS's future adaptive capacity. This study is not true participatory research because its motivation originates outside the CWS management community and the research design was not developed in conjunction with local CWS managers (Park 1999). However, it does use participatory techniques such as semi-structured interviews, focus groups, and participatory modeling (Mendoza and Prabhu 2005). The second phase of the study closely follows the mediated modeling techniques outlined by van den Belt (2004), in which participants work cooperatively with researchers and modelers to build a collaborative computer-based model.

It is imperative that the adaptive capacity scenario construction framework meet the operational needs of CWS managers. This requirement makes the determination of managers' needs for adaptive capacity scenarios the key step in developing the rest of the proposed research. Therefore, this study was guided by four research questions regarding CWS manager perceptions:

1. What are the factors that CWS managers believe affect their future capacity to adapt to hydroclimatic change and variation?
2. How can the needs and concerns of water managers be used to create a framework for constructing adaptive capacity scenarios for community water systems?

3. Does this framework result in cohesive, internally consistent, and plausible adaptive capacity scenarios for these systems?
4. Does the scenario-building process promote organizational and social learning?

Methods

This study was set in Centre County, Pennsylvania, and had two concurrent components: a sequential, two-phase scenario-building component and a learning component. In the first phase of the scenario-building component, I interviewed managers from nine CWS to produce qualitative data that was used to design the scripts for the focus groups during the case study phase. An undergraduate student assisted with note taking and transcribing the interviews from the eight systems that consented to have the interviews recorded. The semi-structured interview scripts used prompts that reflected adaptive capacity determinants and indicators suggested in the literature and based on the history of CWS research in Centre County. I coded the interview results for the eight systems that provided consent using AtlasTI, and these codes provided initial qualitative data on the managers' views of the factors influencing their systems' future adaptive capacity and on their understanding of climate change vulnerability concepts. Conceptual maps of the managers' social and institutional networks from all nine interviews also illustrated the important role of social and institutional capital for the systems.

In the second phase, I recruited the Gregg Township Water Authority (GTWA) as a case study for using mediated modeling techniques to develop a system dynamics model of their CWS's capacity to adapt to climate change in the form of more frequent floods and droughts. The scenario model was constructed using isee systems™ STELLA™ software based on data collected during scripted focus group meetings (Andersen and Richardson 1997; Luna-Reyes et al. 2006). Using a series of three scripted focus groups, we worked through an iterative cycle of developing and adjusting the CWS Future Adaptive Capacity Scenario (CWS-FACS) generator until participants believed it reflected their understanding of climate change adaptive capacity. We held a supplemental informal meeting between the second and final focus groups because the model required another iteration of review and adjustment before the final version could be used for creating adaptive capacity scenarios. Three members of the GTWA board, along with a Gregg Township supervisor and a Pennsylvania Department of Environmental Protection (DEP) sanitarian, remained active in the entire process of assisting me with developing the scenario generator and using it to build several adaptive capacity scenarios for their systems. The GTWA's certified operator, a representative from their hired engineering company, and a local emergency management official also attended the first focus group meeting, but all three were unavailable for subsequent meetings.

These scenarios may be an effective way to educate managers and their employees about the processes contributing to their systems' adaptive capacities. Therefore, the concurrent research component investigated the effect of the scenario-building process on the CWS managers' perceptions of adaptive capacity and documented any proposed changes to the CWS organization because of the managers' changing perceptions. To track participants' changing perceptions throughout the scenario-building process, managers completed surveys before the first focus group and after each group concluded. Both the surveys and the questions in the final focus group script helped to document the changes in behavior ultimately proposed by the GTWA board members.

Dissertation Structure

The results of this research are presented here in the form of three manuscripts for submission to peer-reviewed academic journals. There is no chapter with a comprehensive literature review; rather, literature reviews of relevant material are included in each chapter as appropriate for manuscript submission. The topics of these chapters are:

- CHAPTER 2: Social capital, institutional capital, and rural drinking water management in central Pennsylvania
- CHAPTER 3: Using modified mediated modeling to assess small drinking water systems' abilities to adapt to climatic change and variation
- CHAPTER 4: Promoting preparedness through learning: A process for community drinking water systems to explore climate change adaptive capacity.

To provide the detail required for a dissertation, some chapters are slightly longer that the word limits of the target journals. To conform to thesis standards, references for all chapters are included in a single section at the end of the dissertation.

Chapter 2 includes the results of the interviews conducted for the first phase of the scenario-building component. It concentrates on the importance of social and institutional capital to the managers of the small, rural systems that I interviewed; this unexpected result played a critical role in selecting the case study system and in choosing system dynamics modeling as the platform for scenario building. Chapter 3 describes mediated modeling and the technical structure of the CWS-FACS model. Chapter 4 synthesizes the results of the entire study by discussing both the adaptive capacity scenario results for the GTWA and the impact these scenarios had for helping GTWA members to learn about adaptive capacity. The dissertation concludes with Chapter 5, where I briefly summarize the three manuscripts, discuss the conclusions drawn and lessons learned from the research, and describe the future of system dynamics and mediated modeling for further research and outreach on climate change. In addition to the references section, there are four appendices: the initial interview script (Appendix A), the focus group scripts (Appendix B), screen shots of the CWS-FACS generator sectors and the model code equations (Appendix C), and the four learning assessment survey scripts (Appendix D).

Chapter 2

Social capital, institutional capital, and rural drinking water management in Central Pennsylvania

Often, we think of drinking water management in the United States as a technical endeavor, focusing on hydrology, engineering, infrastructure, population dynamics, contamination, public health, and regulations. However, the process of taking raw water, treating it, and distributing it to taps is embedded within a larger socioeconomic context that can be difficult to quantify, yet vital to effective drinking water management, especially in rural areas. The United States Environmental Protection Agency (EPA) defines a community water system (CWS) as a drinking water system that serves 25 or more customers or has 15 or more connections to households and businesses (U.S. Environmental Protection Agency 1998). Very small CWS (those serving 25-500 customers) and small CWS (those serving 501- 3,300 customers) serve a fraction of the population compared to larger urban systems, but when examining absolute numbers of systems and population served – 24.7 million nationwide in 2008 – very small and small CWS become more significant (U.S. EPA Office of Ground Water and Drinking Water 2008). In Pennsylvania alone, the Department of Environmental Protection (DEP) estimates that small or very small water systems comprised 84% of the estimated 2,100 systems in the Commonwealth in 2007, and these systems provided clean, reliable drinking water for roughly 945,000 residents (PA DEP 2007). State and federal regulatory agencies require these systems to comply with the same water quality standards of the Safe Drinking Water Act (SDWA) that apply to larger systems, but the costs associated with compliance place a disproportionate burden on small systems (Jocoy 2000; U.S. EPA Office of Ground Water and Drinking Water 2002; Cotruvo 2003; U.S. EPA Office of Ground Water and Drinking Water 2003). There are dispensations and financial programs available to help smaller systems meet water quality standards, but even then, small systems face significant challenges. Small customer bases lead to minimal revenue, limiting the funding available for hiring professional consultants and paying for training. Aging systems can be prone to pipe leaks and equipment malfunctions. To combat crumbling infrastructure and to meet stricter water quality regulatory standards, the federal and state governments mandate costly repairs and upgrades, and the costs associated with even small upgrades can be phenomenal in proportion to the revenue stream of a small CWS. In this environment, water managers become so constrained by these stresses that they are limited to responding to emergencies rather than planning for future changes (Flora 2004).

Managers of small CWS must use clever management and political maneuvering to navigate through the human and policy dimensions of drinking water management. These managers must also become proactive rather than reactive managers if they hope to build their capacities to plan for meeting their customers' future needs (Flora 2004). Often, managers' first strategies are to turn to applying for grants to address physical infrastructure issues like replacing aging water mains or altering water treatment technologies. However, survival in changing socioeconomic and political contexts requires more than modern technological fixes or effective demand models. For this purpose, managers of small CWS must learn to access a different set of resources: the elements of community cohesion that enable them to take advantage of local knowledge and skills, and their connections to actors on state and federal scales that gives managers the opportunity to increase their access to aid. In other words, CWS managers must learn to use available social and institutional resources to supplement technical management strategies.

The Ridge and Valley region of Central Pennsylvania provides an excellent example of an area where small and very small rural CWS supplement insufficient financial resources with the tangible and intangible resources provided through a sense of community and a network of actors who can deliver aid for planning and emergency response. In Centre County, Pennsylvania, rural townspeople banded together to provide themselves with adequate supplies of safe, healthy water via centralized drinking water systems since at least the 1890s. Small water systems were founded to serve isolated communities where dominant livelihoods included farming, mills, and, in the case of Centre County, the small land grant college that would one day become the Pennsylvania State University. Several CWS in the county are over 100 years old (PA DEP 2005), but it was only in the modern era that state and federal government began to impose regulatory control (Marrocco, Franklin, and Sedlak 1993; Jocoy 2000). As the area grew and the number of regulations increased, many of the CWS became large enough to formalize their management structure, becoming formal municipally operated utilities with their own employees. Private investment companies purchased some of the other CWS, and these systems progressed to a for-profit model of drinking water management. However, many rural Centre County systems retained their traditional structures of water management via community-run boards of volunteers, who obtained the human capital necessary to run the system through contracts with specialists like certified operators and engineers. All three types of CWS exist in Centre County today, and each develops its own strategies for keeping their systems viable in a complex social and regulatory environment.

This chapter presents the results of nine interviews conducted in spring and summer 2006 with managers from nine Centre County CWS. Part of a larger research agenda on drinking water systems abilities to adapt to climate change, these interviews were originally designed to answer the research question, “What are the factors that affect CWSs’ current capacities to adapt to weather-related events?” During these interviews, a critical role for social and institutional capital in basic CWS operation emerged that deserves treatment in its own right. Several of the smaller, rural systems indicated that they still rely on volunteer assistance to maintain their ability to provide adequate supplies of clean water to their customers. CWS managers also drew maps of their connections to other actors with whom they exchange knowledge, information, and funding. These maps suggest that the systems' abilities to reach out to actors on other scales vary widely, which has implications for their abilities to navigate complex institutional pressures successfully. Therefore, the purpose of this chapter is to describe the roles that social and institutional capital play in water management using the example of CWS in Centre County, Pennsylvania.

Literature Review

Social and Institutional Capital

Founding Conceptions and Definitions

Social capital has been studied extensively since the key works of authors like Granovetter (1973), Bordieu (1985), Coleman (1988), and Putnam (1995). Today, there is still room for debate about its exact definition and components. Much like other capital assets, such as financial capital or physical capital, social capital is a functional conglomerate comprised of multiple entities. In the case of social capital, these entities all relate to social structures and how they facilitate actors' navigation within those structures (Coleman 1988; 1995). Unlike other capital assets, social capital neither has a physical form manifest in the characteristics of individual actors, nor exists as a formal structure.

Individual actors accumulate social capital (Coleman 1988; Pelling and High 2005), but family groups and organizations to which actors belong also benefit from social capital (Lorenzen 2007) to the extent that some authors refer to organizational social capital as a distinct cumulative quantity (Nugent and Abolafia 2006; Oh, Labianca, and Chung 2006; Arregle et al. 2007). Adler and Kwon (2002) include the dynamic organizational relationships that catalyze action and create valuable resources as a part of social capital (Adler and Kwon 2002; see also Arregle et al. 2007). For both individual and organizational actors, social capital encompasses the properties and dynamics of human relationships and the ways these properties enable actors to work toward shared goals, including elements of trust building, norms, and social networks (Putnam 1995; Woolcock 1998; Pelling and High 2005).

Sobel (2002, 148) defines trust as "the willingness to permit the decisions of others to influence your welfare." When actors trust each other, their relationship depends on each party's faith and confidence that both will behave according to certain expectations. Some authors view trust and other social phenomena as part of social capital (Bordieu 1985), whereas others view these as unintentional outcomes resulting from social processes (Coleman 1990; Lorenzen 2007). One motivation for one actor to trust another actor is the promise of some personal benefit in exchange for that trust (Coleman 1988). Co-operation becomes easier when actors trust each other, freeing them from monitoring others and thereby reducing transaction costs (Pretty and Ward 2001). Some studies find that trust boosts economic performance (Knack and Keefer 1997), and trust often facilitates the exchange of knowledge (Hauser, Tappeiner, and Walde 2007). However, while trust may be necessary, its presence is not a sufficient condition for building social capital (Dietz 2000).

Actors who trust each other also become socially obligated to reciprocate that trust through exchanges of value, either simultaneously or over time (Pretty and Ward 2001). This type of expectation is one norm that guides interactions that build and maintain social capital. Norms guide everyday behavior in terms of how people should act to balance individual interests and collective responsibilities. They are meant to minimize negative impacts and exploit positive opportunities for the group (Coleman 1988). However, norms can also be a form of control for the benefit of a select few at the expense of the larger populace, like the unwritten rules that govern organized crime (Johnson 2003).

Social networks are the structures that facilitate flows of social capital (Coleman 1988), and networks may be considered closed or open. Closed networks, in which all actors have some connection to all other actors, depend on norms meant to minimize negative or maximize positive impacts (Arregle et al. 2007). Closed networks have high levels of trust that make transactions between members less costly, because they can assume everyone will adhere to group norms. However, networks with a high degree of closure can also act to exclude new members, and social capital becomes an instrument of discrimination (Johnson 2003). Additionally, membership in a dense, closed network can inhibit success because obligations to others in the network reduce one's ability to focus on individual success. In open networks, ties are less dense because not all actors know all of the other actors in the network (Arregle et al. 2007). An open network structure makes it easier for group members to access new resources and sources of information, but the open structure also makes it more difficult for group members to sanction others who fail to fulfill obligations, thereby reducing the trustworthiness in the network. Each network is different, so each group must find a level of closure that maximizes group productivity.

Voluntary organizations are an expression of social capital – they exist to support some collective purpose of their members. Therefore, it follows that organizations can have social capital and exist within social networks. Organizational network connections can be sorted into three categories: bonding relationships, bridging relationships (Adger 2003), and linking relationships (Franke 2005). Bonding social capital tends to be internal to groups, made up of strong ties based on family, kinship, friendship, and locality. Bridging ties are external to groups, linking them with other groups for economic and other benefits, and these ties are based on trust and reciprocity (Putnam 1995; Adger 2003). Linking ties are similar to bridging ties, but are often presented as a separate category denoting connections between groups across different social strata (Franke 2005) or with individuals in positions of power (Klyza, Isham, and Savage 2006). Bonding ties lead to more dense networks, but bridging ties lead to larger networks (Sobel 2002). Generally, the density of a network of bonding and bridging ties, along with other ways of measuring social capital, have been shown to increase effectiveness and promote economic development (Adger 2003). However, the quality of a relationship matters as much or more than the number of connections a group has, so a balance of ties is key to group success. Large amounts of bonding capital can hamper economic development by reducing reliance on bridging capital, isolating that group of actors, or promoting actions that benefit the actors without benefiting society as a whole (for example, Woolcock 1998 notes organized crime as an example of counterproductive social capital).

Just as human relationships change over time, social capital is dynamic. Flows of social capital depend upon network closure, stability, levels of interaction, and network interdependence (Nahapiet and Ghoshal 1998; Arregle et al. 2007). Increased stability allows trust to accumulate over time and allows norms and structures to mature. As interactions between actors increase, they develop and maintain obligations to each other (Bordieu 1985). Actors come to rely upon each other more, and this interdependence generally fosters the development of higher levels of social capital (Nahapiet and Ghoshal 1998). Within this framework, social capital is both a stock and a flow (Poulsen and Svendsen 2004; Arregle et al. 2007). It is an asset actors use to accomplish their goals (Lorenzen 2007; Wagner and Fernandez-Gimenez 2008), but it is also a process that facilitates both collaboration and action (Adger 2003; Wagner and Fernandez-Gimenez 2008).

Based on the above discussion and the needs of this chapter, I define social capital as an accumulated asset that lies within the trust, norms, and social networks available to an actor in a place. Actors who accumulate social capital may be individuals or organizations. Social capital then becomes a resource that reduces the costs, financial and otherwise, of collaboration within and between groups, thereby enabling actors to make decisions and take actions that accomplish their goals.

Connecting Social Capital to Institutional Capital

One question that has not received as much formal attention in the literature is the connection between social capital and institutional, or political, capital. Institutional capital can be thought of as the broader, formal political conditions and structures that enable or constrain actors' abilities to meet their goals (Scoones 1998). Institutional structures rise from elements of social capital because they are codifications of societal norms that exist to enforce societal expectations when trust is not enough (Maloney, Smith, and Stoker 2000). Regulations, like those governing permitting and quality standards in drinking water management, also create accepted paths for communication between actors across scales. Likewise, social capital facilitates political processes and removes barriers that inhibit effective natural resource management (Mullen and Allison 1999). Areas with higher levels of social capital may also see a higher participation in political processes, stimulating growth and enhancing civic vibrancy (Maloney, Smith, and Stoker 2000; Putnam 2001). Because institutional capital and social capital are so intertwined, it is difficult and perhaps even artificial to separate one concept from the other (Stimson et al. 2003). Consequently, throughout this research I will use the term social capital to refer to informal norms and networks and institutional capital to refer to formal structures.

Measuring Social Capital

One of the chief problems in studying social capital is that no standards exist for its measurement, partly because it is difficult to define quantifiable indicators of social capital. Social capital indicators are less tangible than other types of capital indicators; for example, indicators of human capital may include education, age, and other data that are easy to measure via surveys (Bordieu 1986, Johnson 2003). Trust, however, is more difficult to measure. Surveys and interviews may include questions about trust, but self-reported trust may not be as mutual or as effective as it appears to a research participant. A concept like trust is also contextually specific. A situation that builds trust in one region or nation may not increase trust in other places or under different circumstances. Because of this specific, fluid nature of social capital, standard measurements of it would be misguided at best.

This noted, there are various quantitative and qualitative ways of evaluating the social capital available to a network in a place. The first notable studies of social capital used secondary national-scale data to derive indicators (Knack and Keefer 1997; Knack 2002). For example, Knack and Keefer (1997) used the World Values Surveys of 1981 and 1990-91 to develop some imperfect indicators that were still useful for making general statements about social capital. Currently, most studies investigate social capital by using primary surveys that measure proxy indicators of social capital (e.g., Pretty and Ward 2001; Coffé and Geys 2006; Klyza, Isham, and Savage 2006; Kramer 2007; Krause, Handfield, and Tyler 2007; Miller and Buys 2008; Murphy 2007; Bouma, Bulte, and van Soest 2008; Wagner and Fernandez-Gimenez 2008). Some social capital indicators are more objective, focusing on the number and type of social connections or on behavior that might indicate community involvement, like voting behavior (Coffé and Geys 2006). One advantage to using these types of quantitative indicators with sufficiently large sample sizes is that statistical analysis techniques, like principal components analysis (Coffé and

Geys 2006) and multiple regression techniques (Kramer 2007), can be used to link social capital indicators to environmental variables. The drawback of such indicators is that the absolute number or type of connections is not necessarily indicative of the quality of connections or the likelihood that actors could take advantage of their available social capital in times of need. Additionally, studies must give special care that indicators are appropriate proxies for social capital; for instance, both Coffé and Geys (2006) and Kramer (2007) use some social capital indicators that may be categorized more appropriately as human capital, like level of education and household income. In contrast to such semi-objective indicators, other quantitative social capital indicators rely on respondents' self assessment of various community characteristics (e.g., Wilson 2006; Murphy 2007; Miller and Buys 2008), like emotional support or aid rendered during a disaster. Such proxies are subject to issues of respondent bias, but they can also be valuable for describing the potential social dynamics in an area. To illuminate ambiguities and bias in the quantitative data, some studies use qualitative interviews to triangulate survey results, e.g., Wagner and Fernandez-Gimenez (2008) and Bouma, Bulte, and van Soest (2008). In other cases, rigorous qualitative assessment of interview data, documents, and participant observation served as a basis for social capital analysis (McCallum, Hughey, and Rixecker 2007).

In addition to the traditional quantitative surveys and qualitative interviews, there are several promising tools for measuring social capital in a community. One methodology important in the context of this paper is social network analysis. In analyzing social networks, relations between people serve as the units of analysis and research focuses on network structure as it affects indicators of "the utility of specific resources and their potential accessibility" (Franke 2005, 14). Indicators focus on network properties, diversity, and relational properties, and can include items like the number of people in a network or the strength and nature of relationships. Although researchers can obtain this information through surveys, drawing maps of peoples' connections to each other can also be a helpful technique.

Social Capital, Institutional Capital, and Natural Resource Management

In general, natural resource management presents interesting challenges that lie at the intersection of science and socioeconomic priorities. Water management is difficult in particular because water is imperative to human survival; when water is scarce, people must balance their personal needs with those of society as a whole (Appelgren and Klohn 1999). Scientific knowledge about hydrology is insufficient for successful water management; people must also work within social norms and institutional rule-making structures to ensure that everyone has an adequate supply of high quality water. Effective water management requires actors to make connections that enable conflict resolution and sound policy making, and an inability to do so may even contribute to water scarcity and vulnerability (Appelgren and Klohn 1999; Flora 2004; Downing et al. 2005). These relationships suggest that on some level, social capital is essential to water management.

Water management efforts that include social dimensions have been largely successful. Public participation in water management is growing, and projects that are successful in both the short and long term take place in areas with greater social capital (Mullen and Allison 1999; Pretty and Ward 2001; Khasankhanova 2005) or in structured decision-making environments that require trust building and network expansion for consensus building (McDaniels, Gregory, and Daryl 1999). Additionally, water managers are beginning to realize that social dimensions must be included in hydrologic modeling (Downing et al. 2005). Social norms influence water consumption behavior (Miller and Buys 2008), and community groups can affect water quality and water management (Kramer 2007). Further investigation of the roles that social and institutional capital plays in water management may help managers collaborate with communities to develop viable, sustainable solutions to water management challenges.

Drinking Water Management in Centre County, Pennsylvania

This research is part of a broader research agenda to model the capacity of rural CWS to adapt to climatic variability and change, and completing the first phase of this research required both building trust with local CWS managers and obtaining an understanding of the determinants and indicators of CWS adaptive capacity in Central Pennsylvania. To this end, in spring and summer 2006, I conducted semi-structured interviews with officials from nine of the 36 active CWS in Centre County (Table 2-1); I label them Systems A through System I in this text. A key informant, a Centre County government employee engaged with drinking water management, suggested 15 potential CWS based on anticipated ability for managers to participate. Four of the interviews took place with a single official from each of the four systems; the remaining systems gave group interviews with multiple officials from each of the remaining five CWS. A rich background of prior research on drinking water systems in Central Pennsylvania provided a basis for triangulating results (Pascale 1997; Jocoy 2000; Pike 2001; Windram et al. 2003).

Based on Penn State IRB#22225, I informed participants that their responses would remain anonymous, and officials in eight of the nine interviews consented to having the interviews tape recorded. Interview results from the eight transcribed and coded interviews form the bulk of the data synthesized below, but the discussion below uses all nine social network maps. Participants selected the interview location, and all chose their CWS offices or regular CWS meeting spaces. I structured the interview guide to solicit information about CWS management capital assets: natural resources, technological capital, financial capital, human capital, institutional forces, and social capital. To make participants more comfortable and to help build trust, I placed the questions in an order that enabled respondents to provide simpler, more objective system details before answering more difficult questions about economic concerns and relationships. After responding to the initial questions, participants completed a social network mapping exercise,

Table 2-1: Characteristics of CWS in Centre County, PA, classified by size. Note that the number of reported systems in the county does not include 9 mobile home parks or nursing homes, even though they technically meet the EPA definition of a CWS. These "systems" serve 25 people or more, but a single property owner contracts water management out to a certified operator, and water costs are rolled into lot rent or medical care fees the property owner charges to residents. The number of systems reported above reflects the remaining systems that have municipal management structures or volunteer boards who interact with individual customers.

System definition		*Centre County CWS Total (2005)*		
Type	**# Customers**	**# Active Systems**	**Average # Customers**	**# Active Systems Interviewed**
Very Small	25-500	15	185	3
Small	501-3,300	16	1,349	4
Medium	3,301-10,000	2	7,999	1
Large	10,000+	3	34,698	1

described below. Finally, to assist me in later stages of this research, I asked participants several questions regarding their perceptions of climate change and the connotations they attached to technical terminology, such as vulnerability and adaptive capacity. I do not detail these responses in this paper; however, they were valuable later in helping me to establish effective ways of building consensus on key climate topics using language with which CWS managers are comfortable (see Chapters 3 and 4).

Routine Operational Concerns

One of the fundamental characteristics driving CWSs and their relationships with other actors was the water source type. Of the systems interviewed, three used groundwater wells, and two used surface water. The remaining four systems used groundwater under surface water influence (referred to as groundwater-under-SWIP systems), which means that surface water infiltrates the well easily and the well is more responsive to changes in precipitation. The degree to which managers were concerned about adequate water quantity varied; generally, surface water and groundwater-under-SWIP systems experienced more problems from drought, but one established groundwater system reported seeing responses in its wells during extended dry periods. Water quality, however, was a universal concern. The Pennsylvania DEP did not regulate the smaller CWSs rigorously until after the waterborne disease outbreaks of the 1970s and early 1980s, and many managers of small CWS expressed frustration about water quality “mandates” even though their systems never had a history of *Giardia* or *Cryptosporidium*. For example, several managers reported customer complaints about high levels of chlorine affecting the taste of their water, but managers’ response options are limited because DEP sets the required chlorine amount based on water quality test results.

Water quality regulations are among the pressures that have a significant impact on CWSs' financial abilities. All systems must fund water quality testing, and some systems with surface water or groundwater-under-SWIP are required to build multimillion dollar treatment plants. Systems also expressed concern about their aging infrastructure; water delivery pipes are often several decades old and prone to leakage. CWSs were limited in their ability to raise funds for repair costs and new improvements. All systems expressed reluctance to increasing customers' rates, but the small systems were especially concerned about the impacts of high water prices on small communities where many residents are older and have fixed incomes. Some CWSs had potential financial resources such as property for sale, and the private system had the option of contracting its services to smaller systems, but otherwise systems have few sources for raising additional revenue. Consequently, managers must apply for grants and low interest loans through state and federal programs to fund major repair and capital improvement projects. Several of the systems interviewed were in the process of increasing their eligibility for state and federal funding by converting from systems managed by private owners and neighborhood associations to systems managed by municipal authorities. In these cases, private water associations give the surrounding municipality jurisdiction over the CWS; municipalities return most of the decision-making power back to a water authority board that usually consists of the original water association members.

Norms and Trust

The small and very small rural CWSs began as voluntary community organizations; these organizations' levels of social capital allowed the volunteer work of a few to benefit a whole town. Historically, these community members believed that they had obligations to invest in the physical capital required to produce water for the good of the community; this conflicts with many modern community members' expectations that individuals are entitled to an ample supply of safe water at minimal cost. When people see physical capital as a private good, they invest in it because property rights to that capital ensure that they, as investor, will reap the benefits (Coleman 1988). Treatment of raw water to produce a sustainable, safe water supply turns water into a capital asset, but people still tend to ignore the costs associated with securing that supply and the benefits the community accrues because safe water is available. When CWSs need to make management changes or invest in capital upgrades, managers must balance customers' assumptions that water is vital to life with their willingness to pay for insuring that safe water is available when they need it. This dominant social belief that water is a right constrains CWSs' abilities to raise rates:

> People take it for granted that they have water coming out of their faucet. And they're not willing to pay a ton of money to make sure it happens, it's just something you're supposed to have. It's not like satellite TV or something where people are actually going out looking for it.
>
> -*Manager, System D (large private CWS)*

Customers who take their water supply for granted present a challenge for small rural CWS managers. Managers from three CWS reported having little to no formal water management training, and they rely on long-term commitments from volunteers to serve on water authority boards. These managers live in their communities and are subject to community norms, so they are often reluctant to raise rates when they know it will have a negative impact on their neighbors. When board members need to make changes to system management, they try to explain their decisions to customers and restore trust, but a lack of regular community participation and knowledge about water management hampers their efforts:

> We had a big meeting one night when we first started this and we had a lot of people there; we usually don't get anybody to the meeting, nobody cares… When we were talking about putting in meters and charging they were like "Oh no, we don't want that," but I said, "We're going to have to; we have to monitor the water we use." A lot of people got surprised.

-President, System B (very small water association in transition to municipal authority)

Social norms in the small rural CWSs may work against board members when significant changes to system structure are needed, but in routine and emergency situations, systems are able to successfully use volunteers to make up for a lack of human capital. Five of the nine systems indicated they rely on customers and the community for monitoring leaks and responding to emergencies, suggesting that bonding social capital relationships play a role. Three systems made prominent references to volunteers providing necessary human capital that reduced the CWS's financial costs. Some volunteers, like those for System A, a very small public water association, provide small services like completing daily monitoring requirements while the board member in charge goes on vacation. When a delivery line breaks in System G, a small water association in transition to a municipal authority, volunteers from within the community provide assistance ranging from the free meals provided by the local ladies' auxiliary club to free repair services:

> We've got a guy down there who's an electrician, I haven't paid a bill to him in the last five years, and he's done all the motors and everything. I keep asking for a bill and I never get any. So he's got some money invested in it but he won't hand me a bill so I can't pay it. I even offered to take care of the water bills for him and he said "Hey, don't worry about it."

