Water Shortages and Water Management In Wise County, Virginia:

A System Dynamics Analysis

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Table of Contents

List of Tables

List of Figures

Abstract

Many communities in central Appalachia struggle with water availability. There are several factors that contribute to the issues surrounding potable water in the region. There is a high poverty level in the region, and many households are located in remote areas on rugged terrain. Groundwater contamination due to the geography and past mining activities also limit available options for some communities.

Developing a water supply infrastructure in an area with rugged terrain and across long distances can result in higher maintenance costs per foot of pipeline than in more urban areas. However, as citizens in Appalachia tend to have lower incomes and pay a higher percentage of their income towards utilities than in other parts of America, there is a need to keep water prices down. This creates a tension between maintenance costs and revenue – a tension that can lead to severe degradation of the water infrastructure over time.

This thesis utilizes system dynamics methodology to explore these issues in the community of Big Stone Gap (BSG) in southwest Virginia. While this community's water reservoir is large enough to comfortably meet the needs of the existing population, the past two decades have exhibited ongoing water shortage problems. While some have cited drought conditions as the cause of this problem, other contributing factors exist which can be mitigated through careful management practices.

This thesis describes a new decision support tool that examines the dynamics between water rate changes, population size, infrastructure expansion, and operational costs over a 50-year period. This tool was developed using System Dynamics methodology and allows policy makers and managers to explore the long-term impacts of various management strategies in order to provide a more robust water supply in the presence of the inherent economic, geological, and meteorological uncertainties in the region. The underlying model and management dashboard can be easily adapted for other communities.

Chapter 1: Introduction to the Problem

Introduction

Water is one of our most essential resources for life. While that would seem to be an obvious statement, most of us take for granted that turning on the tap will result in a clean, reliable stream of water to use for any purpose. However, for many parts of the world, and even within the United States, water is not always readily available. This thesis documents a system dynamics study of one community in Virginia that has struggled with water shortages for many years.

The community of Big Stone Gap is located in the Southwestern end of Virginia, nestled in the Cumberland Mountains. The population of Big Stone Gap is around 4856, according to the 2000 US Census. Most of the community's water needs are provided through the local town reservoir, Big Cherry Lake (or Big Cherry Reservoir). The lake is a man-made rain-capture reservoir, which, until recently, was contained by the most dangerous dam in Virginia (Dewberry, 2001). The community frequently experienced water shortages during dry periods (Ibid), so a plan to expand the water supply was developed in 1997 and will be completed in 2008. In addition to mitigating water shortages for Big Stone Gap, the expanded capacity will also provide service to nearby communities currently without public water supplies. Before this project, the Big Cherry Reservoir had a 410 million gallon capacity; a new dam was completed in 2005 that expanded the capacity to 600 million gallons.

However, the source of the past water shortages in the area is not simply a matter of insufficient capacity. In fact, the average per capita water consumption in this region is approximately 4200 gallons a month; this means that with wholesale business, which is

2.2 million gallons per month (mgm), the average monthly consumption is about 22.5 million gallons per month (Lane, 2007a). By simple division, this would mean that the original 410 million gallon reservoir would provide (when full) an eighteen month supply of water.

In addition, in spite of the 22.5 mgm demand, the water treatment plant has actually needed to process about 61 million gallons per month (Hampton, 2007). Using that value, the 410 million gallon capacity reservoir is just over a six month supply. This excess processing requirement of 38.5 mgm is caused by excessive leakage in the system, which is a result of the aging infrastructure and historically poor maintenance in the region. Hence, the water shortage at Big Stone Gap is at least partly due to apparent inefficiencies that are inherent to the management practices used for the water supply infrastructure.

The water treatment plant for Big Stone Gap is rated to process up to a 4.0 million gallons per day (mgd) capacity, and a recent safe yield study for the reservoir estimated a 3.2 mgd safe yield for the new reservoir (Dewberry, 1997). Safe yield is the amount of water that can be removed from the lake per day while still providing minimum flow-by requirements to maintain streams and wildlife in the watershed. Before the expansion, the existing reservoir safe yield was calculated at 2.2 mgd (Dewberry, 2001). The intake for the treatment plant is located approximately 3.7 miles downstream from the reservoir, and water flows via gravity into the intake structure (Ibid). The water treatment facility is located along the South Fork of the Powell River, and the intake consists of a pipe that captures water from the free-flowing stream which is then carried by gravity into the treatment plant.

In response to the recurring water shortages, Big Stone Gap has recently begun an extensive project to replace much of the older infrastructure, coupled with a water rate increase to help fund the project (Lane Engineering, 2007). In addition, the infrastructure has been significantly expanded to provide redundancy and expand service to neighboring communities in Lee County, Virginia. However, it is not clear that these actions will solve the historic water supply problems in the area unless the underlying dynamics that led to those shortages are fully elucidated and explored.

The purpose of the modeling effort described in this thesis is to provide a simulation tool for the community to explain those dynamics and to evaluate whether is the existing management policies and expansion plans will in fact assure a robust water supply infrastructure in the future. While these existing plans for expanding and managing the infrastructure are intended to relieve the water shortage, this thesis and associated model suggest that there are potential unintended consequences from these policies that could in fact further jeopardize the water supplies in all the affected communities.

Purpose of this Research – Decision Support for Developing a Robust Water Supply

One common issue that plagues infrastructure development in regions lacking basic services is a failure to plan for sustainability. That is, will the new infrastructure system provide the same level of quality and quantity of service over an extended lifetime as when it was originally put into place (Abrams, 2007)? This type of sustainability requires that, in addition to the building of the physical infrastructure (pipes, treatment plants, meters, etc), the institutional and financial arrangements to maintain this infrastructure must simultaneously be put into place (Ibid). Unfortunately for Big Stone

Gap, that has not been the case. The water infrastructure in the community has been expanded, but a lack of maintenance funding has lead to extensive leakage throughout the system, thereby raising operating costs, and jeopardizing the long-term viability of the water supply.

In this thesis, a decision-support tool is developed to help town managers and community leaders in Big Stone Gap determine which water management policies best fit the needs and economy of their community over a 50 year period. The reason for the extended time window of 50 years is to allow planners to explore long-term impacts of various water policies over several decades. It is these long-term impacts that are often ignored in policy considerations and that can come back to haunt policymakers (Sterman, 2000).

The public water supply in Big Stone Gap, Virginia, and its interconnections to other communities in the Southwestern Virginia region is the foundation or “case-study” for the development of this tool, which may also be adaptable to other small mountain communities with similar water issues. This tool, the Big Stone Gap Water Infrastructure Maintenance model (BSG-WIM) was developed using the methodology of system dynamics (Sterman, 2000).

The town has historically struggled with poor accountability (loss of water to leakage) within its existing water system, yet has recently expanded the infrastructure (quantity of pipes for service) around the community by approximately 50%. The decision support tool (DST) described in this thesis will help the town determine the most cost effective policies under which this infrastructure can be maintained. If these conditions are not consistent with the town's current water budget, the community leaders can use the tool to evaluate options for developing a robust water supply.

Potable Water: an ongoing concern in Appalachia

Southwestern Virginia, along with much of the rural Appalachian region in the United States, has struggled with rural poverty and its many consequences for several generations. One of the challenges facing any poverty-stricken area is how to develop the infrastructure in order to support economic growth. In a region with a high unemployment rate, and with much of the population living at or below the poverty level, the funds to expand and maintain such infrastructures are often not available. Without sufficient infrastructures, it is difficult for a community to attract businesses to encourage economic growth. This creates a vicious cycle that is difficult to overcome.