-President, System G (small water association in transition to municipal authority)

Social Networks

After the series of initial questions, I gave the participants markers and a sheet of paper and guided them through a social network mapping exercise. I told the participants to think of their CWS as a single entity rather than as individual people, and to draw their connections to other people or entities with whom their CWS interacts (Figure 2-1). After listing each contact,

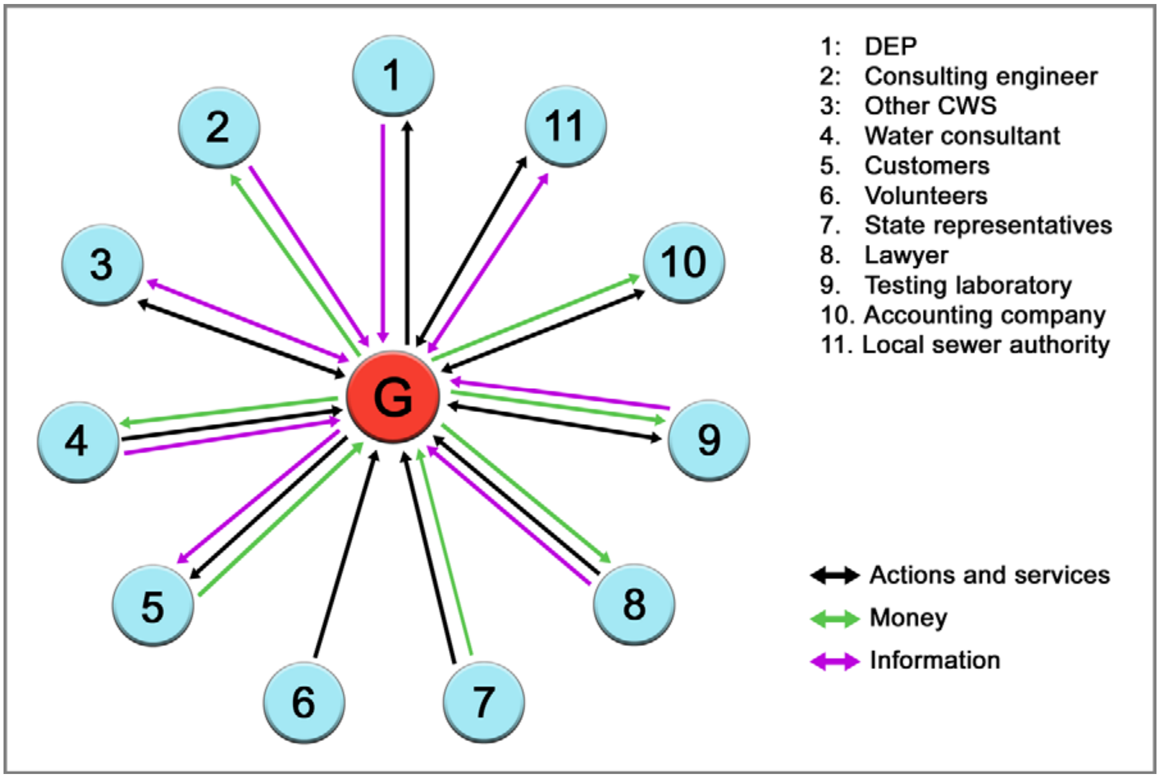

Figure 2-1: Social resource network map, created by Vice-President of System G with the assistance of the system President. This map has been simplified from the hand-drawn version to increase legibility and to synthesize the types of exchanges the participant described into general categories. Black arrows symbolize the exchange of services or actions, such as water testing or help in emergencies. Green arrows indicate some exchange of financial resources, including help with securing funding. Purple arrows symbolize an exchange of information or knowledge, such as describing details of system operation or sharing experiences about system management.

participants described what they receive from and provide to each of their contacts. I encouraged the participants to draw their own maps; however, several of the participants declined to draw their own maps, citing fears of doing the maps incorrectly. In these cases, I drew the maps, but was careful to prompt participants more often to ensure that my sketches reflected the participants' conceptions. These participants' desires to please the interviewer suggests some bias, but because of the nature of the questions asked it is unlikely that this bias negatively influenced the structure of the social network maps produced. Finally, I asked participants to rank the degree to which they thought of each relationship as positive or negative on a Likert-like scale from 1 to 5, where a 1 indicated a strongly negative relationship, a 3 indicated a neutral relationship, and a 5 indicated a strongly positive relationship. The manager of System I declined to rank his contacts, stating that the unusual hierarchical structure of his medium-sized system means "I don't have a negative. I have to make this work, and I have to deal with people, whether they're hard to deal with or not." I summarized the social network maps by compiling the actors the CWS managers listed, the types of exchanges the CWS provides to and receives from each actor, and the number of maps that included each actor with that type of relationship. Interactions with each actor are classified under social capital (informal, Table 2-2) and institutional capital (formal, Table 2-3) relationships. I further subdivide these into bonding, bridging, or linking relationships for both social and institutional capital.

When the CWS managers were making the maps, it became apparent that different systems had different types of relationships with the same actors. Relationships often had both formal and informal components, and actors played multiple roles, even within the same system. For example, all systems listed their customers as actors with whom they have connections. Formal, institutional relationships with customers involve the exchange of funding for the provision of adequate supplies of clean, safe drinking water. Five systems listed additional informal, social

Table 2-2: Compiled list of bonding, bridging, and linking relationships indicating social capital, as presented by CWS managers in their social network maps. Note that two systems thought their relationships with a commercial water bottling plant and volunteers were significant enough to be listed separately from general customers, even though there was some overlap. Actors who contributed to different relationship types are listed separately under each relationship type. Columns indicate what the actor provides to the CWS and what the CWS receives from that actor; these actions are paraphrased from the social network maps. The frequency column indicates the total number of systems whose managers drew that type of connection with that actor.

Type	Actor	CWS Provides	CWS Receives	Frequency
Bridging	Association members/customers	information	assistance recognition donations monitoring	5
	CWS president	information	approval	1
	Bottling plant	water allocation assistance	assistance financial support	1
	volunteers	assistance	assistance	1
	local sewer authority	cooperation infrastructure	cooperation	1
Bridging	Centre County water systems coordinator	advice for other CWS	advice	6
	Schools and community groups	information tours donations	publicity	1
	Local hunters and fishermen	denial	request to use land	1
	Business development groups	plans	more customers planning information	1
	Neighboring CWS	assistance equipment	assistance equipment	3
Linking	State legislators	requests for assistance	cut red tape overlook unwritten state issues	1
	Pennsylvania Rural Water Association (PRWA)	dues requests for assistance	assistance training information leak detection	2

Table 2-3: As in Table 2-2, but of bonding, bridging, and linking relationships indicating institutional capital.

Type	Actor	CWS Provides	CWS Receives	Frequency
Bridging	Association members/customers	information clean water emergency information	funding complaints	9
	Internal management chain of command	information	instructions	1
Bridging	Centre County water systems coordinator	money	certified operator services	7
	Paid contractors	money samples reports	repairs legal services technology chemicals, etc.	1
	Municipality	reports at meetings	assistance grant monitoring ordinances	3
	Development agencies	more customers information on development	plans for expanding system	1
	Neighboring CWS	purchase system money	new system new water supply	1
Linking	Centre County water systems coordinator	information	state-level interactions grant help regionalization help	4
	DEP/other regulatory agencies	good water grant money reports time drought/emergency plans	regulations demands customer complaints inspections	8
	State legislators	request for grant help	grant help	4
	Other utilities	information on facilities/locations money	power phone	1
	Dept. of Transportation	permits	road projects	1

relationships with their customers. Customers assisted CWS managers with monitoring the system for leaks and water quality problems, provided recognition for board members' hard work, and even provided occasional donations of funds. Such contributions to social capital are layered within institutional relationships, and the distinction between the capital types becomes blurred.

The CWSs make up for shortfalls in human capital and in physical capital through their relationships. In addition to their bonding relationships with customers, some turn to neighboring CWS or other utilities within the community to share advice, manpower, and equipment. The Centre County water systems coordinator in the County planning office plays a critical role for several systems, providing institutional bridging relationships through certified operator services and by serving as a liaison for communicating with state and federal regulators. He also went beyond his official duties to be an informal source of advice, and helped systems form bridging connections with other CWS in the region. The large private system actively seeks to build social capital by providing tours and doing outreach with schools and community groups. In all cases, the average manager rating for these relationship types was positive to strongly positive (ranging from 4.1 to 5), suggesting that these relationships add value to the CWS.

The Centre County CWSs had less positive relationships with regulatory authorities. Eight of the nine systems interviewed put a connection to DEP on their maps. The median ranking for relationships with DEP was positive, but several systems' negative experiences with DEP brought the average rating down to neutral (3.3). Regardless of the relationship quality, managers reported that their relationships with DEP are decidedly one-way. DEP is not the only agency with regulatory influence on drinking water in Pennsylvania; the Susquehanna River Basin Commission (SRBC) has extensive authority over water use allocations in the Commonwealth. Surprisingly, only two systems mapped a direct connection with the SRBC, and both systems were municipal authorities that employed their own certified operators. The president of system C, who was also a certified operator for a different CWS, mapped an indirect relationship with the SRBC through the Centre County water systems coordinator. However, the potential exists for water managers to increase their involvement with regulatory agencies, and these relationships may lead to a greater role for individual CWS and policymaking. The manager for system D described collaborative efforts between the EPA and the water industry, and she felt that acceptance of new water quality engineering solutions was higher when the industry was challenged to develop their own measures to meet EPA standards. By increasing their efforts to connect with state and federal agencies, CWSs may begin to create similar environments that give them an opportunity to provide input for policymaking.

Discussion and Conclusions

CWS in Centre County have their roots in strong traditions of community cooperation, and even though management structures have changed, the social and institutional capital available to systems remains important to their abilities to provide adequate supplies of clean water to their customers. Small rural CWSs rely on social and institutional capital to compensate for a lack of human and financial capital:

> Down here it's everybody; the whole town's the water company, really. There's just five people that are picked to run it or direct it... (But) if we have a major problem, different ones will say, "Hey can we help?" They'll pitch in and help.
>
> *-President, System B, very small water association (in transition to municipal authority)*

Volunteers become invested in the process of producing and delivering adequate amounts of potable water. By becoming more active stakeholders, customer volunteers may be more willing to view actions such as raising rates or initiating capital projects as a necessary part of providing water for the community. More research is needed to determine whether small CWSs with large amounts of bonding social capital are more effective at getting customers to view water as a public good rather than a public right.

An examination of CWS social networks tracked strong instances of bonding and bridging social and institutional capital. However, some systems are more effective at communicating beyond the local scale. Further questioning would be required to determine managers' levels of knowledge about significant regulatory authorities beyond the DEP such as the SRBC, but the lack of these connections and the top-down nature of the relationships that do exist seemed to contribute to managers' feelings of frustration with regulations. Raising awareness about the regulatory structure and encouraging linkages beyond the local scale may not immediately translate into better opportunities for CWSs because the regulatory system is not set up to accommodate two-way dialogs. However, with the growing acceptance of participatory water management, systems that make connections with actors on state and federal levels may be able to make more informed decisions in the short term and position themselves to take a role in regional water management in the longer term. Groups like the Pennsylvania Rural Water Association (PRWA) may be helpful in increasing awareness of how local level CWSs fit into the greater regulatory water management picture.

The interview results presented here represent a limited case study; however, there are several lessons to be learned and opportunities for future research. A broader analysis of CWS networks on countywide scales would produce systematic empirical data on the degree to which CWSs rely on social and institutional capital. There are also lessons to be learned about the potential for CWS to build social capital with the goal of making customers more aware of investments in water and of building customer acceptance for raising rates and investing in capital improvements. Finally, the roles of social and institutional capital in drinking water management could be compared to those roles for other public utilities.

Even though social capital and institutional capital are sometimes difficult to distinguish, both can play a role in drinking water management, as suggested by this case study of CWSs in Centre County, Pennsylvania. In small rural communities, trust and the community norm of social service continue to enable the operation of drinking water systems. Even systems that have moved toward the institutionalized model of water management benefit from good relationships in the community and from complex bridging and linking relationships with actors who help CWSs, thereby building both social and institutional capital. Some small, rural CWSs are already adept at using social and institutional capital to supplement shortcomings in financial and human capital. However, there is still room for CWSs to expand and strengthen their networks of social and institutional connections, especially to regulatory authorities on state and federal scales. By becoming aware of social and institutional capital as resources and learning how to build them, CWS managers may be able to increase their capacities for adaptive management. As a result, CWSs will be able to use their increased stocks of social and institutional capital to secure their abilities to provide adequate supplies of clean water to their customers despite pressures from socioeconomic and environmental change.

Chapter 3

Using modified mediated modeling to assess small drinking water systems' abilities to adapt to climatic change and variation

Recently, interest in climate variability and change by municipal water management has grown. New calls for increased research from organizations like the American Water Works Association and the Water Utility Climate Alliance (SFPUC 2008) are evidence that the water industry now takes note of the impacts that climate variability and change can have on drinking water systems' abilities to continue providing safe, reliable drinking water to their customers. Cooperative research between academics, government, and water managers (Kirshen et al. 2004; Miller and Yates 2005) contributes to this awareness and provides valuable methodologies for assessing climate change impacts and adaptation potential. Many of these studies have been conducted jointly with managers of watersheds or of medium to large drinking water systems. However, studies suggest that small and very small rural community water systems (CWS) may be no less vulnerable to climate variability and change than urban systems (Carter and Morehouse 2003), and these small systems' challenging operational contexts make it tricky to assess their abilities to adapt to climate variability and change. These systems face unique financial and social challenges in addition to the usual water management concerns, but previous research fails to address systems of this scale adequately.

The Commonwealth of Pennsylvania provides excellent examples of small system management in the United States. The U.S. Environmental Protection Agency (EPA) classifies public drinking water systems based upon the number of customers a system services. A very small community water system (CWS) serves 25-500 permanent resident customers, and a small CWS serves 501-3,300 permanent resident customers. In 2007, the Pennsylvania Department of

Environmental Protection (DEP) estimated that 84 percent of the approximately 2,100 CWSs in the Commonwealth are very small or small systems; in total these systems serve over 945,000 residents (PA DEP 2007). The unevenly dispersed locations of these small and very small CWS across the state reflect the historically decentralized growth patterns in Pennsylvania (Jocoy 2000).

One major barrier to studying the impacts of climate variability and change in small and very small CWS is that many systems lack extensive formal records, especially in rural areas. These CWSs are required to maintain records of water quality testing data, but records of data on other factors such as water use or financial records are often optional (United States Environmental Protection Agency Office of Water 2006) and therefore not always kept rigorously. Water quality regulations tighten as CWSs expand to accommodate new growth in rural areas, and the increased population strains the systems' outdated infrastructure. To accommodate growth, these systems, often in financial distress, rely on grants to remain in operation and maintain regulatory compliance. Grants are becoming more competitive, and state funding systems like PENNVEST require that CWSs practice more formal recordkeeping and budgeting; many programs even require that former neighborhood water systems replace their casual management with a formal municipal association. Therefore, many rural CWSs began compiling extensive data records only recently.

Small CWSs' limited resources, changing management practices, and reliance on outsiders for technical knowledge about management also present a unique challenge to assessing their capacities to adapt to climate change (see Chapter 2). Managers who lack formal training in water management may find recent assessment techniques, like probabilistic analysis of scenario options (e.g., Dessai and Hulme 2007) or the construction of artificial neural networks for demand forecasting (Bougadis, Adamowski, and Diduch 2005), too complex to use. Researchers in hydrology and climate change vulnerability need to adapt their own methods to accommodate small CWSs.

The purpose of this chapter is to present a system dynamics-based model that allows managers of small water systems to explore their systems' abilities to adapt to climate variability and change. First, it provides a brief overview of how the capacity to adapt to climate variation and change applies to small and very small CWSs. Second, it describes the process of using system dynamics in mediated modeling. Finally, it applies these principles to the construction of the Community Water System Future Adaptive Capacity Scenario (CWS-FACS) generator, a system dynamics model of a small Pennsylvania CWS's adaptive capacity and discusses the implications of such a model for future CWS planning.

Focusing on Small System Adaptive Capacity

The concept of adaptive management, or the process of learning from the results of current management practices to improve future management practices (Holling 1978; Pahl-Wostl 2007), has gained wider acceptance in the water management community (Pahl-Wostl 2002; Westphal et al. 2003; Failing, Horn, and Higgins 2004; Crabbé and Robin 2006; Pahl-Wostl 2007). As part of adaptive management, a water system may seek to build its adaptive capacity (Pahl-Wostl 2007). In the context of this work, CWS adaptive capacity refers to the system's ability to prevent harm or maximize benefits from any future climate change. Adaptive capacity includes how accessible information about climate change is to a system (Pahl-Wostl 2007). As is consistent with the Intergovernmental Panel on Climate Change (IPCC) definition, adaptive capacity also includes the system's ability to make adjustments in management behavior, resource capabilities, and implemented technologies in response to new information (Adger et al. 2007). For example, part of a small CWS's adaptive capacity may be the extent of managers' contacts with those who can provide information about climate change hazards and the degree to which its managers can influence regulatory policy to avoid anticipated damage from those hazards.

Because adaptive capacity is a broad concept, it is often broken into determinants that describe various elements of adaptive capacity. The determinants of adaptive capacity are the conditions that facilitate or constrain the ability of a system to develop and implement adaptive measures (Bohle, Downing, and Watts 1994; Smit et al. 2001; Smit and Wandel 2006). A few studies list the determinants of adaptive capacity (e.g., Smit et al. 2001; Bryant et al. 2000; Yohe and Schlesinger 2002; Yohe and Tol 2002), but there are many more studies on related topics where lists of determinants can also apply to adaptive capacity (e.g., Scoones 1998; Moss, Brenkert, and Malone 2000; Haynes 2003; Adger et al. 2004). Flora (2004) even uses the capital asset framework in the context of adaptive management to outline how small water systems can manage their systems sustainably. Each list varies in length and in detail, but in general determinants fall into the categories of social capital, institutional capital, human capital, financial capacity, natural resources availability, and technological capacity (Polsky et al. 2009).

Adaptive capacity cannot be measured directly, so assessments use proxy indicators of the determinants of adaptive capacity, such as population growth or cooperation between municipal entities, to shed light on these processes (Adger et al. 2004). Indicators may be quantitative or qualitative, and they are specific to systems, sectors, and regions (Yohe and Schlesinger 2002). They are also representative of the cross-scale interactions that shape adaptive capacity, so that a similar value for a particular indicator in two different places may not reflect the same underlying processes shaping that indicator. Furthermore, some indicators depend upon other indicators within or across determinants, and these indicator relationships may vary between places.

Many options exist for assessing adaptation and adaptive capacity in drinking water systems, but not all of these methods are appropriate for small rural CWS with few resources. Common “prediction and control” (Pahl-Wostl 2002; Pahl-Wostl 2007) or “top-down” (Miller and Yates 2005) climate change impact assessments focus on mechanistic operations by forcing climate scenario data on hydrologic systems and using the results to determine appropriate system responses. Often, these approaches are similar to procedures and decision support technologies that many water systems use to optimize short-term system performance and water allocations (Westphal et al. 2003). Other recent studies of the impacts of climate variability and change on water resources focus on analyzing the benefits and risks of specific adaptation options (Dessai and Hulme 2007), but replicating these methodologies can be beyond the capabilities of small CWS. To accomplish such top-down assessments, a CWS would need historical data on local hydrogeology as it influences their water source(s) and on historical local socioeconomic conditions affecting demand; in the case of rural Pennsylvania CWS, the spatial scale, variable physiography, and non-uniform data availability often mean this information does not exist for an individual CWS. Even when these data exist, systems cannot avoid the problems associated with top-down methodologies that assume stationarity, the assumption that historical climatology and hydrogeologic relationships will remain unchanged as the climate changes (Milly et al. 2008); changes in these relationships could have significant impacts on the outcomes of climate change impact and adaptation assessments. Additionally, several factors – notably a perceived lack of ability to influence regulations and operation requirements (Chapter 2) and difficulties in cooperation between institutions with interests in the CWS (Crabbé and Robin 2006) – may limit a system’s ability to plan specific adaptation activities in response to a top-down assessment.

Instead of beginning with climate scenarios and working down to the level of water systems, “bottom up” approaches to assessment begin with water systems’ vulnerabilities and work up to describe how climate change may exacerbate those vulnerabilities (Miller and Yates 2005). Under this “management as learning” approach (Pahl-Wostl 2007), managers then use these assessment results to develop flexible processes that allow them to take this new information and address identified vulnerabilities as they change over time. Comprehensively identifying system vulnerabilities requires input from multiple stakeholder perspectives, so methodologies must encourage participation from a variety of stakeholder groups.

Mediated Modeling

Mediated modeling, also known as cooperative modeling (Cockerill, Passell, and Tidwell 2006), group model building (Rouwette, Vennix, and van Mullekom 2002), shared vision planning, or computer-mediated collaborative decision-making (Cockerill et al. 2008), is one way of bringing stakeholders together to turn complex system concepts into useful decision-making tools (van den Belt 2004). Humans tend to understand complex systems by simplifying them in mental models (Costanza and Ruth 1998), and mediated modeling methodologies exploit this tendency to facilitate bringing scientists and stakeholders together to enhance system understanding by organizing group interactions around building models (van den Belt 2004). Scientists are integral participants in mediated modeling, serving as both facilitators for integrating multiple stakeholder perspectives and as consultants on relevant scientific information (van den Belt 2004). As a result, the collaborative bottom-up process of creating a computer-based model through a carefully designed and well-managed mediated modeling exercise can promote group learning and consensus building, ground the model in stakeholders' reality, and enhance the likelihood that the model will remain useful in decision-making (Costanza and Ruth 1998; Rouwette, Vennix, and van Mullekom 2002; van den Belt 2004; Cockerill, Passell, and Tidwell 2006; Größler 2007; Cockerill et al. 2008; Tidwell and van den Brink 2008). Although unsuccessful mediated modeling is not documented often in the literature (Größler 2007), there are multiple cases of successful mediated modeling exercises used in water management (Cockerill, Passell, and Tidwell 2006; Tidwell and van den Brink 2008).

Mediated modeling is a process that must be adapted to particular places and problems (van den Belt 2004). There is no standardized approach to mediated modeling, but approaching models from an intuitive system dynamics perspective facilitates the process of integrating stakeholder perspectives. In general, a modeling team first determines the suitability of mediated modeling to a particular problem (Tidwell and van den Brink 2008). The modeling team then arranges meetings or workshops with stakeholders to construct a model. In addition to orienting the stakeholders to system dynamics concepts, the modeling team may present a small concept model that helps the group visualize the main goal of the mediated modeling exercise and orients them to the model capabilities and limitations (Luna-Reyes et al. 2006). After all group members understand the model and correct any inaccuracies in the seed model, they proceed to describing model variables, the change of variables with time, and expanding the model structure. During this process, it is ideal for a member of the modeling team to either have access to the computer simulation or work with other visualizations of model structure so that any changes discussed by the group can be captured immediately (van den Belt 2004). This is particularly easy to do if the modeling team is using one of several off-the-shelf system dynamics modeling packages. After the modeling team is able to synthesize the results of these initial meetings, they hold additional meetings to demonstrate to the group how its input was used to change the model and to continue the iterative process of reflecting on the model's structure.

According to van den Belt (2004), mediated modeling has several advantages. It is a powerful tool in encouraging group learning and increasing shared understanding. It also assists participants in developing a consensus on the structure and function of the system in question, resulting in more productive group thinking and discussion. Additionally, the final model serves as a foundation for decision analysis and policymaking. Together, these advantages enable participants to feel as if the group has some ownership of the results. A sense of group ownership helps the participants move forward and prepare to use the model to experiment with scenarios and operationalize the model's use in decision-making (Luna-Reyes et al., 2006). Building this sense of ownership is vital to addressing concerns that resource managers are more likely to use climate-related decision tools when they understand their structure and believe that the tools are relevant (Rayner, Lach, and Ingram 2005; Dow and Carbone 2007; Yarnal et al. 2006; Tribbia and Moser 2008). By taking part in creating the model and ensuring that the group considers all input, it is less likely that group members will consider the results irrelevant.

Case Study

Case Study System Characteristics

In a previous research phase, Whitehead (see Chapter 2) conducted semi-structured interviews with managers from nine of the 36 CWS in Centre County that bill individual customers directly and are operated by investors, groups, municipalities, or the state. During these interviews, participants answered questions designed to identify possible factors that may affect CWS climate change adaptive capacity. The Gregg Township Water Authority (GTWA) was selected from this interview group as the case study CWS because of its members' ability to commit to three group meetings and because of the system's reliance on social capital for system operation during emergencies. The researcher secured the CWS's participation via a presentation before a regularly scheduled GTWA board meeting. The five member board brought the matter to a vote and unanimously agreed to participate in the meetings and assist with building the model as much as possible.

The GTWA is a water authority located in the Penns Valley region of Centre County. Currently, its source is a surface-influenced spring that serves fewer than 200 people. The system has suffered infrastructural and financial damage from both floods and droughts in the past.

During the course of this study, drought conditions forced the CWS to drill a new emergency well, which may become its primary source despite its surface water influence. Both the spring and the well are located in dolomitic limestone (Pennsylvania Department of Conservation and Natural Resources 2001), and CWS authority members report that the spring responds quickly to changes in rainfall. According to Campbell et al. (2003), dependence on variable climatic conditions makes it difficult to separate changes resulting from rainfall and from management decisions. As a result, this CWS is a good candidate for using systems modeling to explore its performance under future climatic conditions that may vary from historical climatology.

In the past four years, required technological upgrades and local economic conditions placed the CWS under significant financial stress. To meet Pennsylvania Department of Environmental Protection (DEP) requirements, the authority must fund and construct a new treatment plant for filtering its source water. Recently, DEP also required that the CWS replace its storage tank with a larger, newer model. In addition to these upgrades, the system also incurs repair expenses from periodic breaks in cast iron transmission lines, which are over 40 years old. Concurrent with these increasing expenses, decreasing non-residential demand began reducing revenues. Because of the economic downturn and rising materials prices, the local industrial company – formerly the CWS's largest customer – reduced its product variety and cut its work force, resulting in a substantial reduction of its water use. The area school district also closed the local school in 2006. In 2007 the school was re-opened as a community center, but the center will use less water than the old school.

To cope with the financial stress, the CWS changed its system management type. For decades, the authority was a neighborhood water association and subject to slightly less stringent regulatory requirements for data collection and financial planning. Unable to fund the storage tank replacement and new treatment plant on its customer revenue, the CWS became a municipal-affiliated authority in 2007 to increase their eligibility for grants and low-interest loans. The municipality opted to delegate all functions except grant administration to the authority board, so management personnel stayed the same. Most of these board members possess no formal training in water system management; they operate the authority based upon its members' decades of experience. To supplement their experience, they retained contracts with the same certified operators and engineering contractors the authority used while it was a water association.

Model Construction

Stakeholders in the case study CWS provided the input used to construct the CWS-FACS model, which runs in the isee systems™ graphical system dynamics modeling software STELLA™. This input included data collected from the participants during three focus groups, held at the location of the CWS's choice. Eight participants attended the first focus group, and five members with central roles in CWS operation continued through the remaining groups; although these groups are small, they are still within the normal group size for mediated modeling (Rouwette, Vennix, and van Mullekom 2002). Because the CWS stakeholders did not initiate the process and took a passive role in physically constructing the STELLA™ model, it was not a true mediated modeling process (van den Belt 2004). However, critical elements of mediated modeling remained intact throughout the case study. Participants learned about the system dynamic structures involved in model construction and used their knowledge to make suggestions for model revisions, many of which the modeler carried out immediately during focus groups. Most importantly, the participants became engaged in the research process, going beyond their formal level of commitment to gather additional quantitative data on system finances. The supplemental data, along with several participants' extra consultations on model structure, allowed the modeler to improve estimations of financial and technological model variables. This level of engagement proved sufficient to help participants remain comfortable with the model and find it useful enough for operational use.

The primary method of knowledge elicitation for constructing the model was a series of three meetings based upon mediated modeling techniques (van den Belt 2004). In general, schedules for the meetings followed the scripting technique introduced by Andersen and Richardson (1997) and used by Luna-Reyes *et al*. (2006) in collaborative system dynamics modeling. This methodology involves constructing a series of well planned group processes and activities designed for facilitating knowledge elicitation and exploratory problem solving. Simple scripts direct the entire research process and include meeting logistics, participatory knowledge elicitation, and model construction steps. Often, researchers use scripts to coordinate research team activities that take place in large workshops with stakeholders. In this case, scripts were used to make the most effective use of the relatively short contact time between the participants (Table 3-1) and the researcher. Formal scripts were used for knowledge elicitation during two initial focus groups.

In the first focus group, participants identified 11 critical indicators they believe affect their CWS's ability to adapt to climate change (Table 3-2). After the group selected these indicators to include in the model, they worked individually to rank the factors according to importance. The researcher used the ranks to prioritize which factors to focus on in the model. For example, participants believed that their ability to respond to accidental contamination events like highway spills is important because these events divert funding that they could use for climate change adaptive measures. After it received a relatively low rank from most participants, the researcher removed it from the model to reduce the model's complexity.

Table 3-1: Focus group participation during model construction by participants' roles in managing the case study CWS.

STAKEHOLDER	GROUP #1	GROUP #2	GROUP #3
Authority president	X	X	X
Authority vice president	X	X	X
Authority treasurer	X	X	X
Pennsylvania Department of Environmental Protection (DEP) sanitarian	X	X	X
Township supervisor	X	X	X
Engineer	X		
Certified operator	X		
Emergency management official	X		

Table 3-2: Adaptive capacity factors mentioned by participants during the first focus group. The mode indicates the most frequent rank each participant gave each factor, and the frequency indicates the number of participants who assigned the most common rank to the factor. For example, five participants thought that funding was the most important factor, but three participants thought that water quantity was the most important factor. There is no mode for infrastructure type and condition because each participant gave this factor a different rank.

ADAPTIVE CAPACITY FACTOR	MODE	FREQUENCY
Funding	1	5
Water quantity	1	3
Ability to meet regulations	2	2
Water quality	3	3
Customer satisfaction and tolerance	6	2
Maintenance, emergency equipment	7	2
Upgrading system	8	2
Area geology	9	2
Constant contamination sources	10	3
Accidental contamination	12	2
Relationship with sewer authority	13	3
Customer sales	13	2
Infrastructure	N/A	0

In the second focus group, participants agreed upon the socioeconomic scenarios used in the model. Participants identified growth and development as their chief concern for non-climatic factors that may reduce or enhance the CWS's adaptive capacity. They described their own narrative scenarios based upon slow, moderate, and fast rates of customer growth, which they assume will occur in the CWS. These scenarios include differences in variable behavior based upon growth rate; for example, under a slow growth scenario it is easier for the CWS managers to solicit volunteer assistance, but under a fast growth scenario participants thought the less "organic" growth would limit community cohesion and therefore limit volunteer involvement. Initially, the scenarios were translated to quantitative growth rates in the number of residential connections and the amount of non-residential use by employing a "business as usual" slow growth scenario based on the Penns Valley regional comprehensive plan (Roth 2006). To facilitate users' abilities to see how changes in certain variable values alter the system's behavior, the fast growth scenario assumes that a development the size of a current residential area being built near the CWS boundaries is added each year and that this rate is sustained over the model's time horizon. Under this scenario, the number of customers in the system approximately triples by the end of the 20-year time horizon. The moderate growth scenario falls between the slow and fast growth scenarios.

The researcher met with the participants a third time for their informal assessment of basic model structure before completing the final draft of the model. Participants evaluated the model for its utility and consistency in a final scripted group interview. Due to scheduling difficulties one participant was unable to attend this final group. To avoid inconveniencing the other participants, the researcher allowed him to participate in a separate semi-structured interview using the same group script. These evaluations' results are discussed below the descriptions of the final model sector structures.

The basic model consists of a series of interacting sectors. These sectors are described in the section below (see Appendix C for screen shots and model equations). A discussion of the model's subsequent adaptive capacity indices follows. To demonstrate some of the model results, examples of significant results presented to the CWS participants are included as part of the case study.

Financial Sector

Because participants identified the CWS's financial condition as the most important factor guiding their ability to adapt to climate change and variation, the central model sector includes the system's financial operations. Its structure reflects this CWS's system of keeping liquid funds available and maintaining a small reserve in a money market account. The system's sole source of income is from customer rates, with separate pricing structures for residential and non-residential customers. Expenses are broken into operations and management categories maintained by the system accountant; the categories used correspond closely with suggested operations and management accounting techniques (Raftelis 2005). Separate converters account for the debt incurred for the system's new planned capital upgrades, which include a new filtration plant and storage tank. To simplify the model, the loans necessary to fund the new well are included in the debt repayment structure for the other capital upgrades. The system makes payments on these debts and other expenses monthly, so the model uses a one-month time step over 20 years.

The participants were only able to provide a history of expenses for the six months prior to the start of the modeling phase (April – September 2007). In these six months, some expenses, like attorney's fees, were higher than the system might normally occur because of the extra expenses required to plan and implement the capital upgrades. However, keeping the model relatively simple required long-term average estimates. To compensate, the CWS president provided his expert judgment on whether the previous six months' costs were representative of the system's annual average. He revised some of the cost estimates, but he also expressed concern that many of his estimates would change based upon the new operations and maintenance costs for the new filter plant. At his suggestion, the graphical user interface was altered to allow users to enter their estimated annual costs for each category. Users enter these costs before running the model, and at each model run pause they have the option to revise these estimates.

Water Supply Sector

Initially, rainfall drives the available water supply in the model, represented as output from the spring currently serving as the CWS's main source. Local dye tests were not available to determine the exact infiltration rate and its relationship to spring output; however, managers' experience with the system over several decades again proved useful. During the first focus group, participants noted that in the past accidents (such as spills at a cannery several miles away) produced a noticeable response in the spring's water quality within a week or less. Because the model uses a time step of one month, it is reasonable to assume that rainfall produces a response in the spring output within the same time step. Data from a former USGS streamflow gauge located on the creek just below the spring gave an estimate of the drainage basin size, thereby making it possible to estimate the amount of water available in the basin. The authority president reported that the CWS has supply shortfalls when the spring output drops below 108,000 GPD; this information, combined with the basin size, allowed the researcher to estimate a relationship between rainfall and spring output via the infiltration rate. This relationship allows the model to calculate flows for both the amount of water infiltrating to the source and the amount overflowing from the spring. Although simple, the model successfully reproduced the water supply shortfall experienced during fall 2007 that resulted in the CWS's failure to meet demand and need to enact water restrictions.

Water Delivery Sector

The flow for water source infiltration leads into the water delivery sector, which describes the process through which water enters the system treatment plant and exits through transmission lines. This sector provides the link between the supply side of the water system and the demand side, as driven by the customer characteristics sector described below. Under the model's initial conditions, the system distributes enough water to meet demand, including both customer usage and the estimated 20 percent loss through pipe leakage. When available water is insufficient to meet demand, the system can only distribute as much water as is available and a shortfall occurs. The model also accommodates growth in the number of customers, so shortfalls may also occur if demand exceeds the treatment plant capacity, pumping capacity, or storage capacity.

The model does not account for seasonal changes in water use patterns. While the model could accommodate this easily, the participants from the CWS stated that they have not observed significant changes in seasonal use. The CWS only recently installed meters so water use data for individual users was not available to support this observation. Mediated modeling is participant-driven; therefore, the model relies on the participants' expert judgment and assumes no seasonal changes in use. This is a plausible claim – Maidment and Miaou (1986) found that in three cities across southern Pennsylvania only an average of 5 percent of the water use was tied to seasonal variations; however, demand forecasting methodologies developed since their study may produce more robust results (Gato, Jayasuriya, and Roberts 2007).

Customer Characteristics Sector

The case study CWS primarily serves residential customers, but it also has connections to a local manufacturing plant, local businesses, and public entities such as the local post office. Accordingly, the CWS maintains a separate rate structure for its residential and non-residential customers. At the beginning of the study, the CWS charged residential customers a flat rate of $30 per month; non-residential customers like the local factory and general store paid $30 per 3000 gallons. During the course of the study, it became apparent that requirements for capital improvement loans would require the system to raise its rates. To accommodate users' needs for altering rates, the model includes a box that allows the user to customize rates.

The customer characteristics sector also affects the water delivery sector through its impact on demand. The model uses a flat estimate for the number of people per household based upon the 1999 US Census data for blocks that intersect system boundaries. The researcher estimated non-residential customer usage data per connection based upon the Penns Valley regional comprehensive plan system estimates (Roth 2006), with industrial use altered based upon more recent knowledge of the local factory's reduced production. The growth scenarios include adjustments on the number of household connections added, the number of non-residential connections added, and the changing amount of water use for the five industrial connections at the local factory.

Water Quality and Regulatory Change Sectors

The water quality and regulatory compliance sectors are intertwined in the model. Primarily, the water quality sector functions to add variations in the CWS's expenses on materials and supplies because changes in levels of routine contamination from non-point sources produce a response in the amount of chlorine and other treatment chemicals that the CWS uses. The CWS did not have data on seasonal variations in chemical use, but its spending on chemicals and supplies varies from month to month. Additionally, it is difficult to estimate how much changes in state and federal regulations would cost an individual small CWS. The system dynamics approach allows the model to treat these problems qualitatively by setting the initial water quality at 1 and changing water quality based on percentages. The model defines a mandated level of water quality as the initial water quality plus a percentage of increased water quality through stricter regulations. Water quality of the CWS changes using a periodic function for constant contamination sources. Spending on materials and supplies increases when observed water quality is less than mandated water quality, and increased spending on materials and supplies reduces the water quality deficit, bringing the CWS into regulatory compliance. Regulations slowly tighten over the course of the model through a step function, therefore requiring more spending to reduce the water quality deficit.

Changes in regulations also affect required expenses on capital upgrades. The model simulates this effect by assuming that new regulations will require an additional capital upgrade 10 years into the model run. The choice of socioeconomic scenario drives the upgrade's cost, with the expanding population in the faster growth scenario requiring a larger capital upgrade than in the slow and moderate scenarios to compensate for the larger CWS size. The capital upgrade value is set at $200,000 for the slow and moderate growth scenarios; this amount is on the order of costs for current minor upgrades like the new storage tank. In the fast growth scenario, the upgrade value is $500,000. This is still a fraction of the cost of the new filtration plant; however, participants anticipate that because of the filtration plant's age and technology future capital upgrades will be less drastic than the recent capital upgrade expenses.

Equipment and Technology Sector

Participants also identified having the correct type of equipment, like heavy machinery and leak detection tools, as a major factor in their ability to initiate preventive measures to adapt to floods and droughts. Initially, participants' immediate concerns were for their current lack of any such equipment. However, they had confidence that the major upgrades the CWS is currently constructing will reduce costs involved with future system adjustments made necessary to cope with more frequent floods and droughts. Though not intended specifically for adapting to climate change, both the filtration plant and the new well are important adaptations that reduce the CWS's sensitivity to climate change. Once completed, these upgrades will increase the reliable water supply, place critical infrastructure away from the flood plain, and expand the system's capacity for adding more customers.

In this case, the limiting factor for adaptive capacity will be the infrastructure's age. The Pennsylvania DEP records the CWS's cast iron transmission main construction date as occurring between 1960 and 1969 (PA DEP 2005). The CWS president also reported that they ordinarily repair one or two major line breaks per year. Over the 20-year model time horizon, these pipes will continue to deteriorate, as will the new filtration plant, storage tank, and well pumping equipment. Adaptation will then become more difficult as it becomes more and more expensive to maintain and upgrade the old infrastructure. The model accounts for this effect holistically through an adaptive index based upon the difference between the expected lifetimes of various infrastructure components and the actual ages of these components.

Climate Scenario Variables Sector

In the CWS-FACS model, users have the option of choosing five different precipitation scenarios, each of which produces a different frequency of floods and droughts. Downscaled GCM data is not available with spatial or temporal resolutions suitable for a single small CWS on a monthly time step, so scenarios were created by adjusting historical rainfall data from a nearby cooperative weather station. The Consortium for Atlantic Regional Assessment (CARA) produced an online database of estimated changes in precipitation statistically downscaled to the level of Historical Climatology Network (HCN) stations for seven GCMs and two Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions scenarios (Consortium for Atlantic Regional Assessment 2006b; Arnell et al. 2004). Using the Hewitson method (2003), CARA calculated seasonal and annual means and standard deviations for each climate model for each HCN station in the Mid-Atlantic region of the US (Consortium for Atlantic Regional Assessment 2006a).

Participants had the most concerns about climate impacts in the near term, so the researcher created 20-year precipitation scenarios using CARA projected seasonal variations in monthly mean precipitation from 2010-2039 for the HCN station in State College, Pennsylvania, which is located less than 25 miles from the cooperative weather station near the CWS. The model precipitation scenarios were based on temporal analogs to two 20-year periods of observed monthly precipitation totals at the cooperative weather station near the CWS for the years 1970-1989 and 1987-2006, the last full year of data available at the time of the case study. The latter 20-year range captures analogs to wetter or drier versions of months in the managers' most recent experiences. The former, earlier range captures analogs to several iconic local flooding events that occurred in the 1970s, most notably the June 1972 flooding from the remnants of Hurricane Agnes that locals still use as an anecdotal benchmark for flood severity. Gaps in the cooperative station data were minimal and corrected using the State College HCN data via simple linear regression. For all seven CARA climate models and both emissions scenarios, the difference between the 1971-2000 observed HCN seasonal monthly precipitation mean and the projected seasonal monthly precipitation mean for the 2010-2039 HCN data was calculated; climate model projections were normalized to the 1971-2000 baseline (Consortium for Atlantic Regional Assessment 2006b). For example, the Hadley Centre for Climate Prediction and Research (HDCM) calculated a mean monthly precipitation of 2.7 inches for December, January, and February in 2010-2039 under the B2 emissions scenario. This estimate is 89 percent of the CARA observed mean of 3.0 inches per month for the HCN station in the same season. To create the CWS-FACS HDCM B2 scenarios, observed monthly totals for the cooperative station near the CWS for each December, January, and February were reduced by 11 percent. This process was repeated for all four seasons. Of the seven CARA models, on average the HDCM and Canadian Climate Centre Model (CCCM) produced the widest variety of variations for both the A2 and B2 emission scenarios. Therefore, a total of five scenarios for each date range – the HDCM and CCCM A2 and B2 scenarios, plus the observed data – are available for CWS-FACS users.

The precipitation scenarios connect to the rest of the model through the financial impacts of floods and droughts. The model bases whether a flood or drought occurred on the monthly precipitation totals for floods and droughts during the two 20-year analog periods. When certain minimum and maximum thresholds in monthly precipitation are exceeded, the CWS-FACS model indicates a flood or a drought is occurring and adjusts the CWS's monthly expenses accordingly. The CWS managers did not have records of the costs of floods and droughts in the past, and the costs of such events in the future will depend on changes in event frequency as well as economic conditions and property values (Bates et al. 2008). Therefore, the participants provided estimates of what they believed to be the average costs of floods and droughts, and they understood that the magnitude of the financial damage suffered is subject to variations in costs. In this case, it is more important for managers to visualize whether variations in climate have any detectable financial impact.

Adaptive Indices

To summarize model results, six adaptive capacity indices help users visualize their relative change in ability to adapt over time. CWS-FACS users access adaptive capacity indices through the graphical interface. The model allows users to watch the changes in graphs of adaptive capacity as the model runs. Based on the Human Development Index (Campbell et al. 2003), the adaptive indices correspond to the six determinants of adaptive capacity. To calculate each index, a desirable maximum and minimum value for each indicator is determined. In general, the adaptive capacity index AC_D for determinant D then takes the form

$$AC_D = \sum_{i=1}^{n} w_i \frac{(x_{it} - x_{i\min})}{(x_{i\max} - x_{i\min})}$$

where n is the number of indicators (i) included in the determinant, w_i is the weight of each indicator (if applicable), x_{it} is the value of indicator i at time t, x_{imin} is the minimum desirable value of i, and x_{imax} is the maximum desirable value of i. Values closer to 1 indicate a higher adaptive capacity, while values closer to zero indicate a low adaptive capacity. Ordinarily this number is between zero and 1; however, when an indicator's value lies outside the desirable range, the index value may be less than zero or greater than one. For example, the financial adaptive capacity index is based on the CWS's financial assets. Financial adaptive capacity is comprised solely of a single indicator of the CWS's total funds, so w_i is 1. Ideally, the CWS carries some debt load because accumulating too much financial capital drastically reduces its grant eligibility; this sets the value of x_{imax}. The minimum x_{imin} is the amount of money the CWS needs to meet both its planned and emergency spending requirements at that time *t*. However, the CWS's actual funds could exceed the desirable amount. As a result, the financial adaptive capacity index can be greater than one, indicating that the financial capital is greater than the desired amount. Likewise, when spending exceeds funding, this larger than ideal debt load leads to a negative adaptive capacity index.

It is worth noting that for this model, only the technological adaptive capacity index is weighted. All other determinants used a single adaptive capacity indicator. During the focus groups, participants expressed concern that certain adaptations take longer than others (for example, it takes less time to replace a storage tank than it does to replace an entire treatment plant). They also expressed confidence that recent capital upgrades would decrease the likelihood of repair expenditures in the near future. To capture these perceptions, the model combines the remaining lifetimes of the filtration plant, the storage tank, the pipes, and other equipment (pumps, heavy equipment) by weighting each by the ratio of the current total replacement cost to the estimated time in months that the CWS would need to replace the equipment. The model uses this information to calculate an adaptive capacity index for the CWS's technological capital.

Adaptive capacity indices for social, human, and institutional capital differ slightly from those for financial capacity, natural resources availability, and technological capacity. Based on the focus groups, participants benefited most from social, human, and institutional capital when an event like a flood, drought, or well drilling occur. During an event, the CWS can access these capitals, resulting in financial savings for the system; for example, in the past the CWS benefited from a local electrician who provided services during pumping emergencies and refused to bill the system managers (Chapter 2). To reflect this operation and to simplify the connection to the financial sector in the model, adaptive capacity index values for social, human, and institutional capital only appear when some emergency – i.e., a flood, a drought, or a demand-driven water shortage – occurs (Figure X – screen capture of AC indices). At the beginning of the model run and during each model pause, users may input the average amount of money certain actors, such as volunteers for social capital or Department of Environmental Protection personnel for institutional capital, save the CWS during a flood or a drought. Because a minimum savings from social, human, or institutional capital would be zero (i.e., no such capital exists, and therefore the CWS incurs no savings), any savings from other actors is a positive contribution to adaptive capacity.

Discussion

Sensitivity Analysis

STELLA's™ sensitivity analysis capabilities allow users to examine how incremental variations in constant variable values alter the final model results. By identifying which variables produce the greatest variations in the model results, one qualitatively determines where the most critical uncertainties lie. Because reliable estimates of standard deviations in cost variables are unavailable for the case study CWS, cost variables were tested by setting up 30 model runs with values ranging in equal increments +/- 50 percent of the original variable values. Sensitivity to the infiltration rate of the spring was also tested by varying the rate by +/- 20 percent. Unsurprisingly, the variables that produced the highest sensitivities in the model centered around the operations costs associated with materials, such as treatment chemicals and the fees for contractors, including the certified operator and others who the system cannot employ full time. These are the largest costs with the most uncertainties, so they have a simple linear impact on the

CWS's financial situation. Sensitivity to the infiltration rate was smaller than cost sensitivities by an order of magnitude.

Validation

Without extensive data records for the CWS, it was impossible to calibrate the CWS-FACS model. In lieu of formal quantitative calibration, in the final meeting participants answered questions about whether the model's behavior was consistent with their anecdotal experience. Participants did express skepticism that the input data were accurate; after viewing graphs of customer growth, they believed that the defined growth scenarios were actually too fast. However, they chose instead to focus on the patterns in variable behavior. If they assumed that the input data were correct, then the model variables for base scenarios changed in ways that reflected their experience with the system. Part of their assessment may reflect the participants' repeated concerns throughout the project that assigning projected numerical values to variables is difficult because of the inherent uncertainties, such as the national economy's impact on growth in the region, that are out of the system's control. They emphasized that because of the system's complexity, they valued learning about how changes in one variable cascade into changes in other variables. Based on this assessment and their conceptions of the model's practical value, the participants judged that the results from the model scenarios were plausible.

Limitations

The largest limitation to the CWS-FACS model is that the information available to this CWS is simply insufficient for CWS-FACS to produce highly predictive, verifiable model results. This problem by no means invalidates the exercise, because validation of the model structure allows users to visualize how the system behaves (van den Belt 2004). As the series of focus groups progressed, without prompting from the researcher the participants began to express awareness that the forces guiding how their abilities to operate their CWS are highly complex and impractical to simulate. They were cognizant that the climate and socioeconomic scenarios were "what if" exercises, and that no single model solution was any more likely than any other. However, they reported that it was valuable for them to work with the model and see how changes in a certain variable, such as adjusting the rates, produced different results in the future. Additionally, the participants decided they need to be more diligent about keeping track of data – not just because of DEP requirements, but also because better information on their costs and rates of growth would allow them to gain more guidance on managing their CWS from the quantitative model results. At the conclusion of the study, the CWS officials requested that the researcher train their accountant in using the CWS-FACS model. As they begin to acquire better data and improve their abilities to estimate costs, they plan to use the new inputs to continue helping them experiment with different outcomes of different management strategies.

Conclusions

Small and very small rural CWS face water management challenges in a financial and social context that is often radically different from large CWS. Managers of small and very small systems need ways to explore climate change impacts that accommodate their systems' unique settings. Tools to explore climate change impacts must also be delivered to managers regardless of their level of professional water management training. The CWS-FACS model uses an intuitive system dynamics approach that allows managers to explore their abilities to adapt to possible climate change impacts while accounting for their systems' financial, technological, human, social, and institutional capabilities. The model does not attempt to predict climate change adaptive capacity, and a system's available historical data on system costs and water availability limits its quantitative value. However, the CWS-FACS model does help managers visualize how simple changes in socioeconomic conditions and management strategies can influence their systems' financial abilities. During a case study, the managers of a small CWS in rural Pennsylvania found this type of visualization valuable because of its flexibility to accommodate multiple scenarios of climate change and local growth.

These case study results suggest that future research should investigate the value of system dynamics as a climate change learning tool on a broader scale. Such an intuitive method for learning about climate change in a decision-making context could assist CWS managers regardless of their level of formal water management training or prior experience with a system. By concentrating on the way a CWS functions based on its climatic and socioeconomic settings rather than simple predictions of financial status or capabilities, managers may be better able to recognize important influences on system operation and use that knowledge to cope with unanticipated impacts and outcomes. As a result, simply using a system dynamics-based tool could in itself be an expansion of a CWS's capacity to adapt to future climatic change and variation.

Chapter 4

Promoting preparedness through learning: A process for community drinking water systems to explore climate change adaptive capacity

A common criticism of climate change research is that it has not translated from academic investigations of the physical and social aspects of climate change to practical applications in the public and private sectors. In recent years, however, research has become more focused on applying climate change impacts, vulnerability, and adaptive capacity assessment results to decision-making in uncertain environments (Smit and Wandel 2006; Carter et al. 2007). Even though climate change could influence the production of adequate amounts of safe drinking water, it is clear that this new focus on applied climate change adaptation assessment is not reaching drinking water managers in the United States on a large scale. Research firmly establishes that water managers do not use climate information like seasonal forecasts in their planning processes because they do not believe the information is salient to them or because they are unable to incorporate this information into current operational practices (Carbone and Dow 2005; O'Connor et al. 2005; Rayner, Lach, and Ingram 2005; Yarnal et al. 2006). Managers' inability and unwillingness to use current climate information for planning on short timescales suggests that it may be even more difficult to get them to use information about future climate on longer time scales. Stresses from climate change will be compounded with more familiar stresses like population growth, aging infrastructure, and changes in regulations. To help water managers continue providing adequate quantities of safe water to their customers, it is critical to explore whether climate change could be the stress that pushes their drinking water systems into insolvency.

For drinking water managers to be prepared for climate change, climate information will have to move past academic discourse and into practical applications. This is particularly true for very small and small community drinking water systems (CWS), which the Environmental Protection Agency (EPA) defines as public drinking water systems with 25-500 customers and 501-3,300 customers, respectively. In fiscal year 2008, the EPA estimated that about 83 percent of the roughly 52,000 CWS in the United States are smaller systems, two thirds of which are very small systems (U.S. EPA Office of Ground Water and Drinking Water 2008). These systems are often dismissed as relatively unimportant because 82 percent of people are served by the largest 8 percent of CWS (*Ibid.*). Consequently, it is unsurprising that research and outreach have not focused on the ways climate change may affect the smallest CWS. Instead, climate change impacts on watershed levels are starting to be addressed through integrated water resource management, which often takes a whole watershed approach to water use (e.g., Dole and Niemi 2002; Booker, Michelsen, and Ward 2005; Langsdale et al. 2007). Other analyses of climate change impacts on drinking water tend to focus on urban systems (e.g., Semadeni-Davies 2004). However, very small and small CWS in the United States still serve approximately 24.7 million people (U.S. EPA Office of Ground Water and Drinking Water 2008). Therefore, it is critical that research on climate change impacts on drinking water resources include applications that managers of smaller CWS can use for decision-making.

In Centre County, Pennsylvania, drinking water management follows a very different model than the management styles in urban areas. The county has three large CWS, but many of the smaller systems are isolated in rural areas (Figure 1-1). Based on a rural, independent history of community water management (Marrocco, Franklin, and Sedlak 1993; Jocoy 2000), many of these systems do not take an active role in water management beyond the local level (Chapter 2). CWS managers may cooperate with other nearby CWS to share equipment or supplement manpower during emergencies, but few small rural CWS managers think of managing their water sources as part of the larger watershed. Many of the small and very small Centre County CWS evolved from volunteer neighborhood water associations; even when systems become municipally affiliated authorities, townships and boroughs routinely return control of the CWS to the original board members (Cromwell and Raucher 2004; Chapter 2). As a result, some CWS managers have little or no professional training in water management, forcing them to rely on paid consultants for human capital, which encompasses the set of skills and knowledge people possess that allow them to perform labor that produces economic value (Campbell et al. 2003). To survive, some systems rely on volunteers to help during emergencies, suggesting that social capital – the trust, norms, and networks in a community – are important to small systems' operation (Flora 2004; Chapter 2). This management context complicates the process of developing a tool that will allow small and very small CWS managers to learn about climate change and incorporate it into planning.

Small CWS need an approach for addressing climate change in ways that integrate both the natural and human issues governing their systems' management contexts. This approach needs to focus on applying climate information to management strategies, but it must also accommodate the data availability challenges and multiple uncertainties involved when examining climate change on the scale of an individual CWS. One approach is to focus on CWSs' adaptive capacity, which is their abilities to prevent damage from or take advantage of benefits of climate change (Brooks et al. 2004; Smit and Wandel 2006; Adger et al. 2007). An emphasis on building adaptive capacity promotes flexibility, so by concentrating on building their abilities to respond to a range of uncertain climate change impacts, CWSs could increase their capabilities for responding to or preventing a variety of surprises. An adaptive capacity perspective that incorporates CWS managers' experiences could also be effective for learning because it would allow managers to apply their knowledge gained through experience to the necessary changes in management structure that would increase the flexibility required for adaptive management

(Berkhout, Hertin, and Gann 2006). By incorporating managers' knowledge into the assessment process, it is possible that CWS managers may believe that the resulting decision support tools for climate change adaptive capacity are salient and comprehensive, increasing the likelihood that these tools would continue to be used for planning in the long term. To accomplish these goals, CWS managers need a process that will guide them through understanding adaptive capacity and interpreting the ways in which adaptive capacity enables them to secure their ability to continue providing their customers with ample supplies of safe water despite changing climatological and socioeconomic contexts.

The purpose of this chapter is to present the results of a participatory process for constructing local scale future climate change adaptive capacity scenarios for small, rural CWS. It addresses three research questions:

1. How can the needs and concerns of water managers be used to create a process for constructing CWS adaptive capacity scenarios?
2. Does this process result in reasonable adaptive capacity scenarios for these systems?
3. Do managers learn from the process?

To answer these questions, I will briefly describe the mediated modeling methods used for facilitating collaboration with the Gregg Township Water Authority (GTWA), a small CWS in Centre County, Pennsylvania. Chapter 3 addressed the technical details of the Community Water System Future Adaptive Capacity Scenario (CWS-FACS) generator, which is the system dynamics model built with the assistance of GTWA board members and other stakeholders. In the remainder of this chapter, I will discuss the adaptive capacity scenario results, focusing on the central role of the GTWA's financial security and the rate of population growth as determinants of the system's capacity to adapt to climate change. Finally, I will reflect upon the co-learning experiences I shared with the participants during this mediated modeling exercise and discuss the applicability of these results to climate outreach and extension strategies.