Of specific interest to this thesis is the development and management of a robust water supply in the Big Stone Gap region. Unfortunately, potable water supplies are increasingly more difficult for even the wealthiest communities to sustain. According to Sandia National Laboratories, demand for water is expected to double by 2035 in the US, and clean, viable sources are becoming a scarcity due to extensive pollution and other damage to watersheds across the country (Sandia, 2004). In southwestern Virginia, the past and present coal mining activity in the region has contaminated groundwater supplies in many areas (Appalachian Regional Commission, 2005). Besides man-made contamination, the karst terrain that composes much of the region leaves clean groundwater supplies prone to easy contamination from a heavy rain. That is, instead of new precipitation filtering slowly into groundwater, channels in the porous, heavily-tunneled limestone terrain transfer the water quickly, carrying microbes and other contaminants rapidly into the water supply (Shabman, 1996). This means the rocky terrain renders many households inaccessible to public water services and also limits the potential for using alternative water supply options such as wells. Hence, many households within this region frequently experience water shortages, or have water a supply that does not meet state water quality standards (Younos et. al., 1997).

Big Stone Gap, VA: A History of Water Shortage

The economy in the Big Stone Gap region was coal-based until the decline of the coal industry during the 40's, when the US coal supply shifted towards Western coal over Eastern bituminous coal. The majority of communities in the region began as "coal camps" – communities where the houses, stores, other facilities and infrastructure were owned by the coal company. The coal company often did not develop a central water supply (Shabman, 1996). Instead, water was provided through individual wells and cisterns, or even hauled in from other locations (like a nearby spring or river). According to John Randolph, keynote speaker at the Southwest Virginia Water Symposium in 1996, only 48% of residents in the region were connected to a public water supply in 1990 (Ibid). Wise County, Virginia, which is where the town of Big Stone Gap is located, provides 84% of its population with public water (Dewberry, 1997). However, neighboring Lee County, Virginia, offers public water service to less than half of its population (Lane Engineering, 2001). Several of the other reservoirs in the region, such as the water supplies in the town of Wise and the town of Appalachia, operate with a generous surplus of water (Shabman, 1996). On the basis of these surplus supplies and the desire for redundancy in the region, several projects to connect town reservoirs and extend service for Lee County have been completed (Lenowisco, 1997).

The Virginia Water Resources Research Center at Virginia Polytechnic Institute and State University has conducted several studies regarding options to provide reliable potable water supplies to the remote communities in Southwestern Virginia. Besides connections to public water supplies, which allow the most control for water quality, there are other acceptable options for some of the communities in the region. Specifically, rooftop rain-capture cisterns were found to be an adequate option allowing sufficient rooftop area and maintenance of the cistern (Younos, et. al., 1998). The Research Center also found that water from abandoned mine cavities in certain communities could provide a reliable, clean source of water with the appropriate treatment techniques (Younos, et. al., 1999). Water stores from mine cavities are used extensively in communities in West Virginia, and sixteen mine cavities were found suitable to provide water for underserved communities in Eastern Kentucky. Both of those areas have similar geography and geologic structure to Southwestern Virginia. There are a handful of communities in Southwestern Virginia that use mine-cavity water as well (Ibid).

Wise County is located in the Central Appalachian region, and is located in far Southwestern Virginia. The County is composed of six small towns and one small city. There are two rivers in the county that provide water for two of the communities there. There are six reservoirs that provide water for the remaining communities (Dewberry 1998). The region has often struggled with water shortages during times of drought, especially in communities that are not connected to a public water supply. The town of Big Stone Gap has historically had difficulty meeting demand during extended dry periods (Dewberry, 2001). Many communities in the surrounding areas have also struggled with shortages, in addition to poor quality or contamination due to lack of access to a public water supply. In addition to the shortages, the Big Cherry Reservoir dam, which is the sole public water supply for Big Stone Gap, was rated the most dangerous dam in Virginia. The dam did not meet “factor of safety” standards for maximum probable flood levels or other, more common loading conditions (Ibid).

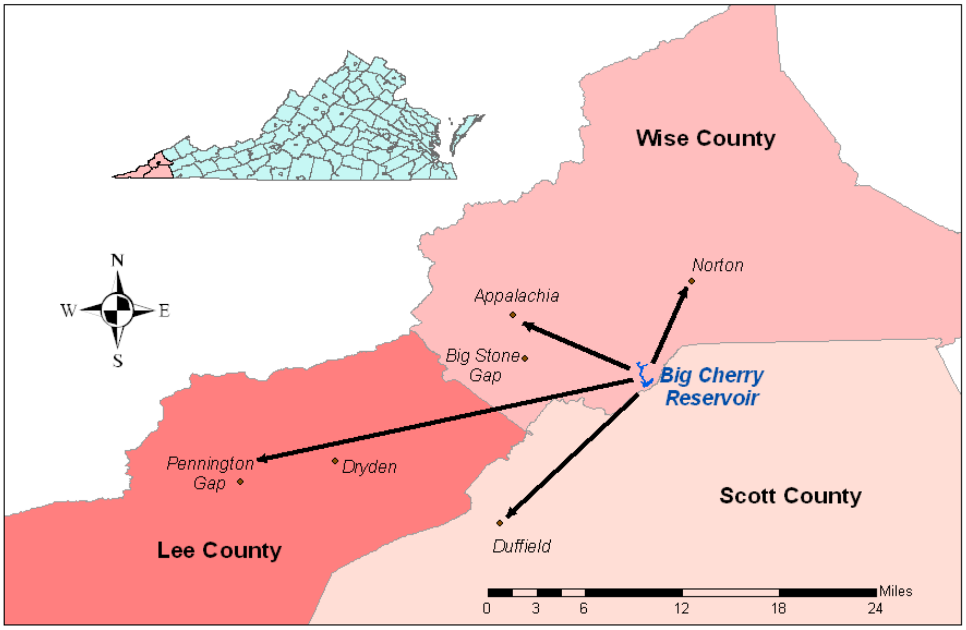
In order to address both the water shortages and the dam safety concerns in the region, a dam project was developed to expand the capacity of the reservoir by 200 million gallons. Engineering studies suggest that this expansion will add enough capacity to address Big Stone Gap’s shortages, as well as provide new service to many customers currently without a potable water supply (Dewberry, 1997).

Additionally, development of a *regional water system* is included in the project, whereby the Big Cherry Reservoir is connected to several other reservoirs in the region. This expands service to several underserved communities via interconnection of community reservoirs. Two of the counties adjacent to Wise County—Lee County, and Scott County, Virginia, have two communities near Big Stone Gap with inadequate private water supplies. These communities are Jasper (Scott County) and Dryden (Lee County)—see Figure 1. Karst conditions and previous mining activity frequently result in contamination of these private supplies. Moreover, these private sources are often insufficient during times of drought (Lane Engineering, 1999).

The Big Cherry reservoir now supplies water to these two communities through long connections to reservoirs in the nearest larger towns (Duffield and Pennington Gap, Virginia, respectively). Since these interconnections cross county lines, water is sold at wholesale rates by Big Stone Gap to the Lee County Water Authority (Lane, 2007a).

Maintenance responsibility is determined by geographic location; that is, Big Stone Gap maintains the pipe to their side of the county line, and Lee County maintains the pipe to their side of the border.

Figure 1: Map of Big Stone Gap's Reservoir and its interconnections to neighboring reservoirs.



Note: This map shows the region and communities involved in the regional water project. The lines connecting the reservoirs do not precisely follow the planned course, but give a sense of the length of the interconnections.

In addition to providing service to two communities that lacked an adequate water supply, these connections between the Big Cherry Reservoir and the reservoirs at Duffield and Pennington Gap are intended to provide redundancy in the case of water shortages or other emergencies among all the communities served by these reservoirs. A connection between Big Stone Gap's reservoir and the City of Norton's reservoir has also been developed, and a connection to another community, Appalachia, Virginia, is underway. The logic for developing these connections is that Big Stone Gap can sell water to the City of Norton, the Town of Appalachia, or to the Lee County Water

Authority in addition to current wholesale water usage during times of drought, or vice versa as needed (Dewberry, 1997).

The decision to interconnect the reservoirs in the region was based on a study called “The Virginia Coalfields Regional Water Study (VCRWS).” In the study, nine regional projects were identified that would provide service to customers without current access to potable water. These projects were ranked by cost per connection, feasibility, and degree of health hazard eliminated. New connections in the system were also given a “present worth” value that is based on expected maintenance and operational expenses (Thompson, 1998). Based on these criteria, the Big Stone Gap interconnect project was rated 5 out of 9 in the priority ranking system (Ibid). However, the “most dangerous” status of the existing Big Cherry dam made the project a higher priority. Other factors that were discussed in the study include project overlap, which addressed the fact that the choice for a water source for one project would impact the options for other projects in some cases.

While these connections are intended to relieve the water shortage in these communities, this thesis and associated model suggest that there are potential unintended consequences from these policies that could in fact *further jeopardize* the water supplies in all the affected communities. In order to understand this dynamic, we must consider the issue of water supply accountability.

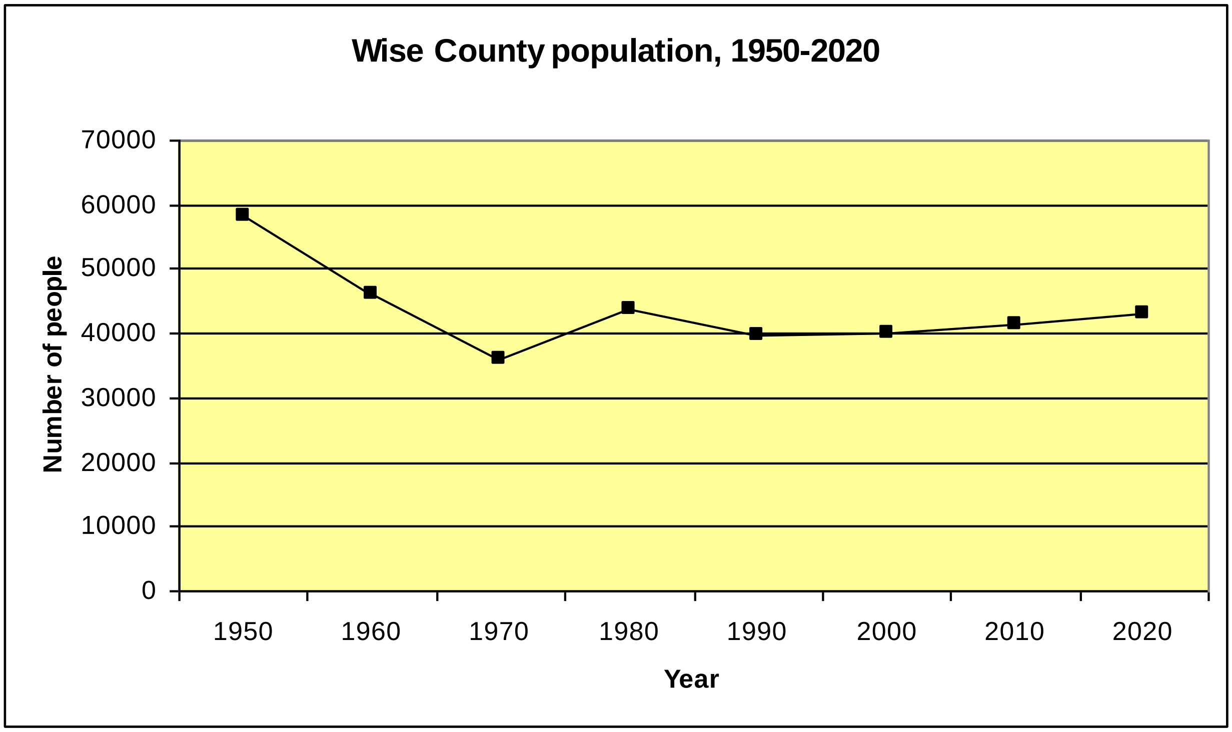
Accountability – The “Lurking Variable” in Managing Water Supply

Accountability is a measure of efficiency in a water system, and is calculated by dividing the quantity of water billed by the quantity of water processed in the water treatment plant. An efficient system should operate at between 85-90% accountability. Specifically, the VCRWS study states:

"…as each project enters a more serious study phase, the effects of water leakage must *be carefully considered. In many projects, it may be found less expensive to repair leaky systems than to construct additional treatment capacity"* (Thompson, 1998).

Accountability in a water supply can deteriorate over time due to neglect (poor maintenance). Since the 1950's, as the population in Wise County has dropped, less revenues have been available for maintaining the existing water infrastructure.

Figure 2: Wise County Population, 1950-2000, with projected growth through 2020 (Lenowisco, 1998).



Moreover, since the "War on Poverty" drive in 1964, many development projects were initiated in the region. These projects focused on ***expanding*** the existing infrastructure in order to supply water to underserved areas (Appalachian Regional Commission website, 2007). There was very little priority placed on developing funding sources to maintain older existing infrastructure, due to the pressing need associated with the high number of households in the region without basic access to a reliable water supply (Shabman, 1996). Unfortunately, as the infrastructure was expanded to provide water to more customers, the costs associated with maintaining that infrastructure necessarily increased…while at the same time the population was on the decrease. The loss of revenue from the population decline led to a significant shortfall in funds for maintaining the system. Hence, accountability deteriorated significantly.

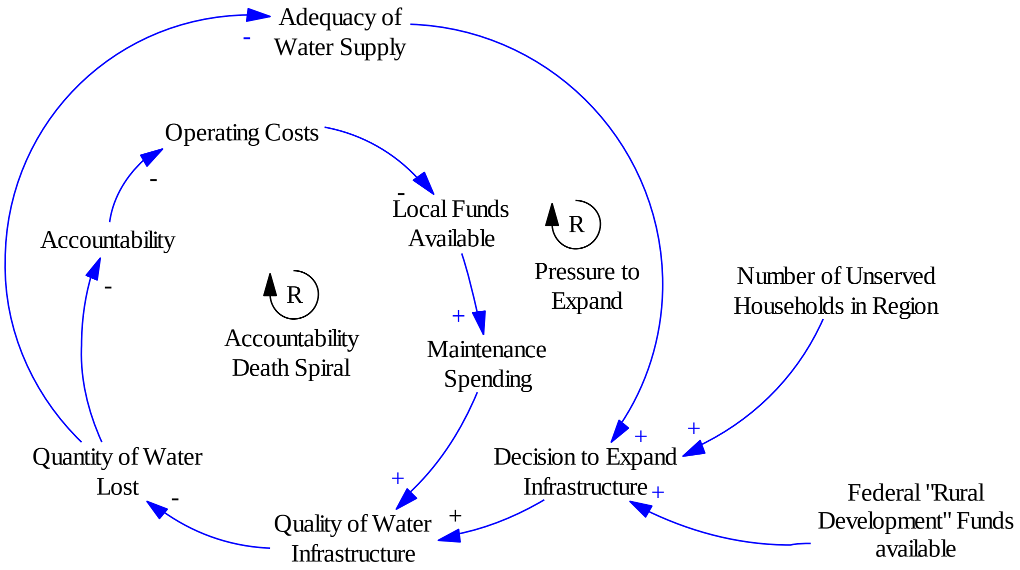
According to the "Wise County Water and Sewer Study," which was conducted in 1997 by Dewberry and Davis Engineering, the system accountability in Big Stone Gap was 47%, which was the lowest accountability in the region (Dewberry, 1998). This study recommended improvements in the system to raise accountability, in addition to interconnections to other systems for improved reliability and service to outlying areas of Lee County. More recently, data provided by the town indicates that Big Stone Gap is currently operating at around 35% accountability (Hampton, 2007).

The Vicious Cycle of Infrastructure Expansion and Accountability

While the aforementioned expansion projects attempted to address the dam safety issues and the need of residents in more remote areas to have access to clean water, they help to feed an important dynamic that could substantially mitigated or negate their intended benefits. This dynamic manifests itself as a vicious cycle of "expansion-decay-expansion" of the water infrastructure.