Literature Review

Adaptive Capacity Measurement

To understand adaptive capacity, one must understand vulnerability in the context of climate change. The IPCC literature generally defines the vulnerability of a system to climate change as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of *climate change*, including climate variability and extremes." Vulnerability is then a function of a system's exposure to climatic hazards, its sensitivity to changes in climate, and its adaptive capacity. Vulnerability is a context-specific concept (Cutter 1996) that includes both physical and human components, the latter of which is often termed "social vulnerability" (e.g., Adger and Kelly 1999; Kelly and Adger 2000; Brooks 2003; Adger et al. 2004). Vulnerability research requires diverse approaches because of this combination of intertwined physical and social vulnerabilities (Adger 2006). In the context of this research, the place-based approach to vulnerability is most appropriate for examining the processes of adaptive capacity (Adger 2001). A place-based approach refers to a local study area that is relatively small in comparison to national or international studies (Schröter, Polsky, and Patt 2005). This perspective aids in incorporating the dynamics of vulnerability into studies, especially when such changes occur across scales simultaneously. Schröter et al. (2005) include a place-based approach as one of the five minimum criteria that vulnerability assessments of coupled human-environment systems should satisfy.

The term adaptive capacity has an extensive history, appearing in studies on climate change (e.g. Handmer, Dovers, and Downing 1999; Lorenzoni, Jordan, O'Riordan et al. 2000), natural hazards (e.g. Mileti 1999; Cutter, Boruff, and Shirley 2003), food security (e.g., Bohle, Downing, and Watts 1994; Stephen and Downing 2001), health, and economics (Alwang, Siegel, and Jørgensen 2001), among others. In its simplest form, adaptive capacity is the ability of a system to "modify its circumstances to move to a less vulnerable condition" (Luers et al. 2003). More specifically, adaptive capacity encompasses the capability of a system to anticipate or respond to climate change by altering its behavior and characteristics to mitigate negative impacts, maximize positive benefits, or simply cope with the consequences (Brooks 2003; Adger et al. 2004; Smit and Wandel 2006; Adger et al. 2007). Processes shaping adaptive capacity act simultaneously at multiple spatial scales and at multiple scales of interaction. Adaptive capacity is also hazard-specific, and different hazards have different relationships to time. If adaptations occur on relatively long time scales, then a system is more likely to cope with a discrete event than to adapt to it (Brooks 2003). These ideas imply that the current adaptive capacity of a system is a determinant of vulnerability to continuous hazards and of future vulnerability to anticipated discrete hazards (Adger et al. 2004; Brooks et al. 2004).

When examining adaptive capacity, the scale of assessment is important. This scale can range from broad adaptive concepts on the level of nations to specific adaptive actions of individuals. For the most part, previous adaptive capacity assessments have favored either international level or household level assessments (Vincent 2007). It is important to recognize the role that psychology plays in individuals' decisions to adapt (Grothmann and Patt 2005), but in the developed world many of the most significant adaptation policy decisions will take place on the scale of organizations (Berkhout, Hertin, and Gann 2006; Pelling et al. 2008). Organizational adaptive capacity encompasses the resource and asset base available to decision-makers for devising feasible adaptation options (Adger 2004; Moser et al. 2008). Just as important as the existence of organizational adaptive capacity is the ability of an organization to realize this capacity when it is affected by climate change and other multiple stresses. To assist organizations in general and resource managers in particular, Yohe and Tol suggest using indicators of the underlying adaptive capacity determinants for structuring planning and adaptive management practices (Yohe and Tol 2002; Moser et al. 2008).

The determinants of adaptive capacity are the conditions that facilitate or constrain the ability of a system to develop and implement adaptive measures (Bohle, Downing, and Watts 1994; Smit et al. 2001). An indicator of these determinants is "a quantitative or qualitative parameter that provides a simple and reliable basis" for describing adaptive capacity (Ebi et al. 2004, 4). A few studies specifically list the determinants of adaptive capacity (e.g., Smit et al. 2001; Bryant et al. 2000; Yohe and Schlesinger 2002; Yohe and Tol 2002), but there are many more studies on related topics where lists of generalized vulnerability determinants can also apply to adaptive capacity (e.g., Scoones 1998; Moss, Brenkert, and Malone 2000; Haynes 2003; Adger et al. 2004). Each list varies in length and in detail, but in general, determinants of adaptive capacity fall into one of six categories (Polsky et al. 2009):

- Social capital
- Institutional capital
- Human capital
- Financial capacity
- Natural resources availability
- Technological capacity

Indicators of adaptive capacity, such as population growth or cooperation between municipal entities, may be quantitative or qualitative, and they cannot always be assessed quickly or thoroughly (Polsky et al. 2009). They are specific to systems, sectors, and regions (Yohe and Schlesinger 2002). They are also representative of the cross-scale interactions that shape adaptive capacity, so that a similar value for a particular indicator in two different places may not reflect the same underlying processes shaping that indicator. Furthermore, some indicators depend upon other indicators within or across determinants, and these indicator relationships may vary between places. As a result, it is futile to attempt to develop a universal indicator list, especially for use in local-scale assessments (Berkhout, Hertin, and Arnell 2004).

The next step in developing methods of adaptive capacity assessment should examine both the processes that change adaptive capacity over time and the potential for future changes in adaptive capacity. O'Brien et al. (2004) suggest that their work could be improved to capture potential changes over time. They also suggest that alternative future socioeconomic scenarios could be used to project the values of adaptive capacity indicators through time. In the following section, a discussion of scenarios will explore the definition and use of scenarios and will speculate about the value of using scenarios to address the changing nature of adaptive capacity.

Using Scenarios to Investigate Adaptive Capacity

Scenarios

The complexities of the physical climate system and the unpredictability of human behavior make attempts to determine quantitatively the magnitude of climate change-related impacts inherently uncertain. Social agency and reflexivity contribute to the difficulty in describing future states of socioeconomic systems. Consequently, social and economic forecasts are subject to four challenges (Berkhout, Hertin, and Jordan 2002):

- Overcoming the danger of oversimplifying complex relationships and rationality of agents
- Accommodating surprises, innovations, and discontinuities
- Acknowledging that choices made by social actors in the past shape social change in the future and that actors are more likely to realize particular visions of the future when those visions are widely desirable
- Attempting objective analyses of politicized potential future pathways

One strategy to compensate for these uncertainties is to create scenarios about how the future may unfold. Greew et al. (2000) define scenarios as "archetypal descriptions of alternative images of the future, created from mental maps or models that reflect different perspectives on past, present and future developments." Scenarios contain baseline, or reference, conditions against which to measure change and other information as necessary. Scenarios are not forecasts or predictions, but they may use projections, or descriptions of pathways to a particular future, as input. The IPCC specifies that scenarios are then coherent, internally consistent, and plausible descriptions of possible future states of a system (Carter et al. 2007). These general qualities make scenario approaches flexible, and they can be used easily in many types of quantitative, qualitative, and mixed methodology research.

Different types of scenarios are valuable for varying applications in research on the human dimensions of climate change. Climate scenarios, especially those in which various assumptions about social conditions around the globe are used to speculate about greenhouse gas emissions, are commonly used in assessing the physical impacts of climate change (Nakicenovic et al. 2000). Socioeconomic scenarios are useful in vulnerability and adaptive capacity assessments (e.g., Lorenzoni, Jordan, Hulme et al. 2000; Berkhout, Hertin, and Jordan 2002; Yohe and Schlesinger

2002; Turnpenny et al. 2004). Scenarios are effective exploratory tools for examining the range of alternative futures (Carter et al. 2007), and researchers are exploring the use of scenarios as tools for facilitating interaction with stakeholders (Lorenzoni, Jordan, O'Riordan et al. 2000; Schlumpf et al. 2001; Bärlund and Carter 2002; Berkhout, Hertin, and Jordan 2002). Scenarios are particularly useful in stakeholder groups as heuristic tools that aid in problem-solving and decision-making processes (Berkhout, Hertin, and Jordan 2002).

Scenarios as Learning Tools

Berkhout, Hertin, and Jordan (2002) believe that one of the objectives of climate impact assessment is to engage in the process of social and organizational learning. Social learning occurs when individuals or groups collectively act and reflect as they work to improve strategies for managing a system of interest (Keen, Brown, and Dyball 2004). Social and organizational learning are important because adaptation is a type of experiential learning process (Adger and Kelly 1999; Berkhout, Hertin, and Arnell 2004; Berkhout, Hertin, and Gann 2006). At the level of organizations, learning occurs as an experiential learning cycle (Pahl-Wostl 2002; Berkhout, Hertin, and Arnell 2004). To learn, organizations interpret their direct experiences and those of others through conceptual frameworks and apply those interpretations to altering routines and dynamic capabilities (Berkhout, Hertin, and Gann 2006). Successful, viable adaptations are founded upon an organization’s “adaptive ability” (Chakravarthy 1982).

Scenario learning tools are appropriate for studies of adaptive capacity because adaptation, the realization of adaptive capacity, is a learning process. Lorenzoni, Jordan, and O’Riordan et al. (2000) note that stakeholders have difficulties envisioning future climate change, so scenarios may be one important way of helping them to understand all of the factors that shape their vulnerability and their adaptive capacity. For example, the Georgia Basin Futures Project

(GBFP) research team used collaborative workshops to solicit stakeholders' responses to scenarios of various areas of expertise (vanWynsberghe et al. 2003). The investigators used their responses to develop a model that helps stakeholders build their own scenarios to discover the range of various available adaptation options. This suggests that scenarios may be effective in promoting social learning for effective adaptive management.

Adaptive Capacity Assessments in Water Management

The scenario approach is not new to water management; water managers plan by using scenarios to investigate possible futures of supply and demand or to examine the impacts of various management policy options (Stewart and Scott 1995). In the context of climate change, previous studies of water management have focused on adaptive capacity (Ivey et al. 2004) or on changes in water demand under various climate scenarios (Giacomelli, Rossetti, and Brambilla 2008; Medellin-Azuara et al. 2008) . Recent integrated water resource management tools like the Water Evaluation and Planning (WEAP) model allow managers to explore the joint pressures of demand, watershed conditions, regulatory environments, infrastructure, and climate variability and change (Yates et al. 2005). For the most part, these assessments take place on the scale of watersheds, with multiple groups of diverse stakeholders participating, and most focus on demand as the driving factor for water management. However, for small rural drinking water systems, years of neglected or aging infrastructure coupled with dwindling populations make a CWS's financial stability an equally important driving factor (Marrocco, Franklin, and Sedlak 1993; Jocoy 2000; see also Chapter 3 of this dissertation). Even small CWS are expensive relative to a small community's ability to pay, leading to higher per capita costs for small systems than for their larger cousins (Rubin 2004). Additionally, social and institutional factors, like regulatory compliance, institutional structures, and a reliance on social capital must be accommodated in any model to make it useful to managers (Flora 2004). Studies suggest that CWS managers simply will not use weather forecasts or scientific climate data when they do not understand it or when concerns about non-climate-related hazards prevail, making it difficult to engage CWS managers in adaptive capacity assessment (Yarnal et al. 2003; Dow et al. 2007; Tribbia and Moser 2008). Therefore, current adaptive capacity assessment approaches need to be scaled appropriately for CWS and bring managers into the process if they are to be useful to small rural CWS.

Participatory modeling, also known as mediated modeling (van den Belt 2004), cooperative modeling (Cockerill, Passell, and Tidwell 2006), group model building (Rouwette, Vennix, and van Mullekom 2002), shared vision planning, or computer-mediated collaborative decision-making (Cockerill et al. 2008), may be appropriate for engaging small CWS with issues of climate change in the face of other operational issues. This approach has been tried successfully on watershed scales (Langsdale et al. 2007; Pahl-Wostl 2007), but an innovation in this research is that participatory modeling processes were downscaled to an individual utility and tested in a small rural CWS whose managers have little formal water management training. User-friendly, transparent models built in a collaborative environment with trust and mutual respect helps stakeholders to learn, especially when scenarios are used that allow participants to explore how changes in critical variables affect differences in the outcomes (Olsson and Anderson 2007). By promoting social learning, participatory models encourage participants to maintain iterative, reflexive thinking about management problems (van den Belt 2004); for CWS, this may prove a valuable technique for understanding and building systems’ capacities to adapt to climate change.

Drinking Water in Central Pennsylvania

Centre County, Pennsylvania, is an excellent region for studying small rural drinking water systems because of the variety of systems that exist. Exclusive of mobile home parks and nursing homes, there were 36 active Centre County CWS in 2005. Of these systems, 31 met the definition of a small or very small CWS (PA DEP 2005). These small systems have a variety of management structures, including private investments, neighborhood water associations, municipal authorities, and municipally or state-operated systems. Multiple agencies have regulatory authority over these systems, but the most influential agencies are the Pennsylvania Department of Environmental Protection (DEP), the U.S. Environmental Protection Agency (EPA), and the Susquehanna River Basin Commission (SRBC). Centre County is unusual in comparison to other central Pennsylvania counties because it has a water systems planning coordinator based in the county planning office. This coordinator is a critical institutional actor in local CWS operation because he assists CWS with everything from providing basic operation knowledge to applying for state and federal grant money. For many systems, he is also an agent on the social level, helping CWS form bridging connections with each other (Chapter 2). This management complexity has interesting implications on the social, institutional, and financial components of adaptive capacity in the small, rural CWS of Centre County.

Centre County also makes a good case study of CWS management because of a rich history of published and unpublished research on weather-related planning processes and water system vulnerability to climate change in the region (e.g., Pascale 1997; O'Connor et al. 1999; Jocoy 2000; Pike 2001; Windram et al. 2003; O'Connor et al. 2005; Booher et al. 2005; Yarnal et al. 2006). The Safe Drinking Water Act of 1974 and its subsequent amendments pushed many CWS to switch to groundwater sources to avoid the higher water quality compliance costs associated with filtering surface water sources, and as a result many systems have become relatively less vulnerable to drought (Pascale 1997). However, the region’s karst topography means that even groundwater wells respond to drought because the water table can drop quickly in some areas (Windram et al. 2003). Additionally, both high and low streamflow events contribute to CWS water quality violations, especially when the CWS operator lacks experience in compensating for such events (Pike 2001). These hydroclimatic stresses couple with socioeconomic difficulties to affect CWSs' abilities to adapt to climate change impacts, like more frequent floods and droughts. Community associations and water authority boards comprised of volunteers from within a community still manage many of the small, rural CWS. The amount of training such volunteers have varies widely, and this factor influences their systems' abilities to plan effective emergency response, apply for funding critical to updating infrastructure, and accommodate changes in population growth (Jocoy 2000; Windram et al. 2003). By assessing adaptive capacity under a variety of climatic and socioeconomic conditions and communicating this information to CWS managers in a manner that helps them to understand the impact of compounding stresses, Centre County CWSs may be more capable of developing flexible adaptive strategies.

Methodology

Case Study CWS: Gregg Township Water Authority

The GTWA is the water authority that supplies the town of Spring Mills in Gregg Township, located in the eastern part of Centre County. It was constructed in the 1960s and run as a water association until 2007, when it became a water authority to increase its eligibility for grant funding. At that time, Gregg Township returned management duties to the volunteer board that ran the original water association; board members have little to no formal water management training, but several board members have been involved with the water system for decades. The GTWA was selected as a case study from the group of nine CWS whose managers were interviewed in a previous research phase (see Chapter 2). The GTWA was one of the small, rural systems that described an extensive reliance on volunteer support, not only from the board members, but also from members inside and outside of the town of Spring Mills. These volunteers provide critical services at reduced or no cost during emergencies like breaks in the cast iron transmission lines, which are over 40 years old. The system has 150 household connections and, at the time of this study, the system had recently suffered a reduction in its non-household revenues because the local elementary school closed and the local factory drastically reduced its water use. At the time, the GTWA was applying for grants to fund a filtration plant required by the DEP to treat its primary source, a surface water-influenced spring. Initial estimates of the filtration plant's cost were around $1.4 million; after the conclusion of this study, it became apparent that costs would be significantly higher. This planned upgrade is in addition to a recent DEP-mandated upgrade to the storage tank.

Adding to these socioeconomic and regulatory pressures, the GTWA members reported that the spring they use as their primary source is sensitive to precipitation. After some heavy precipitation events, they notice a marked increase in spring water turbidity within a day or two. A drought during the course of this study, which began in September 2007 and finished in April 2008, reduced the spring output enough to require water restrictions, and this led the GTWA board members to drill an emergency well. This well may eventually become their new primary source despite possible influences from surface water, because the well depth suggests it may not respond as quickly as the spring responds to drought or contamination during abnormally wet periods. Regardless, throughout the research process managers remained conscious of their CWS's past sensitivities and continued to be engaged in learning about how climate change might affect their system.

To investigate the GTWA's adaptive capacity, I conducted three focus groups and one intermediate meeting that included GTWA board members, a Township supervisor, and a Pennsylvania Department of Environmental Protection water system sanitarian from the regional office. Three additional participants – the GTWA's engineer, their certified operator, and a local emergency management official – attended the first focus group meeting but were unable to attend the remainder of the meetings. The structure of this process followed methodologies used in mediated modeling, which integrates scientific modelers and stakeholder participants in a collaborative, bottom up process (van den Belt 2004). Mediated modeling requires the modeler to become an integral part of the process, so I stepped beyond the role of a facilitator to provide scientific advice on climate change vulnerability and on the technical details of building the system dynamics-based model. The goal of mediated modeling is to promote group learning and facilitate consensus among stakeholders and scientists by building a model that is grounded in stakeholders' realities, thus making it more likely that the model will remain useful to decision-makers after the process concludes (Costanza and Ruth 1998; Rouwette, Vennix, and van Mullekom 2002; van den Belt 2004; Cockerill, Passell, and Tidwell 2006; Cockerill et al. 2008; Tidwell and van den Brink 2008). Participants assessed what they believed they had learned by completing a brief survey at the beginning of the first focus group and at the conclusion of each focus group meeting.

Focus group meetings followed a series of scripts (Andersen and Richardson 1997; Luna-Reyes et al. 2006) to guide participants through the process of constructing a system dynamics model of the GTWA's climate change adaptive capacity while building mutual trust between group members. In the first focus group, participants listened to a brief presentation about climate change and the potential for impacts in the form of more frequent floods and droughts in Centre County. Next, they broke into smaller groups, and each group listed the effects a given hazard (flood, Arctic air outbreak, or bacterial contamination) would have on the CWS and the actions they could take either to prevent damage or to take advantage of the event. After reporting back to the whole group, they learned about and discussed how their answers related to the concepts of vulnerability, adaptation, and adaptive capacity. This provided the foundation for having the participants identify the critical indicators they believe affect the GTWA's present and future abilities to adapt to climate change and rank which of these factors were most important to include in a model (Chapter 3).

In the remainder of the focus group meetings, I introduced the participants to the isee systems™ graphical system dynamics modeling software STELLA™. In the second meeting, I presented them with an initial model based on their input from the first focus group meeting and used that to familiarize them with the simple concepts of system dynamics models and of climate scenarios. They provided feedback on what portions of the initial model reflected their understanding of how their system worked and what influences its ability to adapt. They also decided that the narrative socioeconomic portions of the scenarios should be driven by the rates of growth in and around the system. We added an intermediate meeting before the final focus group to ensure that the expanded model continued to reflect their understanding before presenting them with final results. In the final focus group meeting, participants were presented with model results that reflected their ability to adapt to more frequent floods and droughts. They also had the opportunity to interact with the model by varying the values of the critical variables like system rates and expenses and by running the model again under differing precipitation and development scenarios. Finally, the participants discussed the value of the model and its applicability to their planning processes.

The STELLA™ model resulting from these meetings, dubbed the Community Water System-Future Adaptive Capacity Scenario (CWS-FACS) generator, is a series of interacting sectors based upon the determinants of CWS adaptive capacity (described in detail in Chapter 3 and Appendix C). The CWS-FACS generator runs for 20 years using a monthly time step, pausing every five years to allow users to adjust the values of critical indicators such as customer rates and expenses through a graphical interface. This creates a model time scale that reflects the GTWA managers' actions and decisions. Because the participants believe that the most important factor influencing their climate adaptive capacity is their ability to pay for adaptations, the central sector of the model includes the financial indicators, notably the GTWA's available cash and money market investment accounts. Other sectors include a water supply sector, which is linked to the water delivery sector. The customer characteristics sector, namely, the number of customers and their rate of water use, determines the demand in the water delivery sector and connects to the financial sector via the number of customers paying rates each month. A simple water quality and regulatory change sector factors in expenses from changes in water quality and from additional treatment costs incurred as regulations become more restrictive. The technology sector includes the age of all system components; older infrastructure is more likely to require replacement, making adaptation more difficult. Finally, a human issues sector accounts for GTWA members' estimations of the financial value added to the system through social, human, and institutional capital.

The precipitation scenarios used to drive the CWS-FACS model are located in the water supply sector. Because the intent of the model is to illustrate plausible futures for a single CWS and to focus on learning, it was appropriate to use temporal analogs to two 20-year periods adjusted in a manner consistent with reasonable climate change expectations (Chapter 3). The years 1970-1989 includes multiple notable floods that the participants mentioned had affected the CWS, including the severe flooding from the remnants of Hurricane Agnes in June 1972. The years 1987-2006 captured the last full 20 years for which data were available, which allowed managers to draw comparisons to their most recent experience with floods and droughts. The Consortium for Atlantic Regional Assessment (CARA) online database of statistically downscaled GCM data provided the basis for adjusting these observed data into reasonable future climate scenarios. CARA used the Hewitson (2003) method to calculate seasonal and annual means and standard deviations for each Historical Climatology Network station in the mid-Atlantic region of the United States using seven different GCMs and the A2 and B2

Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions scenarios (Consortium for Atlantic Regional Assessment 2006a, 2006b; see also Arnell 2004). The CWS-FACS precipitation scenarios adjust the observed monthly precipitation totals for the cooperative data station closest to Spring Mills by the percent difference between the CARA 1971-2000 observed seasonal means and the 2010-2039 projected seasonal means. Of the seven CARA models, the Hadley Centre for Climate Prediction and Research (HDCM) and Canadian Climate Centre Model (CCCM) together produced the broadest range of possible changes in wet and dry periods for both the A2 and B2 emission scenarios. Therefore, for each 20-year analog, participants may select one of five precipitation scenarios: the observed data and the HDCM and CCCM A2 and B2-adjusted data.

When running the model, participants have the option of using either the 1970-1989 or the 1987- 2006 analogs. Each analog version of the CWS-FACS model has a graphical interface (Figure 4-1) that allows the user to select one of the five precipitation scenarios and scenarios of slow, moderate, or fast population growth rates. Users may also adjust the average values of critical variables, such as customer rates, expenses, the amount of grant money the GTWA receives, and the option to have the system drill new wells when the system is unable to meet demand for a sustained period because of extended drought or increased customer use. The model includes graphs of critical variables like the amount of money available to the system. The CWS-FACS interface also displays graphs of both instantaneous and cumulative index values based on the determinants of adaptive capacity (Chapter 3).

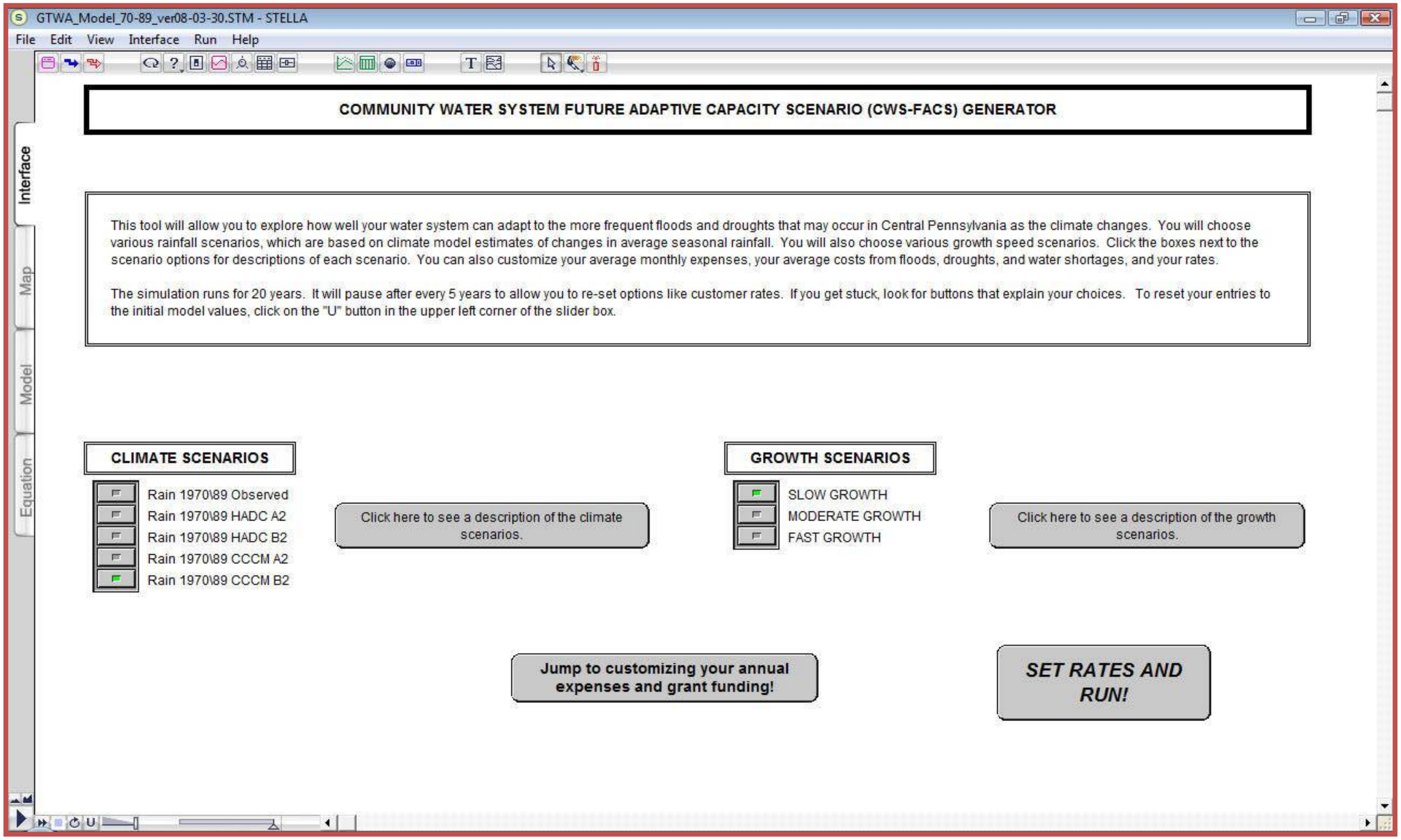

Figure 4-1: Initial graphical interface for the CWS-FACS model. Users select one of five climate scenarios and one of three growth scenarios, then customize other variables if desired.

The instantaneous adaptive capacity index AC_D for determinant D at any time step is calculated by

$$AC_D = \sum_{i=1}^{n} w_i \frac{(x_{it} - x_{i\min})}{(x_{i\max} - x_{i\min})}$$

where n is the number of indicators (i) included in the determinant, w_i is the weight of each indicator, x_{it} is the value of indicator i at time t, x_{imin} is the minimum desirable value of i, and x_{imax} is the maximum desirable value of i. An adaptive capacity index of one suggests high adaptive capacity, and an index of zero suggests low adaptive capacity. If an indicator's value lies outside the desirable range – for example, if the CWS's debt load exceeds what the managers consider a tolerable level – the index value may lay outside the 0 to 1 range. Cumulative adaptive capacity indices are the sum of all instantaneous values normalized by the amount of time that has passed in the model. These cumulative indices provide a measure of the system's overall adaptive capacity and allow comparisons to be made between the 1970-1989 and 1987-2006 analogs.

Results

Case Study CWS Adaptive Capacity

For the scenarios that were initially presented in the final meeting with the GTWA, rates were set at $30 per month and costs were fixed based on the system's spending in summer and fall 2007. No adjustments were made at the five year pauses; that is, no adaptations such as customer rate increases occurred over the 20-year period except for enacting water restrictions and drilling new wells if demand shortfalls exceeded a certain threshold. This adaptation exception was made because the system managers would be required by law to take such measures if the CWS cannot meet demand. In the results, the system's financial capabilities were clearly the most limiting factor on CWS adaptive capacity. This finding was based on examinations of the system's debt load as indicated by the balance of their money market account under the five different climate scenarios and the three growth scenarios (Table 4-1). For each growth scenario, the model was run once for each climate scenario, and the magnitude of the climate-related financial stress due to differences in climate scenario alone is the difference between the minimum and maximum final money market account balances. The added financial stress of climate change in the 1970-1989 analog was roughly double the stress in the 1987-2006 analog; however, this climate-related financial stress was relatively small compared to the overall debt of the system (e.g., for slow growth, the climate-related financial stress at the end of the 1970-1989 analog was $49,800, but the final range of money market account values calculated the range of the GTWA's debt as $697,000-$746,000). It is important to note that the financial impact of the more frequent floods and droughts in the CWS-FACS generator is dependent on what the hazards would actually cost the system. Radar diagrams of the six cumulative adaptive capacity indices are remarkably consistent between the 1970-1989 and 1987-2006 analogs (Figure 4-2). Again, financial adaptive capacity appears to be the limiting factor over the entire 20-year model runs. The GTWA has a high technological adaptive capacity because of the relative age of most system components. The filtration plant and storage tank are some of the most expensive system components, but because both have recently been replaced or are scheduled for immediate replacement, major upgrades or repairs are less likely. Contributions from human, social, and institutional capital initially appear relatively small, but this finding is partially because these contributions are tied to the model via their financial value and so this capital is not invoked unless an emergency occurs. However, for both analogs financial adaptive capacity is well below the minimum desired value of zero. Climate scenarios do not have a large impact on the financial adaptive index value; rather, the financial adaptive capacity is raised by adding more customers.

Table 4-1: Final amount of GTWA debt for both 20-year analogs, represented as the sum of both the system's available funds and the money market account. Debt remains similar in part because of payments for capital expenses like the filtration plant, but other differences are due to changes in flood and drought frequency in each scenario.

Scenario	1970-1989 Final Debt/Surplus (USD)	1987-2006 Final Debt/Surplus (USD)
Slow growth		
Observed	-$697,236	-$695,870
HADC A2	-$723,330	-$692,616
HADC B2	-$741,316	-$711,830
CCCM A2	-$691,476	-$699,719
CCCM B2	-$730,959	-$697,425
Moderate growth		
Observed	-$234,852	-$228,153
HADC A2	-$259,970	-$229,183
HADC B2	-$276,478	-$242,881
CCCM A2	-$234,021	-$235,846
CCCM B2	-$273,510	-$229,680
Fast growth		
Observed	$207,849	$207,210
HADC A2	$186,626	$202,808
HADC B2	$174,176	$185,576
CCCM A2	$215,295	$198,433
CCCM B2	$171,797	$200,549

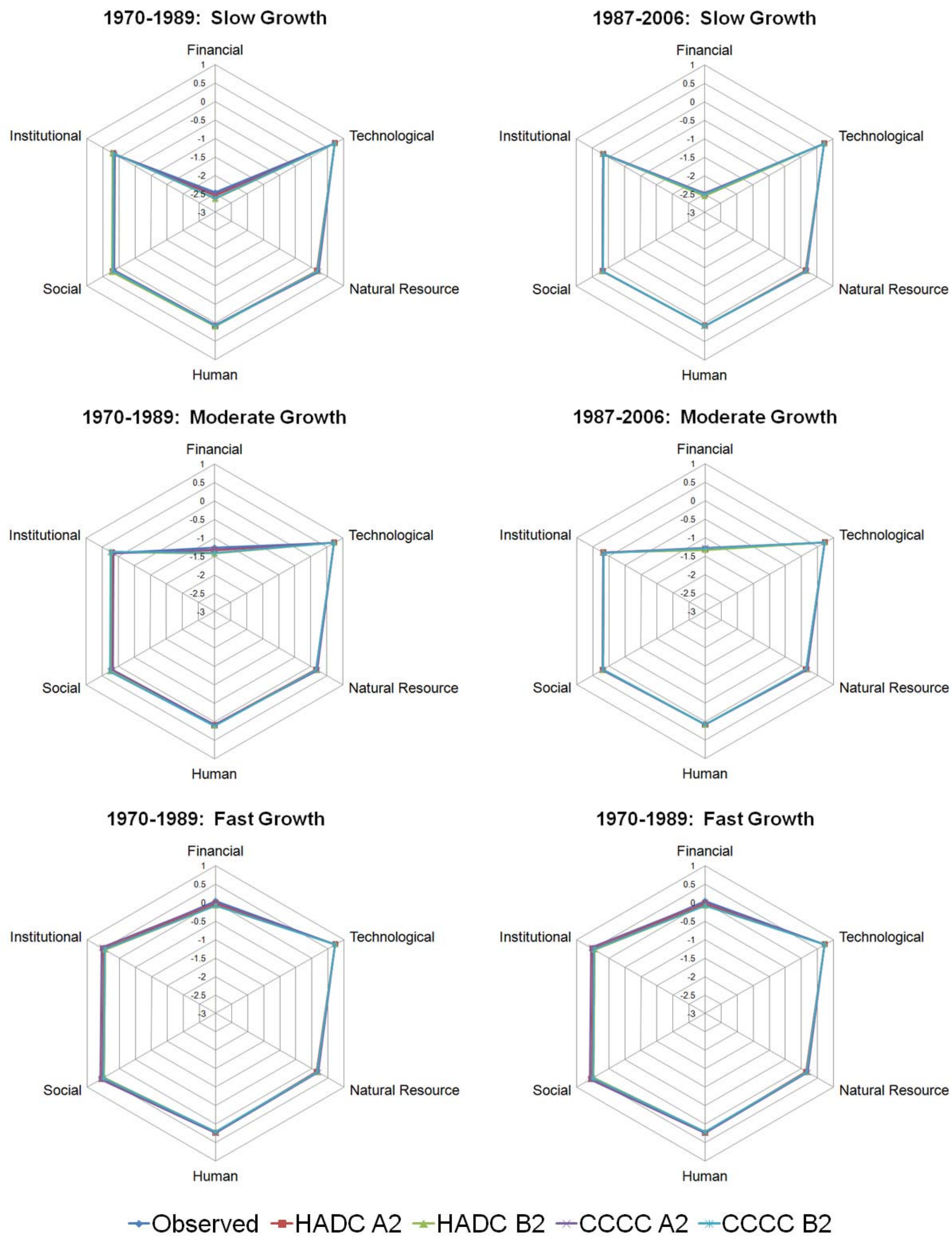

Figure 4-2: Radar diagrams of cumulative adaptive capacity indices for all three growth scenarios for both the 1970-1989 and 1987-2006 analogs. Differences between the climate scenarios are not large, but the diagrams make it clear that the system has very low financial adaptive capacity when compared to the other five determinants.

Participants' Responses to Adaptive Capacity Scenarios

The GTWA members and other stakeholders were unanimous in their belief that the adaptive capacity scenario process was valuable to their system. In the first focus group, they were quick to demonstrate their understanding of the factors that enable or constrain their system. During the second focus group meeting, and in the supplemental meeting that we held, everyone was engaged in examining the model and giving feedback. As we encountered problems with the model, participants began to make connections between the problems revealed in creating the model and actions they could take to increase their adaptive capacity. For example, the GTWA did not have data on water use, the exact infiltration rate to the spring, or extensive, well organized records of the systems expenses. In the final focus group, they discussed how this lack of information led to uncertainties in the model and concluded that it is important for their system to begin keeping systematic, detailed data.

Despite the drawbacks and compromises that had to be made in creating the model, the participants all believed that the scenarios were plausible and consistent. They did not interpret them as forecasts, but instead thought of them as "a pretty good starting point." The climate scenarios allowed them to picture how weather and climate influence their system, giving them a better understanding of their systems relationship to the natural world. The GTWA board members were pleased with the model capabilities as long as they have the ability to change the input scenarios as they get better information. STELLA™ allows users to alter input data like the precipitation scenarios graphically, and one participant wondered if it would be worthwhile to alter some scenarios to explore what would happen if more intense tropical cyclones occurred more frequently.

GTWA members were most impressed with the CWS-FACS capabilities for altering variable values and then watching how those changes were manifested in the model output graphs. This favorable impression of model capacity was especially apparent in the final focus group when they had the chance to make their own scenarios. It was easy for them to see how changes in rates and expenses would affect their available funds, and they saw the impact that grant money availability had on their ability to adapt. They were mostly interested in the next 5 to 10 years, which they believed was a reasonable planning period for their system. The GTWA managers were also pleased with the ability to adjust critical values , such as customer rates, at the five year pauses. The sample scenarios I presented did not include adaptations, but this capability to make adjustments during model pauses allowed them to explore the types of adaptations that would minimize the financial stress on the system. At the conclusion of the final focus group, one of the GTWA board members even suggested adopting the CWS-FACS model to assist them in budget planning.

Although the participant survey sample was too small to determine statistical significance of the measures of participant learning, their responses in the focus groups and comments on the surveys are sufficient to shed light on the GTWA members' perceptions of the process. Most participants began the first focus group with some concern about the impacts of climate change on the CWS, which is not surprising given that participants had noted the impacts of a recent flood and ongoing drought on the GTWA. However, most participants began the first focus group unsure about how easy it would be for the water system to adapt to climate change. By the end of the final group, three of the five participants had become more confident that their system would be able to adapt.

Discussion

The above discussion highlights some of the challenges involved in assessing the capacity of a small rural CWS to adapt to climate change. Like many other small, rural systems, the GTWA lacked extensive records on water use, expenses, and hydrogeologic information. Additionally, downscaled climate scenarios were not available at a scale relevant to the GTWA's planning. Their system relies on volunteer assistance to compensate for shortfalls in human and financial capital, and this reliance can be difficult to capture in models.

Concern is often expressed that managers may be overconfident in unreliable data (Langsdale 2008), but the GTWA members demonstrated a clear understanding of the purpose and limits of climate scenarios. Rather than being restricted by a lack of probabilistic climate change information, they were able to analyze the given scenarios as representatives of numerous possible futures. Perhaps because of their personal experience with the impacts of weather on their water system, they were aware of the inherent uncertainty in weather and climate predictions. Even though the sample scenarios presented by the CWS-FACS model did not indicate dramatic impacts from climate change when compared to the overall financial stresses the system experiences, at the conclusion of the final focus group, the participants were no less concerned about the climate change impacts than they were before the start of the first focus group. They discussed being able to make their own climate scenarios, but one of the participants stressed that they needed an "idiot-proof" way to ensure that their scenarios were within the realm of possibility. Another expressed his concern that the GTWA's financial difficulties mask the effects of climate change, but that this may not be true for larger systems. This pragmatic outlook, along with their willingness to accept these scenarios as demonstrative tools, suggests that climate information can be used in planning processes at all scales, especially when the focus is on explorations of the capacity to adapt as opposed to cost-benefit analyses of specific adaptations.

This modeling process also demonstrates what can be accomplished in data-sparse environments. The lack of data on both the physical and socioeconomic aspects of the GTWA ruled out other sophisticated methodologies for adaptive capacity investigations such as agent-based modeling (e.g., Yu et al. in press). By using a system dynamics platform based on these three simple building blocks of stocks, flows, and descriptive connectors, the group was able to focus on both the quantitative and qualitative aspects of climate change adaptive capacity without rigid data requirements. It also allowed the group to participate in creating a valuable tool in a timely fashion; this research was conducted shortly after the GTWA transitioned from a water association to a water authority and concurrent with the CWS's search for grants to build the filtration plant. By using the simpler modeling methodology instead of waiting for data to be collected or modeling methodologies to be perfected, the GTWA obtained a tool that may be useful in their budgeting process when they needed it.

System dynamics was also essential to bridging the gap between scientific modeling and the GTWA board members' and other participants' experiences. Of the five group members who attended all three focus group meetings, only one had formal water management training. The remaining members are employed in the manufacturing and construction industries, and with their limited computing experience, it would have been difficult to integrate them into a more sophisticated modeling process. Nevertheless, the modeling process was extremely valuable because it allowed the participants to explore the cause and effect relationships that connect their CWS to the human and natural world in a way that builds off of their experience-based water management knowledge. Whether or not the model is used in their budget planning, their suggestions at the conclusion of the process – to keep better data, understand their system's infrastructure, and to broaden the ways in which they serve their customers' needs – are valuable actions that will contribute to increasing the GTWA's adaptive capacity.

The CWS-FACS model findings about adaptive capacity are limited to the GTWA, but the process through which the CWS-FACS was created can be transferred to other contexts easily, making it a valuable tool in climate outreach. The overall structure of scripted focus groups that allow participants to give their input on critical modeling variables is easily applied to other sectors. For example, one of the participants expressed interest in expanding the CWS-FACS model to the sewer system, thereby enhancing their ability to understand how water enters Spring Mills and ultimately leaves the watershed. Similar system dynamics modeling processes have been successful on the scale of entire watersheds (Langsdale et al. 2007). Even when the results are limited in scope, the lessons learned from the process can produce important changes in behavior that increase adaptive capacity.

Resource managers need more than simple climate information; they need assistance in understanding and integrating it into the way they think about management (Tribbia and Moser 2008). Effective climate outreach strategies must address this need, and the cooperative process used to build the CWS-FACS generator could be effective for developing successful climate outreach and extension programs. The simplicity of the modeling process builds trust by making it easier to involve managers from the start, which is an essential component of climate outreach strategies. As the GTWA members worked with me to build the CWS-FACS model, they became increasingly open to sharing their ideas with me, even assembling their own data and holding extra meetings with me to discuss ideas they had about the model. As a result, the model reflects the GTWA stakeholders' perceptions and needs for integrating climate information into their understanding of CWS management. This process of building trust and acknowledging the value of local knowledge is vital especially in areas where many do not acknowledge that climate change is occurring. By creating a multipurpose planning tool with immediate, broad applications, climate outreach professionals may find it easier to bring people who are not concerned with climate change into the conversation with other stakeholders. Finally, the focus on scenarios and capacity building acknowledges the inherent uncertainty in climate change vulnerability and addresses stakeholders' concerns about a lack of highly accurate climate data, which can serve as a barrier to effective climate outreach. Climate change scenarios allow participants to explore a range of possible futures and to examine an envelope of outcomes, turning climate outreach into a learning experience that opens a dialog about "no regrets" strategies to build the capacity to adapt to climate change and to multiple other stresses. The goal of climate outreach and extension is to encourage a behavior change, and this emphasis on understanding and flexibility may be more likely to contribute to lasting changes that increase adaptive capacity.

Conclusions

The CWS-FACS generator is the product of a collaborative mediated modeling process to investigate the ability of the GTWA, a small, rural CWS in Pennsylvania, to adapt to climate change. This generator allows users to select from two 20-year analog periods, each with a combination of five available climate scenarios and three scenarios of growth in Spring Mills, Pennsylvania. To ensure that the GTWA managers' concerns about other stresses, like financial shortfalls and environmental regulations, were accommodated, the generator uses system dynamics to engage participants in modeling qualitative and quantitative aspect of adaptive capacity determinants. The scenarios initially produced and reviewed by GTWA managers and other stakeholders in the focus groups suggested that climate change could have an impact on this CWS, but that the magnitude of the system's debt would mask the climate effect, especially in socioeconomic scenarios with slow and moderate rates of growth. The managers believed these scenario results were reasonable and reflective of plausible futures for the system. Despite these results suggesting that climate change would not be the critical factor determining whether the CWS can continue to function, GTWA members remained concerned about climate change because they were aware of the limitations of the model scenarios and the inherent uncertainty involved.

The true value of the CWS-FACS generator is in its capabilities for supporting learning. Participants enjoyed the model's flexibility and its capabilities for allowing them to customize their own scenarios. They became more aware of the climate as an integral piece of their CWS, and they were able to learn about how different variables affect the CWS by experimenting with the model. Because the participants were involved in creating the model itself, they saw how a lack of data affected their ability to plan effectively. At the conclusion of the process, they agreed to keep better data and maintain flexibility; should they implement this policy, it would be a decision that increases their ability to adapt to climate change. This type of behavior change suggests that projects focusing on adaptive capacity through mediated modeling with system dynamics would be valuable to climate outreach.

Chapter 5

Lessons learned and future directions

Managers of small, rural CWS encounter many challenges to providing adequate supplies of clean, safe water to their customers. The costs associated with treating and delivering water are high when compared to the number of customers providing revenue to CWSs. In central Pennsylvania, as the rest of the United States, climate change could place additional pressure on CWSs, especially through more frequent floods and droughts. To prevent damage from, take advantage of, or cope with climate change, managers will need to develop flexible adaptive strategies, but the capacity of their CWSs to do so will vary based on place and operational context. Larger CWSs may plan by focusing on particular adaptations and running sophisticated supply and demand models to test these adaptations' effectiveness. For many small, rural CWSs, managers' lack of sufficient human capital, low financial capabilities, changing regulatory requirements, aging system infrastructure, and limited ability to seek new water sources all impede this type of adaptation-centered planning. Instead, it may be more worthwhile for small, rural CWS managers to examine their systems' capacities to adapt to climate change. Adaptive capacity analyses focus on CWS strengths and deficiencies so that managers can build flexible management structures that expand their systems' abilities to recover from or take advantage of the variety of surprises that climate change may bring.

For CWS managers to use information about weather and climate, they must believe that the information is relevant to management needs and that it accommodates their systems' operational and management contexts. It is reasonable to believe that managers will hold information about current and future climate change adaptive capacity to the same standard. Therefore, the purpose of this dissertation research was to explore the capacities of CWSs in Centre County, Pennsylvania, to adapt to hydroclimatic variation and change. Specifically, it investigated CWS managers' perceptions of adaptive capacity, the processes shaping current adaptive capacity and interacting to affect future adaptive capacity, and methodologies for engaging CWS managers in assessing adaptive capacity. I combined interviews with officials from nine Centre County CWS and maps of their social networks with a mediated modeling case study of the Gregg Township Water Authority. This modeling exercise involved collaborating with GTWA members and other stakeholders during three formal focus groups and an informal meeting to build a system dynamics-based adaptive capacity scenario generator. This approach enabled me to answer four research questions. In this chapter, I will summarize the answers to each of these questions. I will conclude by discussing the significance of the work, future research needed, and policy implications.

Summary of Research Findings

In Chapter 1, I presented four research questions. Chapters 2 through 4 included answers to these questions in the form of three manuscripts ready for submission to peer-reviewed journals. However, it is worth revisiting the research results as they apply to answering each of the four research questions:

1. What are the factors that CWS managers believe affect their future capacity to adapt to hydroclimatic change and variation?

To answer this question, I used literature reviews of adaptive capacity and previous results from Centre County CWS research to design a semi-structured interview script around six determinants of adaptive capacity – social capital, institutional capital, human capital, financial capacity, natural resources availability, and technological capacity. Several factors consistent with previous research emerged from the coded results from eight of the nine semi-structured interviews with Centre County managers from CWS of varying size and from the nine social network maps created during those interviews. Water quality regulations require expensive treatment technologies, which are difficult for small CWS to afford because they have a relatively small number of customers. Despite these costs and aging system infrastructure, managers are limited in their ability to raise rates. One unanticipated result is the importance of layered social and institutional capital in helping volunteer managers of small, isolated CWSs compensate for these deficiencies. In these rural systems, where "the whole town's the water company," managers rely on volunteers in emergencies and use their relationships to leverage extra time and attention from institutional actors to help them obtain grant money or receive more time to comply with regulations. Managers were not asked to relate these strategies to climate change adaptive capacity in the interviews. However, all of these factors emerged again during the first GTWA focus group meeting, when participants listed the variables they believe affect their CWS's ability to adapt to climate change. In that meeting, the consensus was that the most important factor affecting the GTWA's adaptive capacity is its financial capabilities.

2. How can the needs and concerns of water managers be used to create a framework for constructing adaptive capacity scenarios for community water systems?

To ensure that managers' perceptions and knowledge are reflected in the adaptive capacity scenarios, this research used a modified mediated modeling approach. This collaborative approach brought managers directly into the process of constructing a system dynamics-based adaptive capacity scenario generator. In an initial focus group, GTWA members and stakeholders learned about climate change vulnerability and chose the factors they believe affect their CWS the most. I used this information to build an initial version of the CWS-FACS generator using STELLA™. In the second focus group, participants corrected errors in the initial model and expanded on its structure. They also reviewed climate scenarios and created their own narrative scenarios of growth in the town of Spring Mills. We held an informal intermediate meeting because the model needed further revision, and in this meeting participants discussed data they were able to obtain and continued to evaluate model structure. At the final focus group meeting, they viewed results from the CWS-FACS generator in the form of climate scenarios. As a result of this approach, GTWA managers and stakeholders were engaged at all phases of modeling and ensured that the CWS-FACS generator reflected their understanding of how their system operates.

3. Does this framework result in cohesive, internally consistent, and plausible adaptive capacity scenarios for these systems?

The initial scenarios presented to the GTWA suggest that the system's financial adaptive capacity is highly dependent upon the rate at which the system adds customers. The participants thought that the slower growth rate is most realistic, and for this growth rate financial adaptive capacity was extremely low across all climate scenarios in both 20-year analog models. Many other aspects of their adaptive capacity were higher; for example, technological capacity decayed over time but still remained relatively high because the GTWA's most expensive system components – the filtration plant and the storage tank – are new. The GTWA's available social and institutional capital added value to the system when floods and droughts occurred in the scenarios. As evidenced by the GTWA's final available funds, climate did have a financial impact on the system, but the magnitude of this climate-related stress was relatively small compared to the system's overall financial distress from other factors like growth or upgrade costs. However, the participants were cognizant that the scenarios are only representations of possible futures, and that variations in cost from more frequent floods and droughts could result in more damage to the system. Ultimately, they believed that the scenarios created using the CWS-FACS generator were plausible and consistent.

4. Does the scenario-building process promote organizational and social learning?

Despite the final outcome of the scenarios, the surveys participants took before the first focus group and after each of the three focus groups indicated that they remained concerned about climate change. One of the reasons for this continuing concern may have been the participants' abilities to understand the uncertainty involved with the scenarios. As they participated in the modeling process, they became increasingly aware that a lack of data, such as detailed financial records and water usage statistics, made it difficult to construct portions of the model accurately. They did not perceive the greatest value of the CWS-FACS generator to be its predictive ability; rather, they found the model's interactive graphical interface extremely useful for learning about how changes in one variable, such as costs or grant money awarded, resulted in changes in the system's financial state. The generator allowed them to consider the impacts of both physical and socioeconomic changes simultaneously, giving them the ability to visualize how the GTWA functions within the greater water management context of the area. Perhaps the greatest evidence that learning occurred during the mediated modeling process came at the end of the final focus group, when the participants concluded that they needed to be keeping better data so that they could update scenario results in the future. The GTWA managers recognized this simple adaptation would increase their ability to adapt to climate change by improving their planning abilities.

Significance

The process of building and using the CWS-FACS generator has significance on multiple scales. For the GTWA, this study helped them both learn about the consequences of climate change for their system and consider strategies that will improve their capacity to adapt to climate change and to socioeconomic pressures. For the state of the science, this study demonstrates that decision support tools for considering climate change do not have to be sophisticated or highly accurate to be useful to resource managers. Finally, for the expanding field of climate extension and outreach, this study presents a process that can be used for communicating climate change information and assisting decision-makers with mitigating its impacts. In this section, I discuss each of these significance levels in turn.

At the beginning of this study, the GTWA members were open to learning about how climate change could affect their system. The scenarios presented to them during the final focus group suggested that the financial impacts of more frequent floods and droughts could be less severe than the system's overall financial impacts from other pressures like growth and operational requirements. However, they understood the limitations of these scenarios, looking instead to the value of the CWS-FACS generator as a learning tool for understanding how both climatic and socioeconomic contexts affect the ways in which they manage their system. At the end of the process, the model's focus on adaptive capacity compensated for the uncertainty in these scenarios. This focus on increasing their ability to take adaptive action when confronted with surprises from climate change and regional growth was apparent in the solutions they proposed at the final focus group. They identified data scarcity as a condition that made the modeling process more difficult, and they recognized that keeping better records and maintaining flexible management structures would be an adaptation that increases their ability to plan and to react to stress. Continued contact with the GTWA for several years would be necessary to evaluate the lasting impacts of these learning experiences, but initial actions taken by the CWS towards the end of and shortly after this study support an increased chance that their learning will last. They hired a new accountant to organize financial records more efficiently and to assist them in developing a more comprehensive budget. Although the GTWA is now required by the DEP to submit a budget because of their new status as an authority, their board members' request to train the accountant on using the CWS-FACS generator to explore impacts of changes to the system suggest that their participation in this research will enhance their budgeting process. During this study, a drought also forced them to begin seeking a new water source shortly before the conclusion of the study. They had several reasons for drilling at the well site they chose, but one reason they selected this location was because it is elevated well above the floodplain. Even though many of these actions may have occurred anyway, they recognized the lessons learned from the mediated modeling process and considered them when making decisions.

The mediated modeling methodology employed in this research proved successful in a situation where the managers had little prior knowledge of climate change and little formal training in drinking water management. The system dynamics perspective, with its simple building blocks of stocks, flows, and converters, made it easier to engage the GTWA members with creating the model. The participants' actions were consistent with having a high level of understanding of the modeling process and of their CWS as part of a greater natural and socioeconomic system. They were active during the focus groups, and were helpful in altering the model structure and demonstrating their understanding of interacting variables. This built trust between them as participants and me as the modeler, and after the second focus group, several members of the GTWA board became active in the research process by seeking out better data and developing solutions to compensate for poor data. This sense of empowerment and engagement helped to ensure that the managers' knowledge integrated with my scientific expertise.

Perhaps the most satisfying research result is the participants' expressed intention to change their behavior in ways that increase their adaptive capacity. Consequently, the framework followed during this research – interviewing stakeholders, identifying problems, and working with decision-makers through iterative rounds of developing a decision support tool – would be ideal for climate extension and outreach. The need for extension and outreach strategies, especially efforts conducted through institutions that span the boundaries of research and applied sciences, has been recognized in the literature as a critical need (Tribbia and Moser 2008). In extension and outreach, the goal is to build trust with decision-makers by being an honest broker of scientific information. Extension and outreach professionals assist those decision-makers with using scientific information to understand their choices and alter their behavior accordingly (National Sea Grant College Program 2001). Clearly, the CWS-FACS generator and the process through which it was created are useful for explaining the science of climate change, promoting systems thinking, and exploring the consequences of choices through its interactive interface. By participating in this exercise, the GTWA members concluded that they could benefit by changing their behavior, clearly making this approach an appropriate tool for effective climate extension and outreach.

Future Research

There are several directions for future research, both on community water systems and on methodologies for adaptive capacity assessment and decision support. First, the CWS-FACS generator could be altered to accommodate CWS other than the GTWA, and differences in results should be compared with a CWS that can provide better data. This would help to determine if climate change adaptive capacity is limited most by the financial capabilities in other small, rural CWS. Additionally, it is important to investigate if these conclusions are also similar for larger, urban systems. The CWS-FACS generator could also be expanded to include other services; specifically, one GTWA manager expressed interest in adapting the model for the local sewer company.

More generally, the overall methodology for this research should be tested in other sectors and other regions. Differences may exist in the applicability of the method for small, rural CWS outside of Pennsylvania, where differing state regulations may have an impact on how useful the model can be in terms of altering behavior. The overall methodology should also be tested to determine if the process is effective for other utilities that do not display a reliance on social and institutional capital. In larger, urban areas, the system dynamics approach may be too simplistic. Comparisons of similar mediated modeling exercises using other modeling methodologies, such as agent-based modeling or participatory GIS, would be useful in determining the value of system dynamics on a larger scale.

In terms of policy and applications, this research approach should be employed as part of an extension program. The informality of extension may facilitate the entire modeling process, because focus groups scripts and other methodological approaches could be amended when the need arises without concerns for data consistency. In cases where it becomes apparent that additional perspectives are needed, stakeholders and decision-makers could also be brought into a modeling exercise in progress as full collaborative participants. This freedom may actually allow for a greater co-learning experience between participants and modelers because structures necessary for producing valid research results could be set aside if it becomes apparent they are not conducive for producing an optimal learning environment. Additionally, extension and outreach professionals are trusted members of the communities in which they work. This trust may help participants to be more candid about their concerns and difficulties, thereby allowing the final scenario generator product to be more reflective of an individual CWS's context.

Finally, this research serves as an example of a successful model building experience focused on investigating the capacity to adapt to climate change. It highlights the importance of the factors not normally considered part of utilities management, like the need for volunteers or the role of trust in a community. Through mediated modeling and a system dynamics approach, the GTWA was able to help construct the CWS-FACS scenario generator and ensure that it reflects the knowledge they have accumulated over 30 years of managing a CWS without formal training. Even though the scenarios suggest that damage from climate change would be small in comparison to other potential difficulties, the clear suggestion that financial adaptive capacity would be a limiting factor was a valuable lesson for the GTWA stakeholders. They remained aware of uncertainties and understood the model enough to maintain their concerns about the impacts that climate change may have on their system. Most importantly, the GTWA managers and stakeholders learned from the modeling process that additional, simple strategies can help them increase their adaptive capacity. Thus, the methodological capability to engage participants and change their behavior makes this scenario building framework a potentially valuable tool for both academic endeavors and climate extension and outreach initiatives.

Appendix A

Community Water System (CWS) Interview Guide

This appendix includes the interview guide for the nine semi-structured interviews. As is appropriate during semi-structured interviews, not all questions were asked. Often, managers included responses to subsequent questions in their answers to previous questions, so I omitted these questions to avoid asking the managers to repeat themselves. I also omitted questions that were clearly inapplicable to the participant's CWS. Finally, new questions were allowed to arise if managers mentioned significant markers that required more exploration. The social network maps were drawn with markers on an 11” × 17” sketchpad.