Here is how this cycle works. Policymakers recognized that many individuals in the region did not have access to potable water. Hence, through the "war on poverty," federal funds were provided to expand the water supply infrastructure and provide water to those individuals. Most of this expansion extends into remote, rugged terrain that in turn makes it more difficult to maintain. Unfortunately, the revenues generated from the additional customers who use that water supply are not sufficient to maintain the infrastructure. Hence, the pipelines deteriorate and, over time, more and more water is lost to leakage. That is, accountability decreases over time. This decay in accountability can take many years, and is therefore left undetected for some time. The resulting water loss creates water shortages for customers and limits the ability to supply water to new customers. This in turn creates pressure to increase the water supply. Historically, this increase has been implemented through more expansion projects (to add new customers in addition to improving capacity for existing customers). This creates an even more expansive system, which is even more expensive to maintain. This dynamic is illustrated in Figure 2. The "vicious cycle" describe here is a reinforcing loop that (in the absence of other forces) will inevitably lead to less and less water potable water for the region at greater and greater cost.

Figure 3: Causal Loop Diagram of Expand-Decay-Expand Cycle.



Some would argue that the repair and replacement of ***existing*** infrastructure will more effectively address long-term water needs than expanding the water supply and treatment capacity. Whether this is the case or not, or how long such a policy can be sustained can be difficult to ascertain. The model developed in this thesis is designed to aid decision-makers by more explicitly evaluating the balance between system expansion and system maintenance over a longer time period than might often be considered by policy makers. This will help town managers and engineers make better-informed decisions about where to best invest their water infrastructure dollar.

Past Work on Water Supply Models

The purpose of this thesis is to develop a simulation tool to allow the town's policymakers to evaluate the relative long-term merits of various policies for building and maintaining the water supply. The water shortages in the region are likely as much a function of infrastructure degradation as they are a function of drought conditions, even though drought conditions have often been cited as the primary cause of water shortages (Shabman, 1996).

Current engineering models for evaluating water expansion projects typically assume that sufficient maintenance revenues are available and that accountability degradation is not an important factor. However, in a poverty-stricken area such as Big Stone Gap, such assumptions cannot be made. The model developed for this thesis simulates the quantity of water available in the system each month based on precipitation, capacity of the Big Cherry Reservoir, consumption by people, and leakage from accountability deterioration. Lastly, this model incorporates the local water budget, which is directly affected by the rates charged for water and the cost of treatment, costs of maintenance and repair, and costs to pay off loans for capital projects. If the infrastructure degrades and accountability decreases, the cost of treatment increases as more water must be treated in order to supply the same demand. For example, if the accountability is 100% (i.e. no water is lost to leaks), then every gallon of water that is treated will be used by customers. However, if the accountability is 50% (a level that has been realized at Big Stone Gap), then, for every gallon of water consumed by a customer, two gallons must be treated. This effectively doubles the water treatment costs. These factors directly contribute to the water shortages in Big Stone Gap, and are not incorporated into any other existing water management models that this author has found.

While other system dynamics models for water management have been developed, the focus has been on fast-growing communities in arid regions where the quantity of available water is extremely limited, and where agricultural irrigation is the main source of demand (Sandia, 2005; Fernandez and Selma, 2004; Ford, 1996). For example, Andrew Ford (1996) developed a model of the Snake River in Idaho to examine the impact of over-appropriation of water rights, and the impact of more efficient agricultural irrigation methods. In 2004, Fernandez and Selma explored the effects of agricultural irrigation policies in southern Spain. Their work suggested that this policy drives a self-reinforcing dynamic that leads to increased salination of ground water, and a drop in water tables. This in turns makes irrigated land less productive, thereby requiring even more irrigation over more acreage to make up for the loss of productivity.

Sandia National Laboratories, in cooperation with various regional planning commissions, developed a system dynamics model of the Middle Rio Grande Basin in New Mexico (Passell, 2003). However, that water supply system is significantly different than the systems used in Central Appalachia. Most of the municipal water supply in the Basin is from groundwater pumping; the water supply in Wise County is primarily based on “rain capture” reservoirs or from the local rivers. Another important distinction of the Middle Rio Grande Basin study versus the current study was the significant amount of agricultural irrigation in the region from the Rio Grande (Passell, 2003); in contrast, there is little significant use of irrigation by farmers in Wise County, Virginia. Many farmers use independently-owned wells instead of the municipal water supply in Wise County. Lastly, one of the major water supply issues for the Middle Rio Grande Basin is the competition between several communities for usage of the same water supply. While the cross-jurisdictional nature of the interconnection in Southwestern Virginia could lead to competition between communities, this has not historically been a problem in the region and hence competition dynamics are beyond the scope of this thesis.

None of the aforementioned models directly addresses accountability. Furthermore, as a group, they all focus primarily on agricultural water use (Ibid). However, in Appalachia, water shortages arise primarily because of the inaccessibility of communities and from contamination of available sources. That is, adequate volumes of water exist in the region; it is simply difficult to efficiently distribute clean water across great distances and rugged terrain.

In addition to system dynamics models, simple spreadsheet models are commonly used to simulate water quantities over time. Unfortunately, simplifying assumptions of these models often render these simulations inadequate for long-term planning purposes. For example, an Excel® model was developed by Dewberry and Davis, an outside engineering firm, for the community of Big Stone Gap to simulate the refilling of the reservoir by precipitation and the consumption of water by the community. No boundaries were set for the capacity of the reservoir, so the values for the "quantity of water in the reservoir" frequently exceeded the capacity of the lake—sometimes by as much as 400 million gallons (Dewberry, 2001). The model developed here incorporates the capacity of the lake for more realistic values.

Using System Dynamics to Develop a Decision Support Tool

System dynamics is a systems-level modeling methodology. It was developed in the 1950's at the Massachusetts Institute of Technology as a tool for business managers to analyze complex issues involving the inventories and flows of goods and services (Sterman, 2000). System dynamics methodology operates on the premise that system behavior is governed by the structure of the system and the interaction of the system elements through feedback loops (Sterman, 2000). In the system dynamics approach, a problem is decomposed into a temporally dynamic, spatially aggregated system (Passell, 2003). The scale of the model can range from the molecular level to global populations. Systems are represented as combinations of *stocks* and *flows*. In our example, the quantity of water in the Big Cherry Reservoir is a stock, while the flows consist of water that flows into the reservoir from precipitation and drainage across the watershed, and from water that flows out through consumption by the population, evaporation, flow-by, and leaks in the infrastructure. The volume stored in the reservoir at any time t is the integral of the difference between the inflows less the outflows. The evolution of the reservoir volume over time is determined by a complex system of interconnections, feedbacks and delays. These complex dynamic relationships make it difficult to predict the behavior of the system, thereby inviting policies that can often be counterproductive (Ibid, 2003).

System Dynamics modeling is an iterative process that is comprised of five steps (Sterman, 2000). The first step is *problem definition*: what is the dynamic behavior of interest, and why is it important to understand? This is the most important step in a successful modeling venture, as the boundaries and variables within the model are defined here. In our case, the changes in (1) the quantity of water in the Big Stone Gap community over time, (2) the accumulated operating and investment costs associated with the system, and (3) the adequacy of the system relative to demand are the primary variables of interest. There are other system state variables that are of ancillary interest, i.e. size of the population in the area, size of the water supply infrastructure, funding expenditures for repair and expansion of the infrastructure, and policies affecting those expenditures.

The second step in the modeling process is to develop a *dynamic hypothesis*, which is the modeler's explanation for the system's behavior. This hypothesis seeks to explain the (problematic) behavior of the system in terms of the interrelationships among the main "actors" in the system, along with the feedbacks and delays in those relationships. The dynamic hypothesis is <u>endogenous</u> in focus, seeking to explain the system behavior in terms of the interrelationships among system elements, as opposed to viewing system behavior as being the product of primarily external factors. This endogenous focus contrasts with hypotheses that try to explain the behavior of the system in terms of exogenous variables outside the system. Such explanations often arise simply because we've drawn too narrow of a boundary around all those factors that affect the behavior of the system. That is, we've defined the "system" too narrowly, so that its behavior over time is caused by factors outside that boundary. System dynamics seeks to draw the model boundary wide enough to include all critical factors that interact to give rise to the behavior in question (including some variables that are hard to measure, like public sentiment, for example).