The process will consist of semi-structured individual interviews that are guided conversations where broad questions are asked, which do not constrain the conversation, and new questions are allowed to arise as a result of the discussion. The following is a basic outline of the interview along with a series of possible follow-up questions that may be used to continue discussion. New questions will be allowed to arise, and not all follow-up questions may be used:

Initial prompt:

I'd like to begin by just asking you to tell me about some of the elements and factors that shape the way your community water system operates on a daily basis.

Follow-up topics include:

- ☐ **NATURAL RESOURCES:**
  - **Water quantity**
    - How is precipitation is linked to water recharge rates in your system?
    - What are some of the differences between systems that depend primarily on surface water and systems that depend primarily on groundwater?
  - **Water quality**
    - How does water quality affect your system?
    - Briefly, what are some of the types of actions you have to take if water quality is compromised?

- ☐ **TECHNOLOGY:**
  - **System infrastructure**
    - What kind of infrastructure makes up your water system?
    - How does your system's current capacity relate to how many gallons you could draw per day in the future?
  - **Monitoring**
    - How do you know if your system infrastructure isn't functioning properly?
    - How do you find out about changes in available technology?

- ☐ **INSTITUTIONS:**
  - **Regulations**
    - What regulations affect your system's operation?
    - What are some of the ways you think regulations might change in the future?
  - **Planning**
    - Who do you work with when you plan for the future of the system?
    - How extensive are your plans for the system?

- ☐ **ECONOMICS:**
  - **Expenses**
    - What are your system's most significant expenses?
    - How will your expenses change in the future?
  - **Income**
    - What are your system's sources of income?
    - What are the future funding opportunities for your system?

☐ **HUMAN CAPITAL:**

_ **Customers**
  _ How do you interact with your customers?
  _ What are some of your customers' main concerns?
  _ How do you think your customers' concerns might change in the future?

_ **Water system**
  _ What role do your volunteers or employees play in your water system's operation?
  _ How will your volunteers' or employees' roles change in the future?
  _ What sort of training do managers need?
  _ How do managers keep their knowledge current?

☐ **SOCIAL CAPITAL: Social network mapping exercise**
Materials: large sheet of sketch pad paper, markers

_ Now I'd like to ask you about some of the people or organizations you and your system interact with, but instead of simply asking questions, I'd like to guide you through drawing a map. We'll start by thinking of some of these people and organizations, and then I'll have you draw some lines to indicate the types of things you get from or give to them. Don't worry about whether it's "pretty" or "right" – this is just a way to help you brainstorm and organize some ideas. It also helps me to visualize some of these relationships you're talking about. To begin, I'd like you to draw your system in the center of the map.

_ **Actors**
  _ Who are the government entities that interact with your system?
  _ Who are the local, non-governmental entities that interact with your system?
  _ Who are the entities that may interact with your system more often in the future?

_ **Resources**
  _ What does your system get from these entities?
    - Who gives you money?
    - Who do you have to pay?
    - Who provides you with the other non-monetary resources you need to run the system?
    - Who do you provide with other non-monetary resources?
  _ What are some of the characteristics of these relationships?
  _ How will these relationships change in the future?

☐ **MANAGER PERCEPTIONS OF ADAPTIVE CAPACITY:**

_ **Past risks and responses**
  _ What are some events that have affected your system negatively in the past?
  _ What are some events that have affected your system positively in the past?
  _ How did your system respond to these past events?

_ **Future risks and responses**
  _ What are some of the events you're concerned will affect your system in the future?
  _ What are some of the ways your system might respond to these events?

_ **Perceptions of weather and climate change**
  _ What are some of the things you've heard about climate change?
  _ What are some of the things you've heard about how the climate might change in Central Pennsylvania?
  _ What are some of the concerns climate change raises for your system?

    - _ How can your system react to these changes?
- _ I'd like to close by asking you about your definitions of a few terms when I use them in the context of climate change. I'm not checking to see if your definitions are "right" or "wrong"! Don't worry about how much you think you know – I want to know what comes to your mind when I use these terms. This will help me to understand how you think of these terms. I would like to be able explain to you and to other water managers how I and other researchers think of these terms, so this will also help me learn how best to do that. Again, that won't make your definitions wrong – it will just help us to figure out how to understand each other!
    - _ What is "weather"?
    - _ What is "climate"?
    - _ What is "vulnerability to climate change"?
    - _ What is "exposure to climate change"?
    - _ What is "sensitivity to climate change"?
    - _ What is "adaptive capacity" in the context of climate change?

☐ **CLOSING QUESTIONS ABOUT INTERVIEW PROCESS:**
- _ What was it like to participate in this interview?
- _ Were there any questions that you found difficult or unpleasant to answer?
- _ What are some of the issues that you thought of during the interview that we didn't get to talk about?

Appendix B

Scenario-building Focus Group Guides

This appendix contains all approved scripts for the mediated modeling focus groups (Penn State IRB#22225). The two scripts for Meetings 1 and 2 were followed closely. Early in Meeting 3, it became apparent that the CWS-FACS model was not ready for final evaluation. The group decided by consensus to abandon the Meeting #3 script and follow the Meeting #2 script, which guided the group through another iteration of revising the model structure. To comply with Penn State IRB requirements, a script for a fourth group was submitted, and expanded to cover questions generated during the previous meetings that were not originally captured in the Meeting #3 script. The final script took the form of an interview, because GTWA members were undecided about whether they would prefer a fourth focus group or individual interviews. Ultimately, a group interview took place, but the DEP sanitarian was unable to attend. The sanitarian was interviewed separately, and I did not share the results from the group interview until after the sanitarian's interview was completed to avoid biasing him toward the group's results. The sanitarian's thoughts largely reinforced the conclusions the GTWA members reached at the end of their group interview.

Scenario-building Focus Group Guide: Meeting #1

The process will consist of open-ended focus group interviews that are guided conversations where broad questions are asked and new questions are allowed to arise as a result of the discussion. This interview is the first in a series of three focus groups whose purpose is to solicit stakeholders' assistance to build scenarios of community water systems' (CWS) capacity to adapt to climate change in the form of more frequent floods and droughts. The objective of Meeting #1 is to orient the participants to the project and refine an initial model of CWS adaptive capacity.

The moderator will begin by welcoming the participants and introducing herself and the other researchers present. She will explain the general purpose of our research and outline objectives for the meeting. She will provide general rules for the discussion. Participants will then receive a brief survey establishing their baseline knowledge of concepts and their expectations for the series of focus groups *[see IRB22225_Addendum_Yarnal_Survey_Initial_05-16-07.doc]*. This portion of the meeting should last approximately 10 minutes.

Because adaptive capacity is not an intuitive concept, this focus group will begin with an icebreaking exercise. Participants will be grouped in pairs. Each pair represents a small community water system that experiences a particular hazard (either a flood or source water contamination). The pairs will then generate a list of particular impacts the event has on the system, a list of possible actions the system may take to prevent damage, and a list of possible actions the system may take to take advantage of beneficial impacts. Each pair will briefly present their lists to the full focus group. This activity should last approximately 10 minutes.

The moderator will use the exercise as an example to explain to the participants the concepts of sensitivity, adaptation, and adaptive capacity (analogous to the impacts, actions, and factors influencing the ability to take those actions discussed during the exercise) as they appear in our research. She will place this discussion in the context of the effects climate change may have on precipitation patterns in Central Pennsylvania. Results from previous approved research on CWS adaptive capacity will be summarized. This presentation will last approximately 20 minutes.

FOCUS GROUP MEETING #1 QUESTIONS (50 minutes):

1. What variables affect your CWS's adaptive capacity?
2. How important are these variables? (Rank/score)
3. How do the variables change over time?

The moderator will briefly summarize the discussion and ask, "Is this an adequate summary?"

She will finally ask, “What did our discussion miss?”

Prior to adjourning, participants will again complete a brief survey *[see IRB22225_Addendum_Yarnal_Survey_PostMeeting1_05-16-07.doc]* that asks what they learned, what they would improve about the discussion, and what their expectations are for the second focus group.

The following summarizes the activities listed above:

FOCUS GROUP MEETING #1 SCHEDULE (assume 0:00 is meeting start time):

6:00 – 6:10:	Introduction (moderator); Initial survey (participants)
6:10 – 6:20:	Presentation – Climate change, adaptive capacity, and community water systems in Centre County (moderator)
6:20 – 6:30:	Activity – vulnerability and adaptive capacity in action (participants)
6:30 – 7:00:	Variable elicitation (Questions 1-2)
7:00 – 7:05:	BREAK
7:05 – 7:25:	Variable elicitation (Questions 1-2)
7:25 – 7:55:	Variable behavior (Question 3)
7:55 – 8:00:	Post-Meeting #1 survey
8:00:	Adjourn

Scenario-building Focus Group Guide: Meeting #2

The process will consist of open-ended focus group interviews that are guided conversations where broad questions are asked and new questions are allowed to arise as a result of the discussion. This interview is the second in a series of three focus groups whose purpose is to solicit stakeholders' assistance to build scenarios of community water systems' (CWS) capacity to adapt to climate change in the form of more frequent floods and droughts. This meeting is organized in two parts, separated by a 10 minute break. The objective of the first part is to solicit input to help refine the CWS adaptive capacity model. In the second part, participants' input will assist the development of narrative scenarios for future CWS change.

The moderator will begin by welcoming the participants and thanking them for their continuing participation. She will begin with a brief review of the proceedings in Meeting #1. This portion of the meeting should last approximately 10 minutes.

The moderator will present the model built based on the results of Meeting #1; this model will be the basis of further discussion. This presentation should also last approximately 10 minutes.

FOCUS GROUP MEETING #2 QUESTIONS – 80 minutes (+ 10 minute break):

1. Which of the CWS adaptive capacity model variables are related to each other? How are these variables related?
2. What descriptors do we need to describe these relationships?
3. Which relationships are based on the values of other variables or relationships?
4. What are the goals for the CWS in the future?
5. What events might initiate change in the CWS?
6. How would variables in the model would be altered as a result?
7. What would be the desired outcome based on these changes?

The moderator will briefly summarize the discussion and ask, "Is this an adequate summary?"

She will finally ask, "What did our discussion miss?"

Prior to adjourning, participants will again complete a brief survey *[see IRB22225_Addendum_Yarnal_Survey_PostMeeting2_05-16-07.doc]* that asks what they learned, what they would improve about the discussion, and what their expectations are for the second focus group. This survey is nearly identical to that administered after Meeting #1 (only the meeting number and references to the number of remaining meetings have been changed).

The following summarizes the activities listed above:

FOCUS GROUP MEETING #2 SCHEDULE:

6:00 – 6:10:	Focus group Meeting #1 summary (moderator)
6:10 – 6:20:	Presentation of CWS adaptive capacity model based upon Meeting #1 results (moderator)
6:20 – 7:00:	Describing relationships within CWS adaptive capacity model (Questions 1-3)
7:00 – 7:10:	BREAK
7:10 – 7:50:	Narrative scenario building (Questions 4-7)
7:50 – 8:00:	Post-Meeting #2 survey
8:00:	Adjourn

Scenario-building Focus Group Guide: Meeting #3

The process will consist of open-ended focus group interviews that are guided conversations where broad questions are asked and new questions are allowed to arise as a result of the discussion. This interview is the third in a series of three focus groups whose purpose is to solicit stakeholders' assistance to build scenarios of community water systems' (CWS) capacity to adapt to climate change in the form of more frequent floods and droughts. This meeting is organized in two parts, separated by a 10 minute break. This meeting finalizes the CWS adaptive capacity model and evaluates the scenarios created using the input from Meeting #2.

The moderator will begin by welcoming the participants and thanking them for their continuing participation. She will begin with a brief review of the proceedings in Meeting #2. She will also review the current state of the model that incorporates the results of Meeting #2. This portion of the meeting should last approximately 20 minutes.

Participants will have the opportunity to comment on the current state of the model. Afterward, the moderator will present the model built based on the results of Meeting #2; this model will be the basis of further discussion. This presentation should also last approximately 10 minutes.

FOCUS GROUP #3 QUESTIONS – 70 minutes (+ 10 minute break):

1. How does the CWS adaptive capacity model's performance reflect your understanding of CWS adaptive capacity?
2. How well do the scenarios accommodate non-climate related changes in the system?
3. How well do the scenarios address your concerns about climate change?
4. How plausible are the scenarios?
5. How consistent are the scenario results?
6. For what purpose could you use these scenarios?
7. How can we increase the scenarios' utility?

The moderator will briefly summarize the discussion and ask, "Is this an adequate summary?"

She will finally ask, "What did our discussion miss?"

Prior to adjourning, participants will complete a brief exit survey *[see IRB22225_Addendum_Yarnal_Survey_Final_05-16-07.doc]* that asks what they learned and what they would improve about the discussion. This survey contains the questions in the surveys administered after Meetings #1 and #2. It also asks them to reflect upon the entire process presented in the three focus group meetings.

The following summarizes the activities listed above:

FOCUS GROUP MEETING #3 SCHEDULE

6:00 – 6:10:	Focus group Meeting #2 summary (moderator)
6:10 – 6:20:	Presentation of CWS adaptive capacity model based upon Meeting #2 results (moderator)
6:20 – 6:40:	CWS adaptive capacity model evaluation (Question 1)
6:40 – 6:50:	Presentation of model results using scenario suite (moderator)
6:50 – 7:00:	Scenario comprehensiveness (Questions 2-3)
7:00 – 7:10:	BREAK
7:10 – 7:50:	Scenario evaluation (Questions 4-7)
7:50 – 8:00:	Final survey
8:00:	Adjourn

Community Water System (CWS) Scenario Results Interview Guide

The process will consist of semi-structured interviews that are guided conversations where broad questions are asked, which do not constrain the conversation, and new questions are allowed to arise as a result of the discussion. The following is a basic outline of the interview along with a series of possible follow-up questions that may be used to continue discussion. New questions will be allowed to arise, and not all follow-up questions may be used.

The interview is based upon the final results of a model of CWS adaptive capacity. This system dynamics-based model generates scenarios of how well the CWS might be able to adapt to climate change. The researcher will begin the interview with a brief discussion of the model's purpose, structure, and function. Because interviewees helped to build this model in a series of focus groups, this introduction will be brief.

In interviews, each participant will be presented with climate change and growth scenarios for their CWS. These scenarios will take the form of printed graphical model output on the CWS's financial, natural resource, technological, institutional, human, and social adaptive capacities. The output generated by a model created using both the focus group data and a series of assumptions made by the researcher. The participant will be asked to comment on these scenarios as follows:

1. How well do the scenarios accommodate non-climate related changes in the system?
2. How well do the scenarios address your concerns about climate change?
3. How plausible are the scenarios?
4. How consistent are the scenario results?

Participants will then be allowed to interact with the computer model itself by using the graphical interface to alter the values of various parameters, creating their own scenarios. Participants will access the model using the researcher's laptop computer. **ALL MODEL OUTPUT FROM THE PARTICIPANTS' MODEL INTERACTION MUST BE EXPORTED TO EXCEL AND SAVED IN UNIQUELY PASSWORD-PROTECTED FILES, LABELED BY GROUP MEMBER NUMBER!**

5. Which parameters would you like to adjust to create your own scenarios?
6. How does your assessment of the scenarios change after you've seen the results of your own scenarios?

7. How does the CWS adaptive capacity model's performance reflect your understanding of your CWS's ability to adapt to change in general?
8. How does the model's performance reflect your understanding of your CWS's ability to adapt to climate change and variation?
9. For what purpose could you use these scenarios?
10. How can we increase the scenarios' utility?

The researcher will finish by asking the participant to fill out the final survey.

Appendix C

CWS-FACS Model Equations and Screen Shots

This appendix contains screen shots of the CWS-FACS model. It also includes the STELLA™ equations that the model uses. Each figure includes one or more sectors of the model. The equations for each sector are listed as text after each figure.

There are three general building blocks for the system dynamics model: stocks, flows, and converters. Stocks, represented by squares, accumulate quantities, such as the number of customers or the cumulative financial adaptive capacity indices from all time steps. Material accumulates and drains from stocks through flows, which are the clouds and arrows leading into and out of stocks. Flows change over time. Plain circles are converters, which describe the stocks and flows. Connections are arrows that indicate some action relationship (red solid arrows) or an information relationship (dashed arrows).

STELLA™ allows converters to take the form of graphical inputs, which are represented in the equations by a list of points. Several of these converters appear in the model, including the precipitation scenarios (in inches of precipitation per month). To conserve space, only the first type of each graphical converter includes the full code; remaining similar converters are truncated. Dashed converters are ghosts that are used for reducing the number of connections that cross over other parts of the model. For example, precipitation scenarios are stored in the Scenario Variables sector, but their ghosts appear in the Water Supply sector to avoid having converters cross sectors.

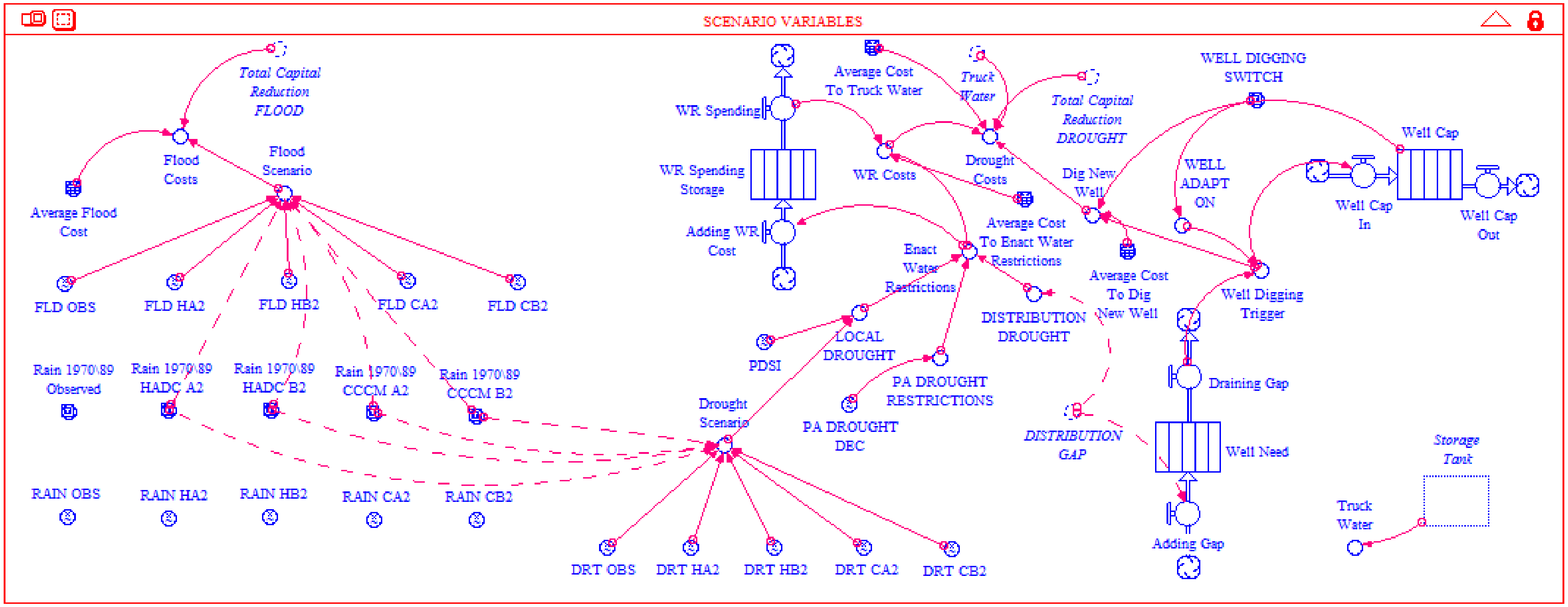

Figure C-1: Scenario Variables Sector of CWS-FACS model. Includes precipitation scenarios and modeling for drought and flood occurrences. This sector connects to Water Supply Sector through the precipitation scenarios and the well trigger, which .initiates the process of digging a well and paying for it when the GTWA is unable to meet demand for a sustained period.

SCENARIO VARIABLES

Well_Cap(t) = Well_Cap(t - dt) + (Well_Cap_In - Well_Cap_Out) * dt

INIT Well_Cap = 0

TRANSIT TIME = 12

INFLOW LIMIT = 1

CAPACITY = 4

INFLOWS:

Well_Cap_In = Well_Digging_Trigger*4

OUTFLOWS:

Well_Cap_Out = CONVEYOR OUTFLOW

Well_Need(t) = Well_Need(t - dt) + (Adding_Gap - Draining_Gap) * dt

INIT Well_Need = 0

TRANSIT TIME = 2

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:

Adding_Gap = DISTRIBUTION_GAP

OUTFLOWS:

Draining_Gap = CONVEYOR OUTFLOW

WR_Spending_Storage(t) = WR_Spending_Storage(t - dt) + (Adding_WR_Cost - WR_Spending) * dt

INIT WR_Spending_Storage = 0

TRANSIT TIME = 1

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:

Adding_WR_Cost = IF Enact_Water_Restrictions<1 THEN 6500 ELSE 0

OUTFLOWS:

WR_Spending = CONVEYOR OUTFLOW

Average_Cost_To_Dig__New_Well = 9900

Average_Cost_To_Enact_Water_Restrictions = 6500

Average_Cost_To_Truck_Water = 1000

Average_Flood_Cost = 10000

Dig_New_Well = IF Well_Digging_Trigger=1 AND Well_Cap=1 THEN Average_Cost_To_Dig__New_Well ELSE 0

DISTRIBUTION_DROUGHT = IF (TIME<3) THEN 1 ELSE IF (DISTRIBUTION_GAP>250000) THEN 0.8 ELSE IF (DISTRIBUTION_GAP>150000) THEN 0.9 ELSE IF (DISTRIBUTION_GAP>5000) THEN 0.95 ELSE 1

Drought_Costs = IF TIME<3 THEN 0 ELSE (Dig_New_Well+(Truck_Water*Average_Cost_To_Truck_Water)+WR_Costs-(IF (Dig_New_Well+(Truck_Water*Average_Cost_To_Truck_Water)+WR_Costs)>Total_Capital_Reduction_DROUGHT THEN Total_Capital_Reduction_DROUGHT ELSE 0))

Drought_Scenario = IF Rain_1970\89_HADC_A2 THEN DRT_HA2 ELSE IF Rain_1970\89_HADC_B2 THEN DRT_HB2 ELSE IF Rain_1970\89_CCCM_A2 THEN DRT_CA2 ELSE IF Rain_1970\89_CCCM_B2 THEN DRT_CB2 ELSE DRT_OBS

Enact_Water_Restrictions = MIN(DISTRIBUTION_DROUGHT,LOCAL_DROUGHT,PA_DROUGHT_RESTRICTIONS)

Flood_Costs = (Average_Flood_Cost*Flood_Scenario)-(IF(Average_Flood_Cost*Flood_Scenario>0)THEN Total_Capital_Reduction_FLOOD ELSE 0)

Flood_Scenario = (IF Rain_1970\89_HADC_A2=1 THEN FLD_HA2 ELSE (IF Rain_1970\89_HADC_B2=1 THEN FLD_HB2 ELSE (IF Rain_1970\89_CCCM_A2=1 THEN FLD_CA2 ELSE (IF Rain_1970\89_CCCM_B2=1 THEN FLD_CB2 ELSE FLD_OBS))))

LOCAL_DROUGHT = IF (TIME<3) THEN 1 ELSE IF (PDSI<0 AND Drought_Scenario=3) THEN 0.8 ELSE IF (PDSI<0 AND Drought_Scenario=2) THEN 0.9 ELSE IF (PDSI<0 AND Drought_Scenario=1) THEN 0.95 ELSE 1

PA_DROUGHT_RESTRICTIONS = IF (TIME<3) THEN 1 ELSE IF (PA_DROUGHT_DEC=3) THEN 0.8 ELSE IF (PA_DROUGHT_DEC=2) THEN 0.9 ELSE IF (PA_DROUGHT_DEC=1) THEN 0.95 ELSE 1

Rain_1970\89_CCCM_A2 = 0

Rain_1970\89_CCCM_B2 = 0

Rain_1970\89_HADC_A2 = 0

Rain_1970\89_HADC_B2 = 0

Rain_1970\89_Observed = 1

Truck_Water = IF Storage_Tank=0 THEN 1 ELSE 0

WELL_ADAPT_ON = WELL_DIGGING_SWITCH

WELL_DIGGING_SWITCH = 0

Well_Digging_Trigger = IF (TIME<4) then 0 else IF Draining_Gap>200000 THEN (1*WELL_ADAPT_ON) ELSE 0

WR_Costs = IF (Enact_Water_Restrictions<1) AND (WR_Spending=0) THEN Average_Cost_To_Enact_Water_Restrictions ELSE 0

DRT_CA2 = GRAPH(TIME)

(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 1.00), (17.0, 1.00), (18.0, 3.00), (19.0, 1.00), (20.0, 1.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 1.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 1.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 1.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 1.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 1.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.00), (76.0, 1.00), (77.0, 2.00), (78.0, 1.00), (79.0, 0.00), (80.0, 0.00), (81.0, 0.00), (82.0, 0.00), (83.0, 0.00), (84.0, 0.00), (85.0, 0.00), (86.0, 3.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 0.00), (102, 0.00), (103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.00), (109, 0.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.00), (118, 0.00), (119, 0.00), (120, 0.00), (121, 0.00), (122, 0.00), (123, 0.00), (124, 0.00), (125, 0.00), (126, 0.00), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.00), (131, 0.00), (132, 0.00), (133, 0.00), (134, 0.00), (135, 0.00), (136, 1.00), (137, 1.00), (138, 3.00), (139, 1.00), (140, 1.00), (141, 0.00), (142, 0.00), (143, 0.00), (144, 0.00), (145, 1.00), (146, 0.00), (147, 0.00), (148, 0.00), (149, 0.00), (150, 0.00), (151, 0.00), (152, 0.00), (153, 0.00), (154, 1.00), (155, 0.00), (156, 0.00), (157, 0.00), (158, 0.00), (159, 0.00), (160, 0.00), (161, 0.00), (162, 0.00), (163, 0.00), (164, 1.00), (165, 0.00), (166, 0.00), (167, 0.00), (168, 0.00), (169, 0.00), (170, 0.00), (171, 0.00), (172, 0.00), (173, 1.00), (174, 0.00), (175, 0.00), (176, 0.00), (177, 0.00), (178, 0.00), (179, 0.00), (180, 0.00), (181, 0.00), (182, 0.00), (183, 0.00), (184, 0.00), (185, 0.00), (186, 0.00), (187, 1.00), (188, 0.00), (189, 0.00), (190, 0.00), (191, 0.00), (192, 0.00), (193, 0.00), (194, 0.00), (195, 0.00), (196, 1.00), (197, 2.00), (198, 1.00), (199, 0.00), (200, 0.00), (201, 0.00), (202, 0.00), (203, 0.00), (204, 0.00), (205, 0.00), (206, 3.00), (207, 0.00), (208, 0.00), (209, 0.00), (210, 0.00), (211, 0.00), (212, 0.00), (213, 0.00), (214, 0.00), (215, 0.00), (216, 0.00), (217, 0.00), (218, 0.00), (219, 0.00), (220, 0.00), (221, 0.00), (222, 0.00), (223, 0.00), (224, 0.00), (225, 0.00), (226, 0.00), (227, 0.00), (228, 0.00), (229, 0.00), (230, 0.00), (231, 0.00), (232, 0.00), (233, 0.00), (234, 0.00), (235, 0.00), (236, 0.00), (237, 0.00), (238, 0.00), (239, 0.00), (240, 0.00)

DRT_CB2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.00)

DRT_HA2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 2.00)

DRT_HB2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 1.00)

DRT_OBS = GRAPH(TIME)

(0.00, 0.00), …, (240, 1.00)

FLD_CA2 = GRAPH(TIME)