For example, some have argued that the chronic water shortage at Big Stone Gap has occurred because of extended drought conditions in the area (Thompson, 1998). Others have argued that poor management practices by planners are at the root of the problem (Shabman, 1996). Still others suggest that the high poverty levels in the community have so weakened the tax base that there are insufficient funds to maintain a reliable supply of water (Ibid). In reality, these (and other factors) all interact in complex ways that in turn influence managers and policy makers who then implement policies that further affect the behavior of the system. The problem is that these complex relationships may not be adequately understood, giving rise to policies that are ineffective or even harmful. The dynamic hypothesis seeks to elucidate those interactions and feedback relationships.

The water supply problems described here are not exclusive to Big Stone Gap. Many communities in the United States and all over the world struggle with deteriorating infrastructure and water shortages. Such communities are often unable to provide adequate water service to everyone within the community. This thesis is aimed at evaluating which management and investment strategies are best. That is, how much money should be spent in repairing or replacing existing infrastructure versus expanding or replacing the existing system? Which is the best strategy for a community to develop a robust water supply? In the case of Big Stone Gap, the question is whether the expanded Big Cherry Reservoir and interconnects with other reservoirs will provide the community with a reliable water supply, or if there are still present within the system the seeds of a continuing recurrence of water shortage problems that may take years or decades to manifest themselves.

Chapter 2: Overview of the Model

Intended use for the Model

The purpose of this modeling effort is to model the dynamic behavior of the BSG water supply and to simulate how that behavior is affected by management policies for capital improvements, expansion, and maintenance. The model necessarily incorporates some simplifying assumptions (as in any useful model, see Sterman, 2001). These simplifying assumptions are addressed in the more detailed sector descriptions to follow.

The model is designed to serve as a *flight simulator* or *management dashboard* for the engineers and planners who manage Big Stone Gap's water supply. While the model was developed in a proprietary software package, a free "reader" software package is available to allow the town or other users to access the model. The user can evaluate maintenance and replacement policies for the water system to determine how to cost-effectively maintain a sustainable water supply for the region; a user interface allows manipulation of these variables to evaluate policies. For example, as the system ages and becomes more expensive to maintain, it may be more economic over the long term to replace the infrastructure than to continue repairs on an outdated, hard to maintain system. On the other hand, the town may be able to supply more water at less cost through repairs, rather than expansion projects. The model will ultimately allow planners to explore various management scenarios and observe their economic and sustainability impacts over several decades, thereby providing insights that are not available from current models.

Introduction to Stocks and Flows

All system dynamics models employ a stock and flow structure to represent the important elements of a system. A stock represents an accumulation of a variable over time, such as the number of gallons of water in a reservoir. The value of the stock at any given point in time is determined by the inflows and outflows (positive and negative rates of change) and the previous value of the stock (Sterman, 2000). Mathematically, the content of a stock at any time t is described by the following equation:

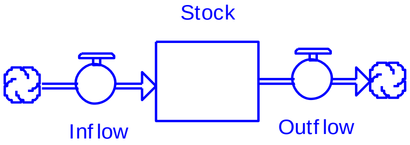
$$\text{stock}(t) = \int_0^t [(\text{inflows} - \text{outflows})]ds + \text{stock}(t_0)$$

The flows describe the rate of change in the stock. Hence, and the net rate of change of a stock at time t is described by the difference between the inflows and outflows at time t, i.e.

$$\frac{d\left[stock(t)\right]}{dt} = \sum\left[inflows(t)\right] - \sum\left[outflows(t)\right]$$

In the modeling software used for this thesis (STELLA©, v 9.0), the stocks and flows are schematically represented as follows:

Figure 4: Example of stock-and-flow structure in STELLA©.



By definition, it follows that a change in the rates represented by any of the inflows or outflows will have a corresponding change in the value of the stock. For example, consider the flow of water from a faucet into a tub of water that is also draining at the same rate (a state known as “dynamic equilibrium”). If these rates remain unchanged, the volume of water in the tub will remain the same. A change in the rate of water flowing from the faucet, or out of the drain will change the volume of water in the tub. That is, if the rate of inflow decreases, the stock begin to lose “volume” over time and will be smaller than it would have been; if the inflow increases, the “volume” of the stock will begin to increase and will be larger than it would have been. The same is true for a change in the rate of an outflow. If water flows out of the drain at a higher rate than before, the volume of water in the tub decreases, and so forth.

Overview of Model structure: Three Sectors

In order to simplify the model development and testing, the Big Stone Gap water supply model was subdivided into “sectors.” This also allows easier conceptualization of the “subsystems” that constitute the overall system. These sectors are:

- The ***water sector***, which models the water volume stored in the lake. Hence, this sector’s stock and flow backbone consists of the lake and its inflows and outflows. Essentially, the lake is refilled with runoff from precipitation, and water is taken out to feed streams for wildlife (flow-by) and to supply water to customers.

- The ***infrastructure sector***, which represents the pipes used to distribute the water supply to treatment plants and ultimately customers. The main purpose of this sector is to model the “health” and size of the water infrastructure. This sector also models the deterioration of the system over time (i.e. through decreasing accountability). This deterioration is based on historical trends, and can be impacted only be impacted based on funding strategies that are modeled in the

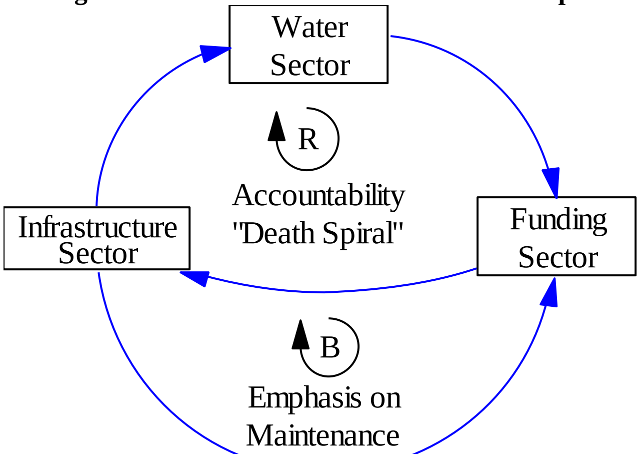
funding sector (below). The management and maintenance of the infrastructure determines the accountability of the system over time, which ultimately drives how much water is taken out of the lake each month and, correspondingly, how much it costs to treat the water used by customers (and lost to leaks in the system).

- The ***funding sector***, which models the overall monthly budget for the town, includes the inflow of funds from the sale of water or and the outflow of funds to support maintenance, operating costs, and repayment of debts from expansion or replacement of the existing water infrastructure.

Figure 5, shown below, illustrates these sectors and highlights some of the interrelationships. Figure 5 illustrates an important reinforcing feedback loop that is critical in affecting the behavior of this system over time and that is easily neglected by managers, as its impact may take years to be appreciably felt. This feedback dynamic works like this. As the infrastructure ages, system accountability decreases, causing operating costs increase (because more water must be processed to satisfy the same demand from customers); this in turn reduces the funds available for maintenance. This self-reinforcing dynamic (which is called the "***accountability death spiral***" throughout this thesis) can lead to a downward spiral in accountability, driving operating costs higher, and further accelerating the loss of accountability. This reinforcing feedback loop is explicitly shown in Figure 5 by the causal connector arrows beginning at the ***funding sector*** (where revenues are generated from water sales and where maintenance expenditure levels are determined), running then to the ***infrastructure sector*** (where maintenance decisions and the age of the infrastructure determines the accountability levels), and finally back to the ***funding sector*** (where the accountability levels impact operating costs, thereby affecting the funds available for maintenance activities).