(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 1.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 1.00), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.00), (76.0, 0.00), (77.0, 0.00), (78.0, 0.00), (79.0, 0.00), (80.0, 0.00), (81.0, 0.00), (82.0, 1.00), (83.0, 0.00), (84.0, 0.00), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 1.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 1.00), (102, 0.00), (103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.00), (109, 1.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 1.00), (118, 0.00), (119, 0.00), (120, 0.00), (121, 0.00), (122, 0.00), (123, 0.00), (124, 0.00), (125, 0.00), (126, 0.00), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.00), (131, 0.00), (132, 0.00), (133, 0.00), (134, 0.00), (135, 0.00), (136, 0.00), (137, 0.00), (138, 0.00), (139, 0.00), (140, 0.00), (141, 0.00), (142, 0.00), (143, 0.00), (144, 0.00), (145, 0.00), (146, 0.00), (147, 0.00), (148, 0.00), (149, 0.00), (150, 0.00), (151, 0.00), (152, 0.00), (153, 0.00), (154, 0.00), (155, 0.00), (156, 0.00), (157, 0.00), (158, 0.00), (159, 0.00), (160, 0.00), (161, 0.00), (162, 0.00), (163, 0.00), (164, 0.00), (165, 0.00), (166, 0.00), (167, 0.00), (168, 0.00), (169, 0.00), (170, 0.00), (171, 0.00), (172, 0.00), (173, 0.00), (174, 0.00), (175, 0.00), (176, 0.00), (177, 0.00), (178, 0.00), (179, 0.00), (180, 0.00), (181, 0.00), (182, 0.00), (183, 0.00), (184, 0.00), (185, 0.00), (186, 0.00), (187, 0.00), (188, 0.00), (189, 0.00), (190, 0.00), (191, 0.00), (192, 0.00), (193, 0.00), (194, 0.00), (195, 0.00), (196, 0.00), (197, 0.00), (198, 0.00), (199, 0.00), (200, 0.00), (201, 0.00), (202, 0.00), (203, 0.00), (204, 0.00), (205, 0.00), (206, 0.00), (207, 0.00), (208, 0.00), (209, 0.00), (210, 0.00), (211, 0.00), (212, 0.00), (213, 0.00), (214, 0.00), (215, 0.00), (216, 0.00), (217, 0.00), (218, 0.00), (219, 0.00), (220, 0.00), (221, 0.00), (222, 0.00), (223, 0.00), (224, 0.00), (225, 0.00), (226, 0.00), (227, 0.00), (228, 0.00), (229, 0.00), (230, 0.00), (231, 0.00), (232, 0.00), (233, 0.00), (234, 0.00), (235, 0.00), (236, 0.00), (237, 1.00), (238, 0.00), (239, 0.00), (240, 0.00)

FLD_CB2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.00)

FLD_HA2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.00)

FLD_HB2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.00)

FLD_OBS = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.00)

PA_DROUGHT_DEC = GRAPH(TIME)

(0.00, 0.00), (1.00, 0.00), (2.00, 0.00), (3.00, 0.00), (4.00, 0.00), (5.00, 0.00), (6.00, 0.00), (7.00, 0.00), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 0.00), (16.0, 0.00), (17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00), (51.0, 0.00), (52.0, 0.00), (53.0, 0.00), (54.0, 0.00), (55.0, 0.00), (56.0, 0.00), (57.0, 0.00), (58.0, 0.00), (59.0, 0.00), (60.0, 0.00), (61.0, 0.00), (62.0, 0.00), (63.0, 0.00), (64.0, 0.00), (65.0, 0.00), (66.0, 0.00), (67.0, 0.00), (68.0, 0.00), (69.0, 0.00), (70.0, 0.00), (71.0, 0.00), (72.0, 0.00), (73.0, 0.00), (74.0, 0.00), (75.0, 0.00), (76.0, 0.00), (77.0, 0.00), (78.0, 0.00), (79.0, 0.00), (80.0, 0.00), (81.0, 0.00), (82.0, 0.00), (83.0, 0.00), (84.0, 0.00), (85.0, 0.00), (86.0, 0.00), (87.0, 0.00), (88.0, 0.00), (89.0, 0.00), (90.0, 0.00), (91.0, 0.00), (92.0, 0.00), (93.0, 0.00), (94.0, 0.00), (95.0, 0.00), (96.0, 0.00), (97.0, 0.00), (98.0, 0.00), (99.0, 0.00), (100, 0.00), (101, 0.00), (102, 0.00), (103, 0.00), (104, 0.00), (105, 0.00), (106, 0.00), (107, 0.00), (108, 0.00), (109, 0.00), (110, 0.00), (111, 0.00), (112, 0.00), (113, 0.00), (114, 0.00), (115, 0.00), (116, 0.00), (117, 0.00), (118, 0.00), (119, 0.00), (120, 0.00), (121, 0.00), (122, 0.00), (123, 0.00), (124, 0.00), (125, 0.00), (126, 0.00), (127, 0.00), (128, 0.00), (129, 0.00), (130, 0.00), (131, 0.00), (132, 3.00), (133, 3.00), (134, 3.00), (135, 3.00), (136, 3.00), (137, 3.00), (138, 3.00), (139, 3.00), (140, 3.00), (141, 3.00), (142, 3.00), (143, 3.00), (144, 3.00), (145, 3.00), (146, 3.00), (147, 3.00), (148, 3.00), (149, 0.00), (150, 0.00), (151, 0.00), (152, 0.00), (153, 0.00), (154, 0.00), (155, 0.00), (156, 0.00), (157, 0.00), (158, 0.00), (159, 0.00), (160, 0.00), (161, 0.00), (162, 0.00), (163, 0.00), (164, 0.00), (165, 0.00), (166, 0.00), (167, 0.00), (168, 0.00), (169, 0.00), (170, 0.00), (171, 0.00), (172, 0.00), (173, 0.00), (174, 0.00), (175, 0.00), (176, 0.00), (177, 0.00), (178, 0.00), (179, 0.00), (180, 0.00), (181, 0.00), (182, 0.00), (183, 0.00), (184, 0.00), (185, 1.00), (186, 1.00), (187, 1.00), (188, 1.00), (189, 1.00), (190, 1.00), (191, 3.00), (192, 3.00), (193, 0.00), (194, 0.00), (195, 0.00), (196, 0.00), (197, 0.00), (198, 0.00), (199, 0.00), (200, 0.00), (201, 0.00), (202, 0.00), (203, 0.00), (204, 0.00), (205, 0.00), (206, 0.00), (207, 0.00), (208, 0.00), (209, 0.00), (210, 0.00), (211, 0.00), (212, 0.00), (213, 0.00), (214, 0.00), (215, 0.00), (216, 0.00), (217, 0.00), (218, 0.00), (219, 0.00), (220, 0.00), (221, 0.00), (222, 0.00), (223, 1.00), (224, 1.00), (225, 2.00), (226, 2.00), (227, 2.00), (228, 0.00), (229, 0.00), (230, 0.00), (231, 1.00), (232, 1.00), (233, 1.00), (234, 0.00), (235, 0.00), (236, 0.00), (237, 0.00), (238, 0.00), (239, 0.00), (240, 0.00)

PDSI = GRAPH(TIME)

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RAIN_CA2 = GRAPH(TIME)

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RAIN_CB2 = GRAPH(TIME)

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RAIN_HA2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.673)

RAIN_HB2 = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.627)

RAIN_OBS = GRAPH(TIME)

(0.00, 0.00), …, (240, 0.65)

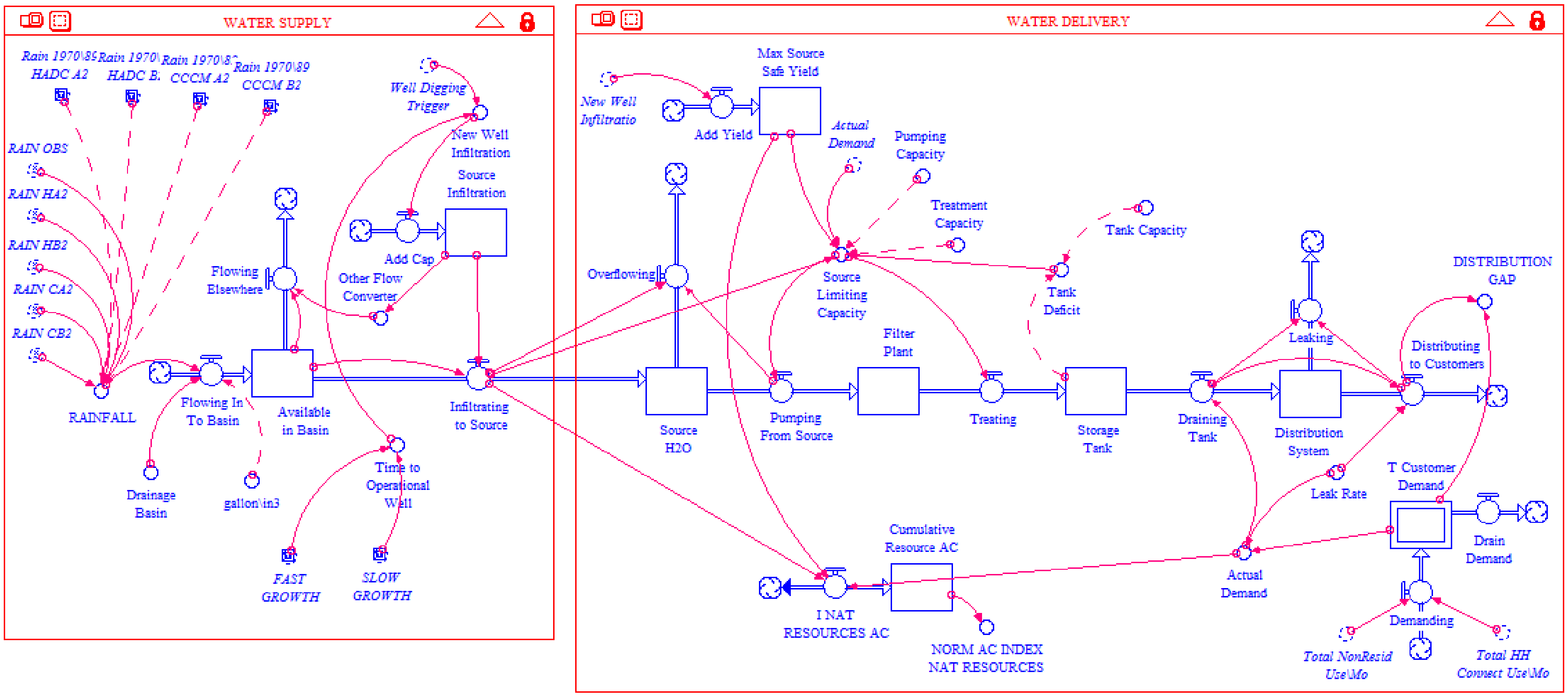

Figure C-2: Water Supply and Water Delivery Sectors. Water Supply directly leads to Water Delivery via infiltration into the source spring. The Water Delivery Sector is also connected to the Customer Characteristics Sector because nonresidential and residential water uses drive how much water the GTWA treats and delivers.

WATER SUPPLY

Available__in_Basin(t) = Available__in_Basin(t - dt) + (Flowing_In_To_Basin - Infiltrating_to_Source - Flowing_Elsewhere) * dt

INIT Available__in_Basin = 1144506483.38

INFLOWS:

Flowing_In_To_Basin = Drainage_Basin*RAINFALL*gallon\in3

OUTFLOWS:

Infiltrating_to_Source = Available__in_Basin*Source_Infiltration

Flowing_Elsewhere = Available__in_Basin*Other_Flow_Converter

Source_Infiltration(t) = Source_Infiltration(t - dt) + (Add_Cap) * dt

INIT Source_Infiltration = 0.001

INFLOWS:

Add_Cap = New_Well_Infiltration*0.0004

Drainage_Basin = 70253567999.99998

gallon\in3 = 1/213

New_Well_Infiltration = DELAY(Well_Digging_Trigger,Time_to_Operational_Well)

Other_Flow_Converter = 1-(Source_Infiltration)

RAINFALL = IF Rain_1970\89_HADC_A2=1 THEN RAIN_HA2 ELSE (IF Rain_1970\89_HADC_B2=1 THEN RAIN_HB2 ELSE (IF Rain_1970\89_CCCM_A2=1 THEN RAIN_CA2 ELSE (IF Rain_1970\89_CCCM_B2=1 THEN RAIN_CB2 ELSE RAIN_OBS)))

Time_to_Operational_Well = IF FAST_GROWTH=1 THEN 9 ELSE IF SLOW_GROWTH=1 THEN 18 ELSE 12

WATER DELIVERY

Cumulative__Resource_AC(t) = Cumulative__Resource_AC(t - dt) + (I_NAT_RESOURCES_AC) * dt

INIT Cumulative__Resource_AC = 0

INFLOWS:

I_NAT_RESOURCES_AC = IF TIME<3 THEN 0 ELSE (((Infiltrating_to_Source/Actual_Demand)-1)/((Max_Source_Safe_Yield/Actual_Demand)-1))

Distribution_System(t) = Distribution_System(t - dt) + (Draining_Tank - Leaking - Distributing_to_Cust) * dt

INIT Distribution_System = 0

INFLOWS:

Draining_Tank = Actual_Demand

OUTFLOWS:

Leaking = Draining_Tank-Distributing_to_Cust

Distributing_to_Cust = Draining_Tank/(1+Leak_Rate)

Filter_Plant(t) = Filter_Plant(t - dt) + (Pumping_From_Source - Treating) * dt

INIT Filter_Plant = 0

INFLOWS:

Pumping_From_Source = Source_Limiting_Capacity

OUTFLOWS:

Treating = Source_Limiting_Capacity

Max_Source_Safe_Yield(t) = Max_Source_Safe_Yield(t - dt) + (Add_Yield) * dt

INIT Max_Source_Safe_Yield = 108000*(365/12)

INFLOWS:

Add_Yield = New_Well_Infiltration*(50000*(365/12))

Source_H2O(t) = Source_H2O(t - dt) + (Infiltrating_to_Source - Pumping_From_Source - Overflowing) * dt

INIT Source_H2O = 0

INFLOWS:

Infiltrating_to_Source   (IN SECTOR: WATER SUPPLY)

OUTFLOWS:

Pumping_From_Source = Source_Limiting_Capacity

Overflowing = (Infiltrating_to_Source-Pumping_From_Source)

Storage_Tank(t) = Storage_Tank(t - dt) + (Treating - Draining_Tank) * dt

INIT Storage_Tank = 0

INFLOWS:

Treating = Source_Limiting_Capacity

OUTFLOWS:

Draining_Tank = Actual_Demand

T_Customer_Demand(t) = T_Customer_Demand(t - dt) + (Demanding - Drain_Demand) * dt

INIT T_Customer_Demand = 0

COOK TIME = 1

CAPACITY = INF

FILL TIME = DT

INFLOWS:

Demanding = (Total_HH_Connect_Use\Mo+Total_NonResid__Use\Mo)

OUTFLOWS:

Drain_Demand = CONTENTS OF OVEN AFTER COOK TIME, ZERO OTHERWISE

Actual_Demand = ((T_Customer_Demand*4)+((T_Customer_Demand*4)*Leak_Rate))

DISTRIBUTION_GAP = (T_Customer_Demand*4)-Distributing_to_Cust

Leak_Rate = 0.2

NORM_AC_INDEX_NAT_RESOURCES = IF TIME=0 THEN 0 ELSE (Cumulative__Resource_AC/TIME)

Pumping_Capacity = 64800*(365/12)

Source_Limiting_Capacity = MIN(Infiltrating_to_Source,Max_Source_Safe_Yield,Treatment_Capacity,Pumping_Capacity,(Actual_Demand+Tank_Deficit))

Tank_Capacity = 150000

Tank_Deficit = (Tank_Capacity-Storage_Tank)

Treatment_Capacity = (90000*(365/12))

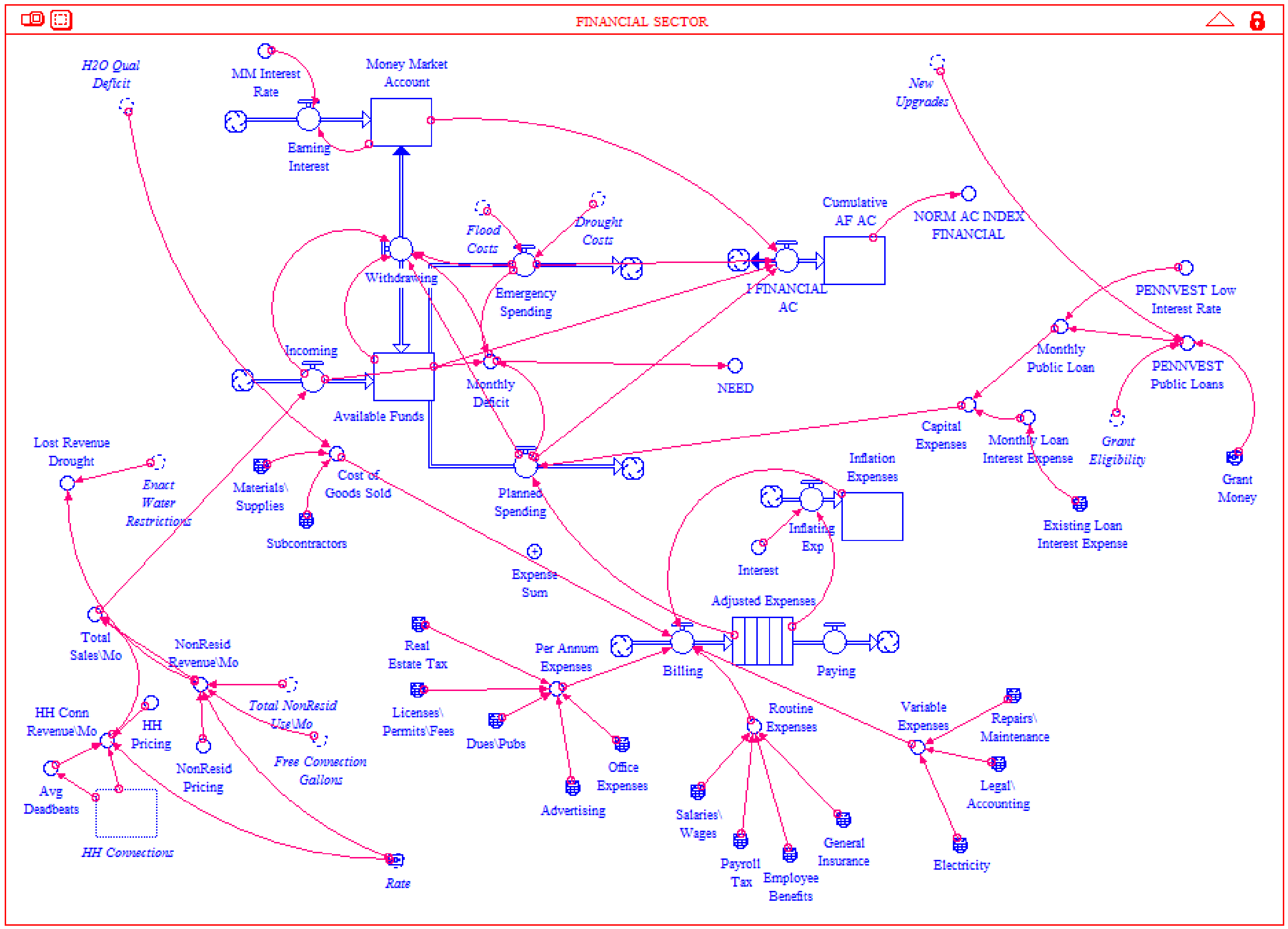

Figure C-3: Financial Sector. It is connected to the Customer Characteristics Sector through customer usage and rates. It is also connected to the Water Quality and Regulatory Change Sectors, because additional treatment requirements and required upgrades result in additional costs to the CWS. Average flood and drought costs connect the Financial Sector to the Scenario Variables Sector.

FINANCIAL SECTOR

Adjusted_Expenses(t) = Adjusted_Expenses(t - dt) + (Billing - Paying) * dt

INIT Adjusted_Expenses = 0

TRANSIT TIME = 1

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:

Billing = Inflation_Expenses+Variable_Expenses+Cost_of_Goods_Sold+Per_Annum_Expenses+Routine_Expenses

OUTFLOWS:

Paying = CONVEYOR OUTFLOW

Available_Funds(t) = Available_Funds(t - dt) + (Incoming + Withdrawing - Planned_Spending - Emergency_Spending) * dt

INIT Available_Funds = 30000

INFLOWS:

Incoming = Total_Sales\Mo

Withdrawing = IF ((Planned_Spending+Emergency_Spending)>Incoming) AND (Available_Funds<Incoming) THEN Monthly_Deficit ELSE IF ((Planned_Spending+Emergency_Spending)<Incoming) AND (Available_Funds>(INIT(Available_Funds)+5000)) THEN Monthly_Deficit ELSE 0

OUTFLOWS:

Planned_Spending = Adjusted_Expenses+Capital_Expenses

Emergency_Spending = Drought_Costs+Flood_Costs

Cumulative_AF_AC(t) = Cumulative_AF_AC(t - dt) + (I_FINANCIAL_AC) * dt

INIT Cumulative_AF_AC = 0

INFLOWS:

I_FINANCIAL_AC = ((Available_Funds+Money_Market_Account)-(Planned_Spending+Emergency_Spending))/(135500-(Planned_Spending+Emergency_Spending))

Inflation_Expenses(t) = Inflation_Expenses(t - dt) + (Inflating_Exp) * dt

INIT Inflation_Expenses = 0

INFLOWS:

Inflating_Exp = pulse(Interest*Adjusted_Expenses,12,12)

Money_Market_Account(t) = Money_Market_Account(t - dt) + (Earning_Interest - Withdrawing) * dt

INIT Money_Market_Account = 30000

INFLOWS:

Earning_Interest = Money_Market_Account*MM_Interest_Rate

OUTFLOWS:

Withdrawing = IF ((Planned_Spending+Emergency_Spending)>Incoming) AND (Available_Funds<Incoming) THEN Monthly_Deficit ELSE IF ((Planned_Spending+Emergency_Spending)<Incoming) AND (Available_Funds>(INIT(Available_Funds)+5000)) THEN Monthly_Deficit ELSE 0

Advertising = 490

Avg_Deadbeats = ROUND(0.02*HH_Connections)

Capital_Expenses = Monthly_Loan_Interest_Expense+Monthly_Public_Loan

Cost_of_Goods_Sold = (Materials_Supplies+(Materials_Supplies*H2O_Qual_Deficit)+Subcontractors)/12

Dues\Pubs = 380

Electricity = 2770

Employee_Benefits = 55

Existing_Loan_Interest_Expense = 2190

Expense_Sum = Variable_Expenses + Cost_of_Goods_Sold + Per_Annum_Expenses + Routine_Expenses

General_Insurance = 300

Grant_Money = 0

HH_Conn_Revenue\Mo = (Rate*(HH_Connections-Avg_Deadbeats)*HH_Pricing)+((Rate*0.67)*Avg_Deadbeats*HH_Pricing)

HH_Pricing = 1

Interest = 0.03

Legal_Accounting = 1000

Licenses_Permits\Fees = 7830

Lost_Revenue_Drought = Enact_Water_Restrictions*NonResid_Revenue\Mo

Materials_Supplies = 8000

MM_Interest_Rate = 0.0138/12

Monthly_Deficit = (Emergency_Spending+Planned_Spending)-Incoming

Monthly_Loan_Interest_Expense = Existing_Loan_Interest_Expense/12

Monthly_Public_Loan = (PENNVEST_Low__Interest_Rate*PENNVEST_Public_Loans)/((1-(1+PENNVEST_Low__Interest_Rate)^-318))

NEED = IF (Monthly_Deficit>200) THEN 1 ELSE 0

NonResid_Pricing = 3000

NonResid_Revenue\Mo = ((Rate/NonResid_Pricing)*Total_NonResid__Use\Mo)-((Rate/NonResid_Pricing)*Free_Connection_Gallons)

NORM_AC_INDEX_FINANCIAL = IF TIME=0 THEN 0 ELSE (Cumulative_AF_AC/TIME)

Office_Expenses = 140

Payroll_Tax = 155

PENNVEST_Low__Interest_Rate = 0.01/12

PENNVEST_Public_Loans = (1750000-(Grant_Money*Grant_Eligibility))+New_Upgrades

Per_Annum_Expenses = (Advertising+Dues\Pubs+Licenses_Permits\Fees+Office_Expenses+Real_Estate_Tax)/12

Real_Estate_Tax = 450

Repairs_Maintenance = 4000

Routine_Expenses = (Employee_Benefits+General_Insurance+Payroll_Tax+Salaries_Wages)/12

Salaries_Wages = 2600

Subcontractors = 11000

Total_Sales\Mo = (HH_Conn_Revenue\Mo+NonResid_Revenue\Mo)

Variable_Expenses = (Electricity+Legal_Accounting+Repairs_Maintenance)/12

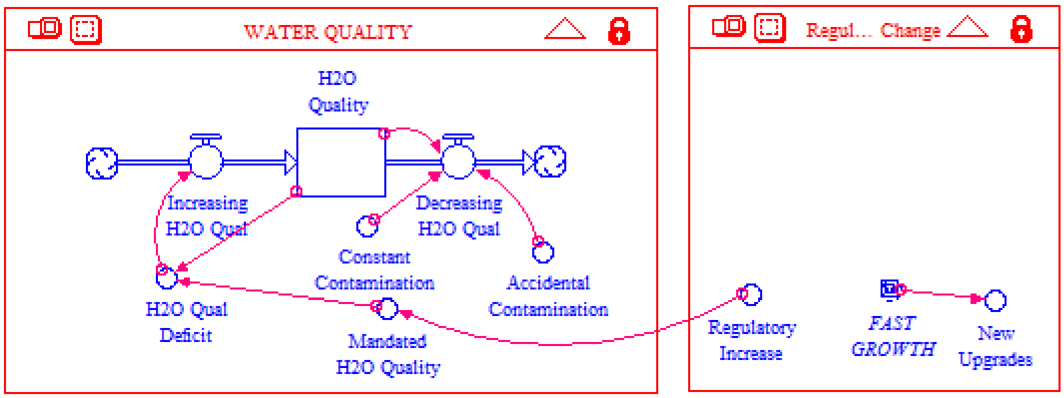

Figure C-4: Water Quality and Regulatory Change Sectors. Regulatory Change Sector connects to Customer Characteristics sector via the speed of growth. The New Upgrades converter is only connected to Fast Growth because the speed of required updates is the same for slow and medium growth, so the different values are input using an ELSE statement.

WATER QUALITY

H2O_Quality(t) = H2O_Quality(t - dt) + (Increasing_H2O_Qual - Decreasing_H2O_Qual) * dt

INIT H2O_Quality = 1

INFLOWS:

Increasing_H2O_Qual = H2O_Qual_Deficit

OUTFLOWS:

Decreasing_H2O_Qual = (H2O_Quality*Constant_Contamination)+(H2O_Quality*Accidental_Contamination)

Accidental_Contamination = 0

Constant_Contamination = (COSWAVE(0.2,2))+2*(SINWAVE(-0.1,6))

H2O_Qual_Deficit = (Mandated_H2O_Quality-H2O_Quality)+0.01

Mandated_H2O_Quality = 1+Regulatory_Increase

Regulatory Change

New_Upgrades = IF FAST_GROWTH=1 THEN STEP(500000,120) ELSE STEP(200000,120)

Regulatory_Increase = STEP(0.2,6)

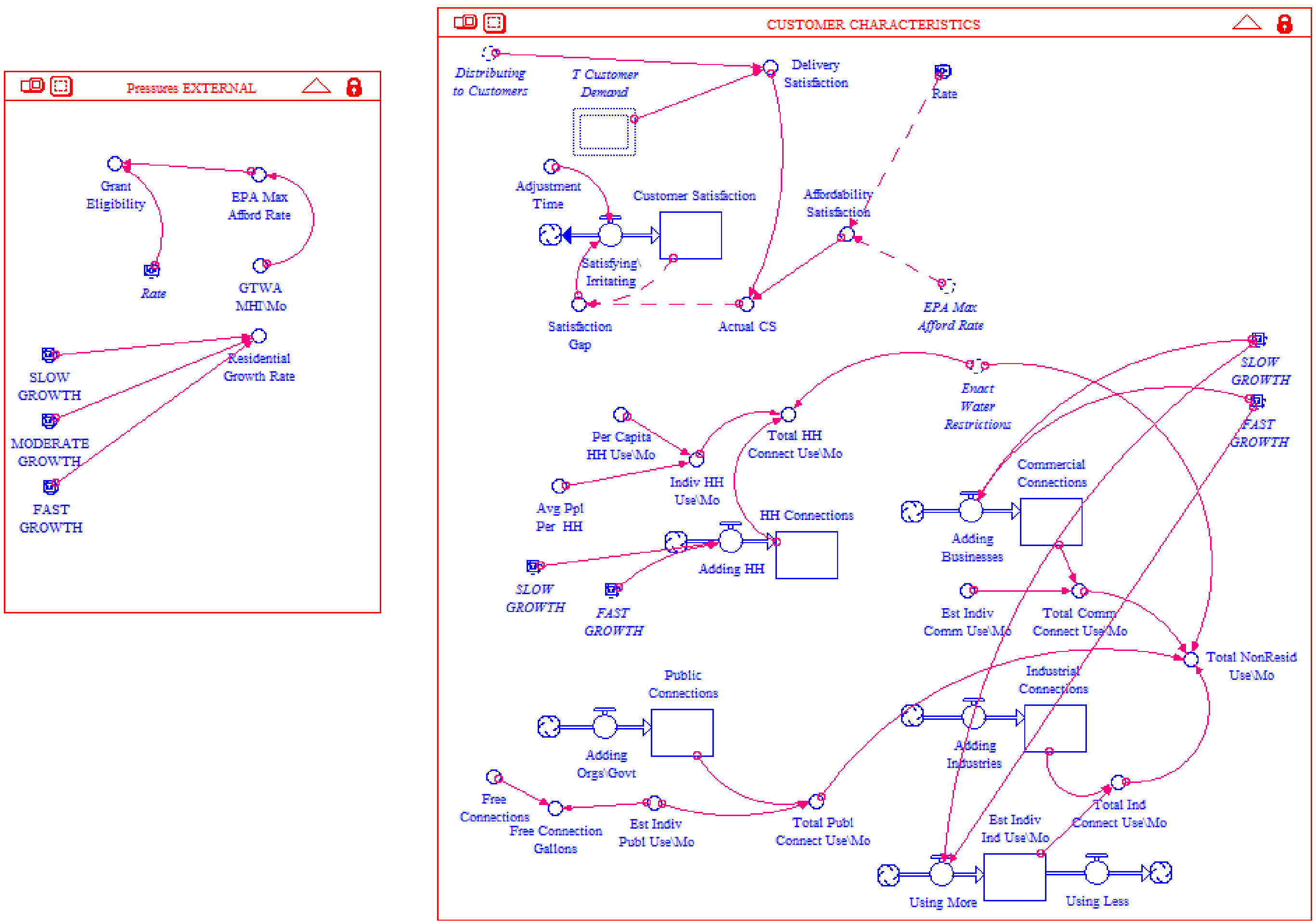

Figure C-5: Customer Characteristics and External Pressures Sectors. The Customer Characteristics sector connects to both the Financial Sector and the Water Delivery Sector, as referenced in Figure C-2. It also connects to the External Pressures Sector through the growth scenarios.

CUSTOMER CHARACTERISTICS

Commercial_Connections(t) = Commercial_Connections(t - dt) + (Adding_Businesses) * dt

INIT Commercial_Connections = 5

INFLOWS:

Adding_Businesses = IF (SLOW_GROWTH=1) THEN PULSE(1,60,60) ELSE IF (FAST_GROWTH=1) THEN PULSE(1,12,12) ELSE PULSE(1,36,36)

Customer_Satisfaction(t) = Customer_Satisfaction(t - dt) + (Satisfying_Irritating) * dt

INIT Customer_Satisfaction = 2

INFLOWS:

Satisfying_Irritating = Satisfaction_Gap/Adjustment_Time

Est_Indiv_Ind_Use\Mo(t) = Est_Indiv_Ind_Use\Mo(t - dt) + (Using_More - Using_Less) * dt

INIT Est_Indiv_Ind_Use\Mo = 3650

INFLOWS:

Using_More = IF SLOW_GROWTH=1 THEN PULSE(1000,36,36) ELSE IF FAST_GROWTH=1 THEN PULSE(1000,12,12) ELSE PULSE(1000,24,24)

OUTFLOWS:

Using_Less = 0

HH_Connections(t) = HH_Connections(t - dt) + (Adding_HH) * dt

INIT HH_Connections = 151

INFLOWS:

Adding_HH = IF SLOW_GROWTH=1 THEN PULSE(2,6,6) ELSE IF FAST_GROWTH=1 THEN PULSE(8,6,6) ELSE PULSE(5,6,6)

Industrial_Connections(t) = Industrial_Connections(t - dt) + (Adding_Industries) * dt

INIT Industrial_Connections = 5

INFLOWS:

Adding_Industries = 0

Public_Connections(t) = Public_Connections(t - dt) + (Adding_Orgs\Govt) * dt

INIT Public_Connections = 4

INFLOWS:

Adding_Orgs\Govt = 0

Actual_CS = Affordability_Satisfaction+Delivery_Satisfaction

Adjustment_Time = 3

Affordability_Satisfaction = IF (Rate/EPA_Max_Afford_Rate)<1 THEN 0 ELSE 1

Avg_Ppl_Per__HH = 2.65

Delivery_Satisfaction = IF (Distributing_to_Cust/(T_Customer_Demand*4))<1 THEN 0 ELSE 1

Est_Indiv_Comm_Use\Mo = 10646

Est_Indiv_Publ_Use\Mo = 1901

Free_Connection_Gallons = Free_Connections*Est_Indiv_Publ_Use\Mo

Free_Connections = 2

Indiv_HH_Use\Mo = Avg_Ppl_Per__HH*Per_Capita_HH_Use\Mo

Per_Capita_HH_Use\Mo = 44.8*(365/12)

Rate = 30

Satisfaction_Gap = Actual_CS-Customer_Satisfaction

Total_Comm_Connect_Use\Mo = Est_Indiv_Comm_Use\Mo*Commercial_Connections

Total_HH_Connect_Use\Mo =
(Indiv_HH_Use\Mo*HH_Connections)*Enact_Water_Restrictions

Total_Ind_Connect_Use\Mo = Industrial_Connections*Est_Indiv_Ind_Use\Mo

Total_NonResid__Use\Mo =
(Total_Comm_Connect_Use\Mo+Total_Ind_Connect_Use\Mo+Total_Publ_Connect_Use\Mo)*
Enact_Water_Restrictions

Total_Publ_Connect_Use\Mo = Est_Indiv_Publ_Use\Mo*Public_Connections

Pressures EXTERNAL

EPA_Max_Afford_Rate = 0.0099*(GTWA_MHI\Mo)

FAST_GROWTH = 0

Grant_Eligibility = SWITCH(Rate, EPA_Max_Afford_Rate)

GTWA_MHI\Mo = 36006/12

MODERATE_GROWTH = 1

Residential_Growth_Rate =
(0.0008*SLOW_GROWTH)+(0.00042*MODERATE_GROWTH)+(0.00075*FAST_GROWTH
)

SLOW_GROWTH = 0

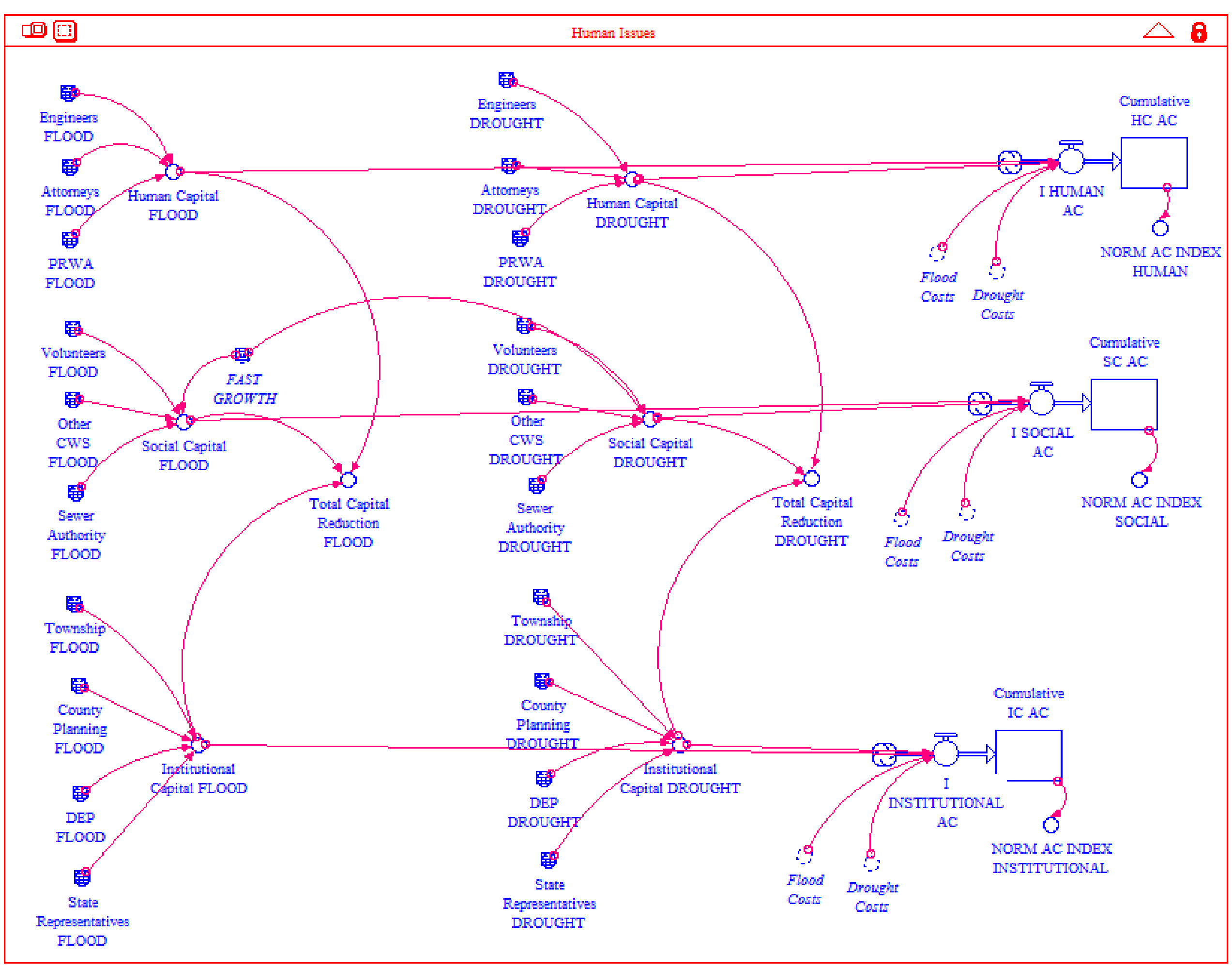

Figure C-6: Human Issues Sector. This sector calculates adaptive indices for human, social, and institutional capital. It also links to Scenario Variables Sector via Flood Costs and Drought Costs. The model subtracts the total value added from each actor's involvement from the overall flood and drought costs, which then link to the Financial Sector.

Human Issues

Cumulative_HC_AC(t) = Cumulative_HC_AC(t - dt) + (I_HUMAN_AC) * dt

INIT Cumulative_HC_AC = 0

INFLOWS:

I_HUMAN_AC = IF (Flood_Costs+Drought_Costs=0) THEN 0 ELSE ((Human_Capital_FLOOD+Human_Capital_DROUGHT)/(Flood_Costs+Drought_Costs))

Cumulative_IC_AC(t) = Cumulative_IC_AC(t - dt) + (I__INSTITUTIONAL_AC) * dt

INIT Cumulative_IC_AC = 0

INFLOWS:

I__INSTITUTIONAL_AC = IF (Flood_Costs+Drought_Costs=0) THEN 0 ELSE ((Institutional_Capital_FLOOD+Institutional_Capital_DROUGHT)/(Flood_Costs+Drought_Costs))

Cumulative_SC_AC(t) = Cumulative_SC_AC(t - dt) + (I_SOCIAL_AC) * dt

INIT Cumulative_SC_AC = 0

INFLOWS:

I_SOCIAL_AC = IF (Flood_Costs+Drought_Costs=0) THEN 0 ELSE ((Social_Capital_FLOOD+Social_Capital_DROUGHT)/(Flood_Costs+Drought_Costs))

Attorneys_DROUGHT = 0

Attorneys_FLOOD = 0

County_Planning_DROUGHT = 0

County_Planning_FLOOD = 0

DEP_DROUGHT = 0

DEP_FLOOD = 0

Engineers_DROUGHT = 0

Engineers_FLOOD = 0

Human_Capital_DROUGHT = Attorneys_DROUGHT+Engineers_DROUGHT+PRWA_DROUGHT

Human_Capital_FLOOD = Attorneys_FLOOD+Engineers_FLOOD+PRWA_FLOOD

Institutional_Capital_DROUGHT = County_Planning_DROUGHT+DEP_DROUGHT+State_Representatives_DROUGHT+Township_DROUGHT

Institutional_Capital_FLOOD = County_Planning_FLOOD+DEP_FLOOD+State_Representatives_FLOOD+Township_FLOOD

NORM_AC_INDEX_HUMAN = IF TIME=0 THEN 0 ELSE (Cumulative_HC_AC/TIME)

NORM_AC_INDEX_INSTITUTIONAL = IF TIME=0 THEN 0 ELSE (Cumulative_IC_AC/TIME)

NORM_AC_INDEX_SOCIAL = IF TIME=0 THEN 0 ELSE (Cumulative_SC_AC/TIME)

Other_CWS_DROUGHT = 0

Other_CWS_FLOOD = 0

PRWA_DROUGHT = 0

PRWA_FLOOD = 0

Sewer_Authority_DROUGHT = 0

Sewer_Authority_FLOOD = 0

Social_Capital_DROUGHT = IF FAST_GROWTH=1 THEN ((0.8*Volunteers_DROUGHT)+Other_CWS_DROUGHT+Sewer_Authority_DROUGHT) ELSE Volunteers_DROUGHT+Other_CWS_DROUGHT+Sewer_Authority_DROUGHT

Social_Capital_FLOOD = IF FAST_GROWTH=1 THEN ((0.8*Volunteers_FLOOD)+Other_CWS_FLOOD+Sewer_Authority_FLOOD) ELSE (Volunteers_FLOOD+Other_CWS_FLOOD+Sewer_Authority_FLOOD)

State_Representatives_DROUGHT = 0

State_Representatives_FLOOD = 0

Total_Capital_Reduction_DROUGHT = Human_Capital_DROUGHT+Institutional_Capital_DROUGHT+Social_Capital_DROUGHT

Total_Capital_Reduction_FLOOD = Human_Capital_FLOOD+Institutional_Capital_FLOOD+Social_Capital_FLOOD

Township_DROUGHT = 0

Township_FLOOD = 0

Volunteers_DROUGHT = 0

Volunteers_FLOOD = 0

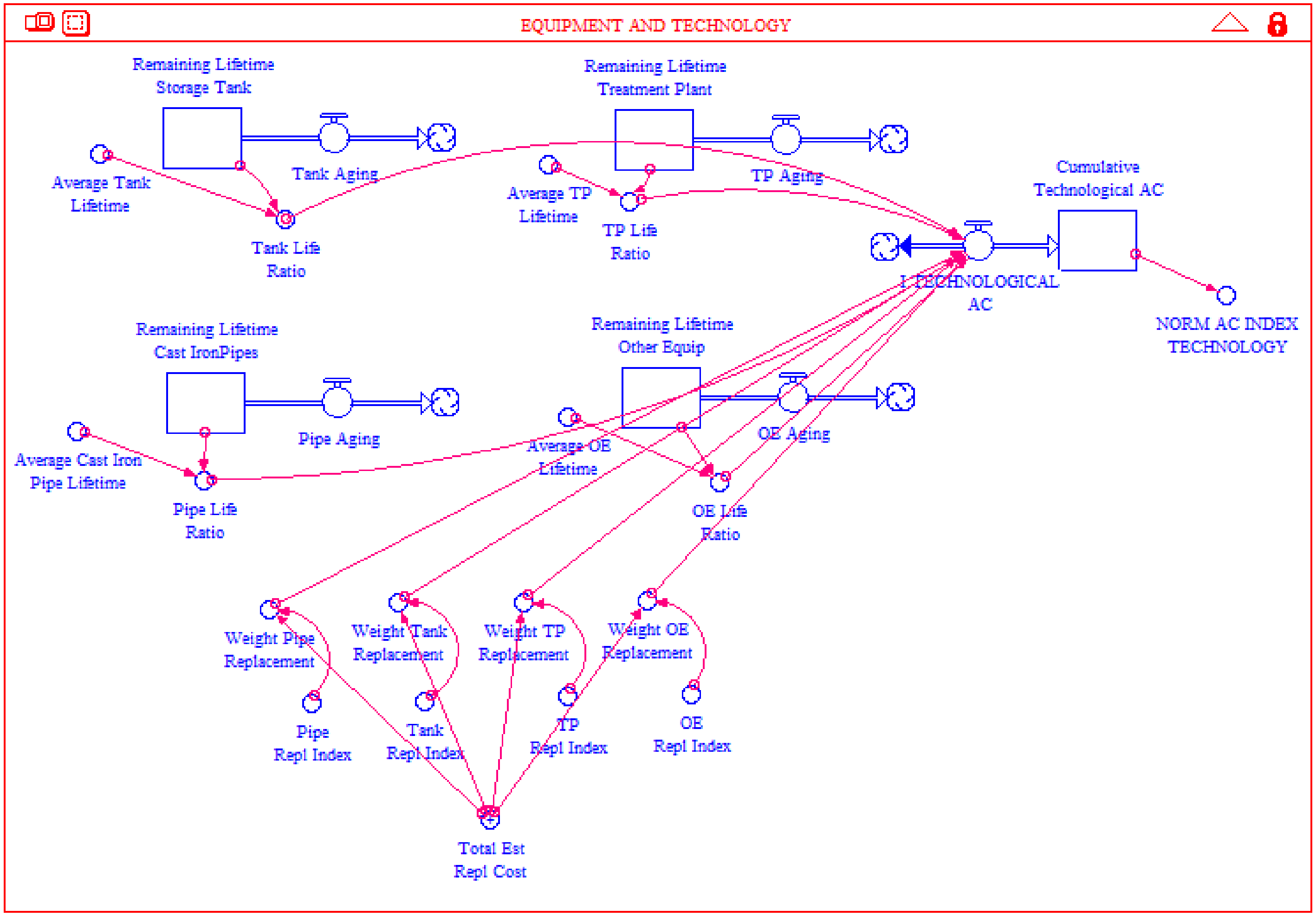

Figure C-7: Equipment and Technology Sector. This is the sole sector that is not connected to the other sectors, because the value of Total Estimated Replacement Costs is only used to calculate the technological adaptive capacity index.

EQUIPMENT AND TECHNOLOGY

Cumulative_Technological_AC(t) = Cumulative_Technological_AC(t - dt) + (I_TECHNOLOGICAL_AC) * dt

INIT Cumulative_Technological_AC = 0

INFLOWS:

I_TECHNOLOGICAL_AC = (((OE_Life_Ratio*Weight_OE_Replacement)+(Pipe_Life_Ratio*Weight_Pipe_Replacement)+(Tank_Life_Ratio*Weight_Tank_Replacement)+(TP_Life_Ratio*Weight_TP_Replacement))-0)/(Weight_OE_Replacement+Weight_Pipe_Replacement+Weight_Tank_Replacement+Weight_TP_Replacement)

Remaining_Lifetime_Cast_IronPipes(t) = Remaining_Lifetime_Cast_IronPipes(t - dt) + (-Pipe_Aging) * dt

INIT Remaining_Lifetime_Cast_IronPipes = Average_Cast_Iron_Pipe_Lifetime-480

OUTFLOWS:

Pipe_Aging = 1

Remaining_Lifetime_Other_Equip(t) = Remaining_Lifetime_Other_Equip(t - dt) + (- OE_Aging) * dt

INIT Remaining_Lifetime_Other_Equip = Average_OE_Lifetime-0

OUTFLOWS:

OE_Aging = 1

Remaining_Lifetime_Storage_Tank(t) = Remaining_Lifetime_Storage_Tank(t - dt) + (-Tank_Aging) * dt

INIT Remaining_Lifetime_Storage_Tank = Average_Tank_Lifetime-0

OUTFLOWS:

Tank_Aging = 1

Remaining_Lifetime_Treatment_Plant(t) = Remaining_Lifetime_Treatment_Plant(t - dt) + (-TP_Aging) * dt

INIT Remaining_Lifetime_Treatment_Plant = Average_TP_Lifetime-0

OUTFLOWS:

TP_Aging = 1

Average_Cast_Iron_Pipe_Lifetime = 1200

Average_OE_Lifetime = 120

Average_Tank_Lifetime = 300

Average_TP_Lifetime = 600

NORM_AC_INDEX_TECHNOLOGY = IF TIME=0 THEN 0 ELSE (Cumulative_Technological_AC/TIME)

OE_Life_Ratio = IF TIME=0 THEN 0 ELSE Remaining_Lifetime_Other_Equip/Average_OE_Lifetime

OE_Repl_Index = (15000/5)/1

Pipe_Life_Ratio = IF TIME=0 THEN 0 ELSE Remaining_Lifetime_Cast_IronPipes/Average_Cast_Iron_Pipe_Lifetime

Pipe_Repl_Index = (1500000/500)/1

Tank_Life_Ratio = IF TIME=0 THEN 0 ELSE (Remaining_Lifetime_Storage_Tank/Average_Tank_Lifetime)

Tank_Repl_Index = 500000/24

Total_Est_Repl_Cost = Pipe_Repl_Index + Tank_Repl_Index + TP_Repl_Index + OE_Repl_Index

TP_Life_Ratio = IF TIME=0 THEN 0 ELSE Remaining_Lifetime_Treatment_Plant/Average_TP_Lifetime

TP_Repl_Index = 1750000/24

Weight_OE_Replacement = OE_Repl_Index/Total_Est_Repl_Cost

Weight_Pipe_Replacement = Pipe_Repl_Index/Total_Est_Repl_Cost

Weight_Tank_Replacement = Tank_Repl_Index/Total_Est_Repl_Cost

Weight_TP_Replacement = TP_Repl_Index/Total_Est_Repl_Cost

Appendix D

Pre- and Post-meeting Surveys

This section includes all four surveys administered immediately before the first focus group and after each of the three formal focus groups. A survey was not administered at the informal meeting. Instead, participants completed the final survey after the final focus group at which the sample scenarios were presented. For this dissertation, the survey formats have been altered from their original versions to remove the extra space for short answer questions.

BUILDING SCENARIOS OF CWS ADAPTIVE CAPACITY: INITIAL SURVEY

In our series of three focus group meetings, we will model the ability of this community water system (CWS) to adapt to climate change. We will also use our focus group results to build scenarios of how that adaptive ability might change in the future. The purpose of this brief survey is to assess your initial opinions and expectations before we begin the scenario-building process. During this series of focus group meetings you will also fill out three other surveys. These post-meeting surveys are designed to see how your opinions and expectations change over time.

Please label each survey with your group member number. Then, circle the number that best represents your agreement with these statements using the following scale:

1 = Strongly disagree
2 = Disagree
3 = Neither disagree nor agree
4 = Agree
5 = Strongly agree

1.	This CWS should be concerned about climate change.	1	2	3	4	5
2.	It will be easy for this CWS to adapt to climate change.	1	2	3	4	5
3.	I understand the processes that affect this CWS's ability to adapt to climate change.	1	2	3	4	5
4.	We should develop new ways of planning for the future to consider the CWS's ability to adapt to climate change.	1	2	3	4	5
5.	I feel comfortable sharing my ideas with the group.	1	2	3	4	5
6.	I am open to new ideas suggested by other group members.	1	2	3	4	5
7.	Even if I don't agree with other group members, I learn from their input.	1	2	3	4	5

8.	Other group members share my view of the CWS's ability to adapt to climate change.	1	2	3	4	5
9.	I believe that these group meetings will be productive.	1	2	3	4	5
10.	I would be willing to work in a similar focus group to develop solutions to other problems involving the water system.	1	2	3	4	5

If you could change this CWS was managed in the past, what would you have done differently? (Briefly list any top ideas)

What do you expect to learn in these meetings?

What do you hope will happen in these meetings?

Please describe any concerns you have about what might happen in these meetings:

BUILDING SCENARIOS OF CWS ADAPTIVE CAPACITY: POST-MEETING #1 SURVEY

In our series of three focus group meetings, we are working together to model the ability of this community water system (CWS) to adapt to climate change. We are also using our focus group results to build scenarios of how that adaptive ability could change in the future. The purpose of this brief survey is to reflect upon what you learned during Meeting #1. It will also help us learn what your expectations are for the next meetings. Based on your input, we can adjust the following meetings to make them more valuable and productive!

Please label each survey with your group member number. Then, circle the number that best represents your agreement with these statements using the following scale:

1 = Strongly disagree
2 = Disagree
3 = Neither disagree nor agree
4 = Agree
5 = Strongly agree

1.	This CWS should be concerned about climate change.	1	2	3	4	5
2.	It will be easy for this CWS to adapt to climate change.	1	2	3	4	5
3.	I understand the processes that affect this CWS's ability to adapt to climate change.	1	2	3	4	5
4.	We should develop new ways of planning for the future to consider the CWS's ability to adapt to climate change.	1	2	3	4	5
5.	I feel comfortable sharing my ideas with the group.	1	2	3	4	5
6.	I am open to new ideas suggested by other group members.	1	2	3	4	5
7.	Even if I don't agree with other group members, I learn from their input.	1	2	3	4	5

8.	Other group members share my view of the CWS's ability to adapt to climate change.	1	2	3	4	5
9.	I believe that these group meetings will be productive.	1	2	3	4	5
10.	I would be willing to work in a similar focus group to develop solutions to other problems involving the water system.	1	2	3	4	5

Briefly describe one thing you learned today as a result of this group meeting.

Based on what you've learned today, what would you change about how this CWS was managed in the past? (Briefly list any top ideas)

What would you change about this group meeting?

What would you like the group to address in the next meeting?

BUILDING SCENARIOS OF CWS ADAPTIVE CAPACITY: POST-MEETING #2 SURVEY

In our series of three focus group meetings, we are working together to model the ability of this community water system (CWS) to adapt to climate change. We are also using our focus group results to build scenarios of how that adaptive ability could change in the future. The purpose of this brief survey is to reflect upon what you learned during Meeting #2. It will also help us learn what your expectations are for the final meeting. Based on your input, we can adjust the following meeting to make it more valuable and productive!

Please label each survey with your group member number. Then, circle the number that best represents your agreement with these statements using the following scale:

1 = Strongly disagree
2 = Disagree
3 = Neither disagree nor agree
4 = Agree
5 = Strongly agree

1.	This CWS should be concerned about climate change.	1	2	3	4	5
2.	It will be easy for this CWS to adapt to climate change.	1	2	3	4	5
3.	I understand the processes that affect this CWS's ability to adapt to climate change.	1	2	3	4	5
4.	We should develop new ways of planning for the future to consider the CWS's ability to adapt to climate change.	1	2	3	4	5
5.	I feel comfortable sharing my ideas with the group.	1	2	3	4	5
6.	I am open to new ideas suggested by other group members.	1	2	3	4	5
7.	Even if I don't agree with other group members, I learn from their input.	1	2	3	4	5

8.	Other group members share my view of the CWS's ability to adapt to climate change.	1	2	3	4	5
9.	I believe that these group meetings will be productive.	1	2	3	4	5
10.	I would be willing to work in a similar focus group to develop solutions to other problems involving the water system.	1	2	3	4	5

Briefly describe one thing you learned today as a result of this group meeting.

Based on what you've learned today, what would you change about how this CWS was managed in the past? (Briefly list any top ideas)

What would you change about this group meeting?

What would you like the group to address in the next meeting?

BUILDING SCENARIOS OF CWS ADAPTIVE CAPACITY: FINAL SURVEY

In our series of three focus group meetings, we modeled the ability of this community water system (CWS) to adapt to climate change. We also used our focus group results to build scenarios of how that adaptive ability could change in the future, which you evaluated during this interview. The purpose of this brief survey is to reflect upon what you learned during the scenario-building process. It will also help determine if this process is useful for analyzing CWS adaptive ability. We hope to take the process we've developed together and turn it into a useful tool for climate change planning.

Please label each survey with your group member number. Then, circle the number that best represents your agreement with these statements using the following scale:

1 = Strongly disagree
2 = Disagree
3 = Neither disagree nor agree
4 = Agree
5 = Strongly agree

1.	This CWS should be concerned about climate change.	1	2	3	4	5
2.	It will be easy for this CWS to adapt to climate change.	1	2	3	4	5
3.	I understand the processes that affect this CWS's ability to adapt to climate change.	1	2	3	4	5
4.	We should develop new ways of planning for the future to consider the CWS's ability to adapt to climate change.	1	2	3	4	5
5.	I feel comfortable sharing my ideas with the group.	1	2	3	4	5
6.	I am open to new ideas suggested by other group members.	1	2	3	4	5

7.	Even if I don't agree with other group members, I learn from their input.	1	2	3	4	5
8.	Other group members share my view of the CWS's ability to adapt to climate change.	1	2	3	4	5
9.	I believe that these group meetings were productive.	1	2	3	4	5
10.	I would be willing to work in a similar focus group to develop solutions to other problems involving the water system.	1	2	3	4	5

11. What is the most important thing you learned from participating in the group meetings?

12. Based on what you've learned in the focus groups and in this session, what would you change about how this CWS was managed in the past? (Briefly list any top ideas)

13. What would you improve about the scenario model-building process?

14. What would you improve about the focus group meetings? (Please answer only if you attended all three focus group meetings).

In this section, you will answer a few basic questions about your role in CWS management. These questions are for classification purposes only.

15. How many years have you worked with water systems in general? ____________________

16. How many years have you worked with your current CWS? ____________________

17. What is your job title or role in this CWS?

18. Do you receive financial compensation for your association with this water system? _____

19. What was the last weather-related event that affected your system? This could include droughts, floods, extreme cold, lightning strikes, etc.

20. When did the last weather-related event that affected your system occur?

21. What is the worst weather-related event that you remember affecting your system? This could include droughts, floods, extreme cold, lightning strikes, etc.

22. When did the worst weather-related event that affected your system occur?

23. What education do you have in water management?

24. What is your occupation?

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