The ***accountability death spiral*** dynamic can be overcome via management policies over the life of the system. In the model developed in this thesis, the user is allowed to impact the "health" of the infrastructure through policy decisions on water rates, investment, and maintenance expenditures (all within the bounds of available funds). By impacting the health of the infrastructure, those policies in turn affect the availability of water for customers and determine the long-term viability of the system. .

Figure 5: Model sectors and their relationships.



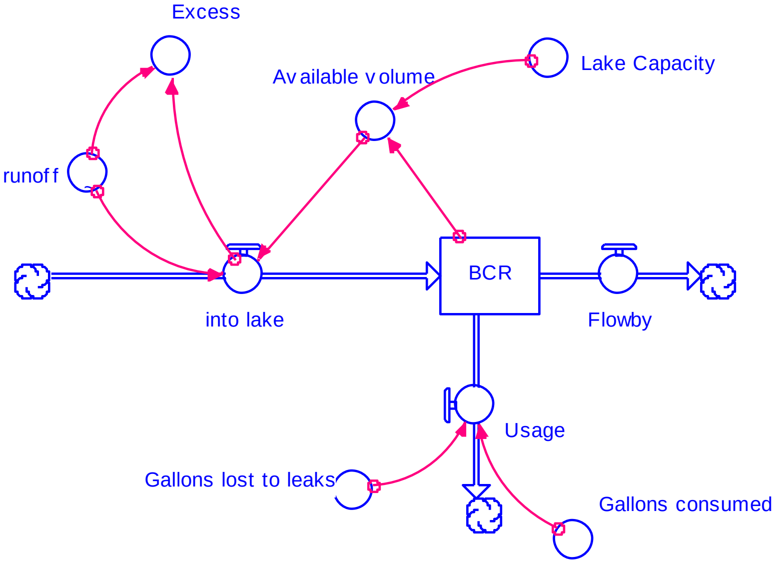
Overview of the Water Supply sector:

A simplified version of the stock and flow structure in this sector is given in Figure 7. Note that the only stock in this sector is the ***BCR*** stock, which is the quantity of water in the Big Cherry Reservoir, expressed in gallons. The volume of water in the BCR stock at any given time changes in response to the values of one inflow (***into lake***) and two outflows (***flowby*** and ***usage***).

Hence, the volume of water in the BCR stock at any time t is calculated as:

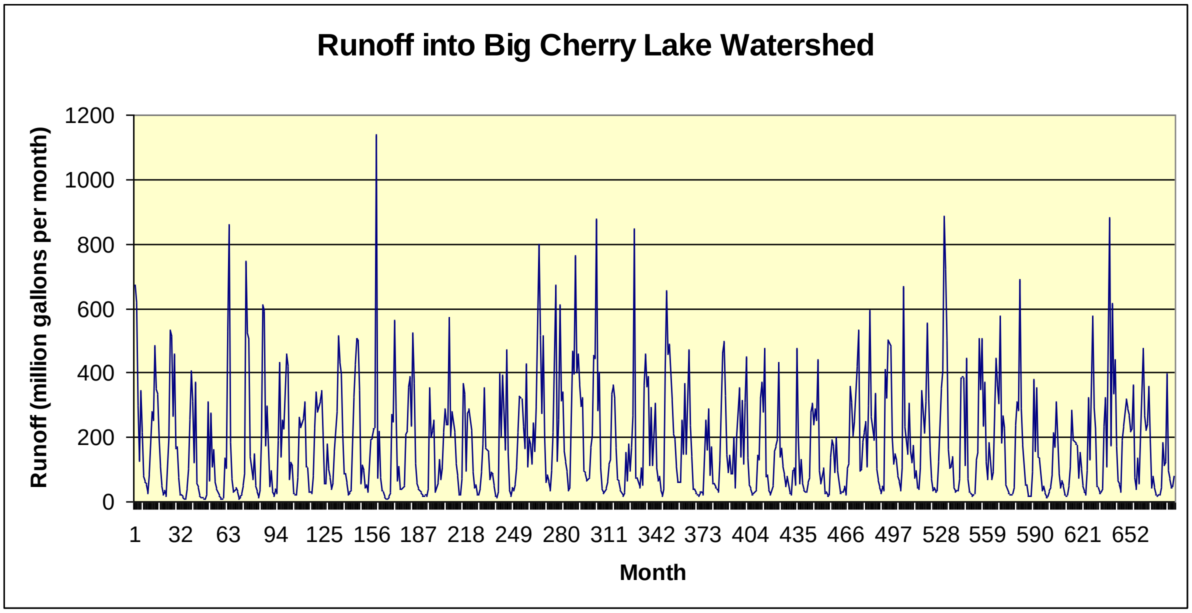
$$BCR(t) = BCR(0) + \int_0^t \left[into\ lake(s) - (usage(s) + flowby(s)) \right] ds$$

Figure 6: Water sector of Big Stone Gap model.



Because one unit of simulated time in the model represents one month of real time, the flows are expressed in gallons of water per month. Here we make the simplifying assumption that all the months are 30 days in length. The ***into lake*** flow represents water that enters the lake from ***runoff*** in the surrounding watershed. This quantity is determined by the net amount of monthly precipitation in the watershed after subtracting the amount absorbed by plants or migrating into underground aquifers. The amount of ***runoff*** for the period from 1950-2005 was determined by historical records and was calculated using the method described in the Dewberry and Davis "New Big Cherry Dam Technical Memoranda." While the purpose of their model was to calculate the safe yield of the reservoir, the concept of using the size of the watershed and the monthly precipitation to calculate the runoff into the lake is applicable to this simulation (safe yield is the maximum demand the reservoir can safely supply). A graph of the historical calculated runoff for each month from 1950 to 2006 is shown in Figure 6. A table of the calculated gallons per month is listed in Appendix A. These values were used as exogenous inputs specifying the value of the runoff inflow during the historical period from 1950 to 2006. For simulations beyond 2006, the runoff values are assumed to follow a similar pattern as the previous fifty years. Annual precipitation patterns are fairly consistent in the region, and as there is no data for future precipitation, assuming a similar pattern with the new infrastructure size is a reasonable assumption to examine the effects of different infrastructure maintenance policies.

Figure 7: Runoff into Big Cherry Lake watershed, 1950-2006.



Historic runoff values in Big Stone Gap are calculated from data collected from a stream gauge operated by the United States Geologic Service in the Powell River in nearby Jonesville, Virginia. The Powell River flows near Big Cherry Lake, and the geology of the watershed for the river is similar enough to be applied to the lake watershed. That is, the change in the water level of the stream, which is based on precipitation and the absorption of the water level, is assumed to be same for the Lake as for the River. The change in stream-flow is given in inches, and the size of the watershed for the stream is known. This means that the runoff per acre for the river can be calculated and then applied to the lake (Dewberry, 2001). Big Cherry Lake's watershed is approximately 3500 acres. Multiplying the gallons per acre found by the previous calculation by the size of the Big Cherry Lake watershed will give the approximate monthly runoff into the lake (Ibid). Once the runoff is known for a given month, a volume equal to the remaining capacity in the BCR stock will flow into the reservoir. The rest flows over the dam as ***excess*** and is not stored for later use.

The ***usage*** outflow represents the rate at which water is consumed by the local population, plus water that is lost due to lack of accountability. The ***flowby*** outflow represents the minimal monthly flow out of the dam required to sustain life downstream of the reservoir. The numeric values that were used for these variables (and the sources of those values) are given in table 1.

Table 1: Numeric Values for Selected variables in the Water Sector Stock and Flow Diagram in Figure 7.

Variable	Units	Numeric value	Source
BCR stock	Millions of gallons	Initial value = 410	Dewberry, 2001
into lake	Millions of gallons per 30-day month	Minimum of ***Runoff*** and ***Available volume***	Dewberry, 2001
Flow-by	Millions of gallons per 30-day month	15	Dewberry, 2001
Runoff	Millions of gallons per 30-day month	Determined from historical precipitation data	Mass balance[1]
Usage	Millions of gallons per 30-day month	Determined by population consumption and losses to poor accountability	Mass balance[1]
Excess	Millions of gallons per 30-day month	***Into lake*** – ***excess*** runoff	Mass balance[1]

[1] *When "Mass Balance" is cited as the source, this means that indicated quantity is calculated under the assumption that all the water in the system must be accounted for.*

The resulting calculations are typically straightforward algebraic expressions. The details are available in the appendix.

Note that in Table 1 inflow “into lake” is calculated by the taking the minimum function of the remaining ***BCR*** capacity and net runoff. This limits the inflow so that the reservoir never exceeds its capacity. The ***usage*** outflow is the sum of all of the water processed in the water treatment plant associated with the reservoir. This includes the water consumed by the town’s customers, and the water lost to leaks. The ***gallons consumed*** variable is calculated by multiplying the per capita monthly demand (4200 gallons per month) and the population, which is made up of 4100 customers in town (although the population varies over time, based on historic values), and 250 businesses that consume approximately 25,000 per month (Lane Engineering, 2006). Leakage is calculated by first calculating the “gallons leaked per gallon consumed;” this is simply the leakage fraction (1-accountability) divided by the accountability. This value, “gallons leaked per gallon consumed” is then multiplied by the “gallons consumed” to get the total amount of water lost to leaks each month (see Figure 5).

There are other factors that affect the water level in any reservoir that were excluded from this model. First, evaporation would also remove water from the supply. Additionally, the physical shape of the lake basin would also determine the amount of evaporation and the available volume for rain capture. Assuming the same total volume of water, evaporation is a function of the surface area; a deeper lake would have less surface area, or a shallow lake would have more, and therefore more evaporation. The humidity of the air would also dictate how much water was lost to evaporation, as drier conditions would increase the evaporative cycle as well. These factors would add a great deal of complexity to the model, but the quantities are not significant enough to greatly influence the simulated quantity of water in the supply (Dewberry, 1997). Upon examining the evaporation estimates from the Big Cherry Dam study, average loss to evaporation per month is roughly a two-day supply; the difference between whether the town is experiencing a severe water shortage or not would not be determined by a few million gallons loss over a one-month period.

Overview of the Funding Sector

The next sector of the model is the "funding" sector (see Figure 8). This sector is composed of two stocks, "Funds" and "Debt." The funds in the water system are determined by inflow of funds from the sale of water to customers on the Big Stone Gap system, and by outflows of funds for maintenance, operation expenses, and water-related debt repayment. An important variable in this sector that can be directly manipulated by managers is the amount charged for the sale of water (the ***consumer water rate*** and ***wholesale water rate***). The ***consumer water rate*** is the amount charged per gallon to town customers, while the ***wholesale water rate*** is the amount charged per gallon to wholesale customers. The sale of water to these two types of buyers is the only inflow the funds stock in this sector. There are other fixed costs, such as short-term asset replacement, and reserve requirements (for emergency needs and also to meet standards for loans) that are incorporated into the "saving" outflow. Overall, operating costs are fixed, with the exception of processing and distribution costs, which are dictated by water usage. Administrative and staffing costs are based on annual salaries and do not vary within the model; those variables are set to fixed values based on town budget information (Lane, 2007b). Debt repayment is simply a function of the terms of the loans used to underwrite capital projects. This rate is assumed to be fixed until the loan is paid in full (and the "Total Debt" stock is empty). That is, the loan payment each month is a fixed quantity that is amortized over the life of the loan using a fixed interest rate. As payments are made, the debt stock and funds stock will both decrease until loan is paid in full. Table 2 lists the values used in the model and their sources.

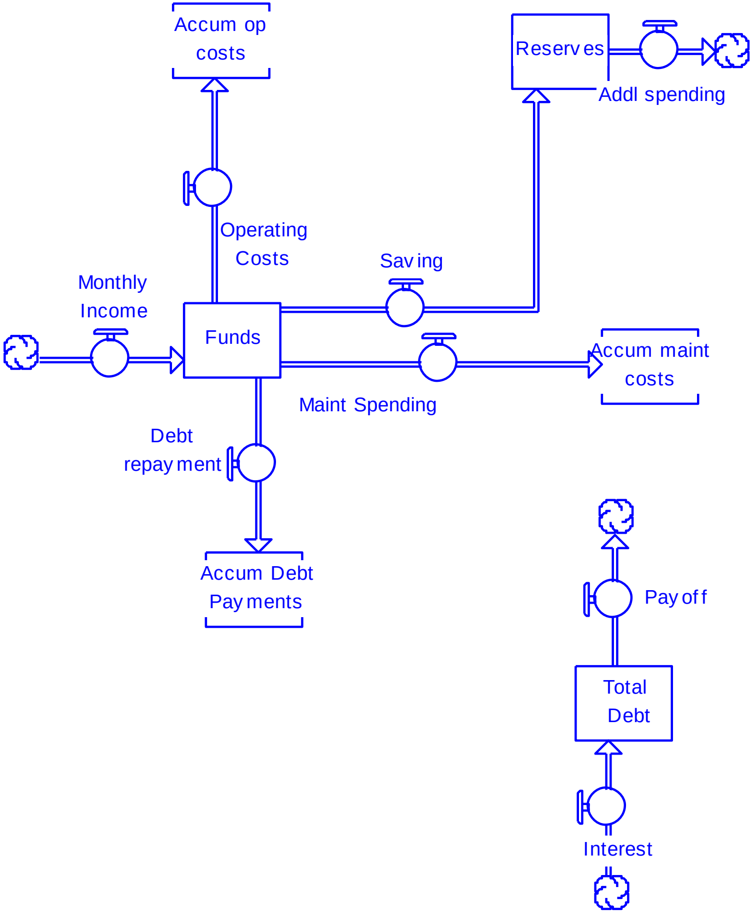
Table 2: Numeric values for selected variables in Figure 8.

Variable	Value	Source
Consumer Water Rate	$0.005, $0.007/gallon	Lane, 2007b
Wholesale Water Rate	$0.0035/gallon	Lane, 2007b
Initial Loan Amount	$30,000,000	estimated from projects
Interest rate	0.05	Lane, 2007b
Dist cost per gallon	$0.008/gallon	Lane, 2007c
Proc cost per gallon	$0.009/gallon	Lane, 2007c
Admin costs	$6250/month	Lane, 2007c

Note: Loan amount is estimated from the cost of recent projects and the size of the existing infrastructure.

There are several simplifying assumptions implicit to the logic of this sector of the model. First, all of the rates are in today's dollars, and do not incorporate any changes in the time value of money. That is, the funding sector uses undiscounted values in today's nominal dollars, assumes that costs are constant throughout the 50-year period, and that the underlying cost structure of the water system for operation and maintenance does not change. Additionally, water consumption is assumed to remain constant even with a rate increase; in fact, customers may conserve water, which would affect a cost increase policy's effectiveness in generating revenue. Lastly, while the town is assumed to carry a baseline amount of debt, borrowed funds cannot be used toward maintenance or operating costs in the model; they are assumed to be utilized in a fashion that does not have an effect on accountability.

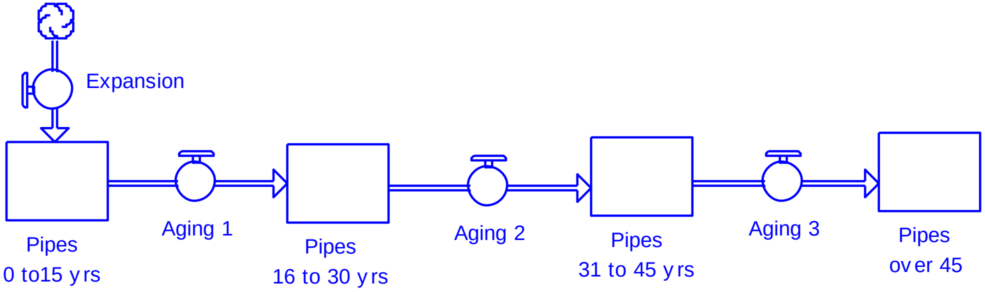
Figure 8: Funding sector of BSG-WIM model.



Overview of the Infrastructure Sector

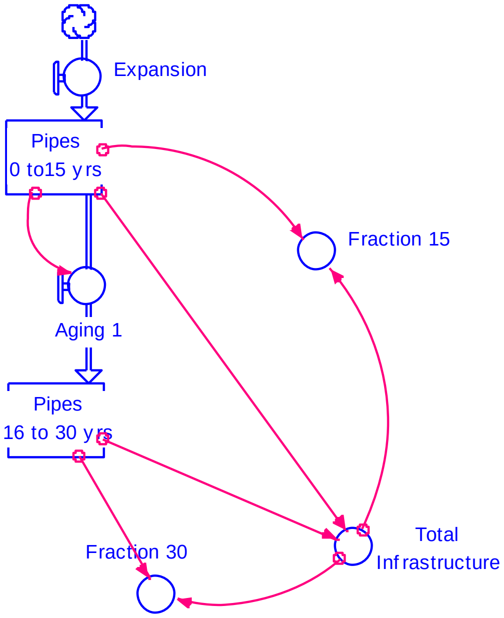
The largest and most complex part of the model is the infrastructure sector (see Figure 11). The town's infrastructure is broken down into 15-year "cohorts" or blocks. There are four cohorts—new infrastructure aged 0-15 years, called ***Pipes 0-15 years***; infrastructure less than 30 years old, named ***Pipes 16-30 years***; older infrastructure, called ***Pipes 31-45 years***; and the oldest infrastructure, which is ***Pipes over 45 years*** old.

Figure 9: Infrastructure cohorts.



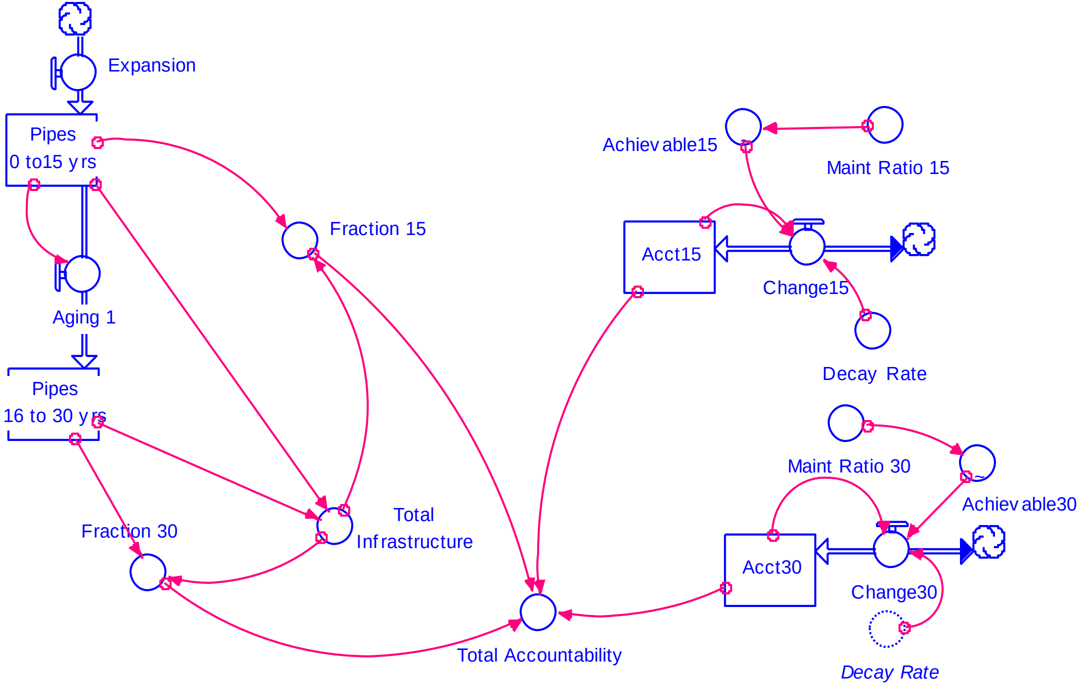
The aging of the infrastructure is simulated in the model as infrastructure in the earlier cohorts migrates via the ***Aging*** flows into the older cohorts. The rates of these ***Aging*** flows are calculated by simply dividing the size of the cohort from which the flow exits by the ***aging rate*** (180 months or 15 years). As the infrastructure ages, it becomes more expensive to maintain, the accountability deteriorates, and it is more difficult to maintain acceptable accountability levels. In addition, each cohort has an associated expected maintenance cost rate and an associated accountability that together determine the accountability and cost of the entire system.

Figure 10: Example of Total Infrastructure and Infrastructure Fractions for Two Cohorts



All of the cohorts are summed to give the total infrastructure size (expressed as feet of pipe). At each time step, the quantity of pipe in the cohort is divided by the total size to estimate what proportion of the infrastructure at that time is in that cohort, described as ***Fraction 15***, ***Fraction 30***, etc. Each fraction is then factored in with the accountability for that cohort to calculate the total accountability of the system. The next figure illustrates how accountability is calculated for the entire system.

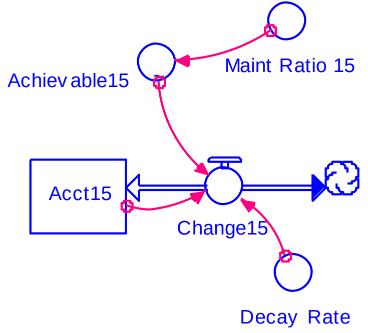
Figure 11: Example of Total Accountability from Infrastructure Sector, using Two Cohorts



The accountability for each cohort is based on maintenance. There is a ***required maintenance cost*** (which will be explained in a moment) for each cohort; the ratio of actual spending to the required amount is the ***maintenance ratio***. The maintenance ratio has an associated ***achievable accountability*** that can be expected for infrastructure of that age with adequate maintenance. For example, spending a ratio of 1.0 will eventually result in an accountability level that is historically typical for pipes that age (i.e. the

achievable accountability corresponds to historical levels). Spending less than a 1.0 maintenance ratio will lead to a decline toward some lower ***achievable accountability***; spending more will cause improvements toward a higher ***achievable accountability***. However, the affect is not instantaneous—decay or improvement of a system does not occur all at once (except in the case of a wholesale replacement of the entire cohort). Instead, accountability changes each month toward the ***achievable accountability*** level according to an exponential rate. If the ***maintenance ratio*** were to remain constant, the ***accountability*** would eventually converge at the ***achievable*** level determined by that ***maintenance ratio***. Figure 12 below describes this structure for the 0-15 year cohort. All other cohorts follow an identical structure. Note that there is a "bi-flow" instead of an inflow and outflow feeding the stock; this is because the accountability may increase or decrease based on investment in each time-step of the model. Also note that the exponential rate constant is the Decay Rate, which, for all cohorts, is set to 0.005 inverse months. This value was chosen based on simulation runs to mimic historical behavior.

Figure 12: Decay in Accountability based on Maintenance Policy



: Based on the estimates used in Lane Engineering's preliminary engineering reports (Lane Engineering, 2007, 2004, 2001, 1999), the cost of maintenance for new pipeline is approximately $0.05 per foot per year. However, to maintain accountability (but not to improve it), the Town of Big Stone Gap spends approximately $0.19 per foot per year to maintain their existing older system, which is mostly over 50 years old (Lane, 2007a). These values were used to calculate the necessary maintenance cost for each cohort of infrastructure as it ages. The maintenance cost per foot (***mcpf***) values for the intermediate cohorts were calculated based on a linear relationship between cost and age.

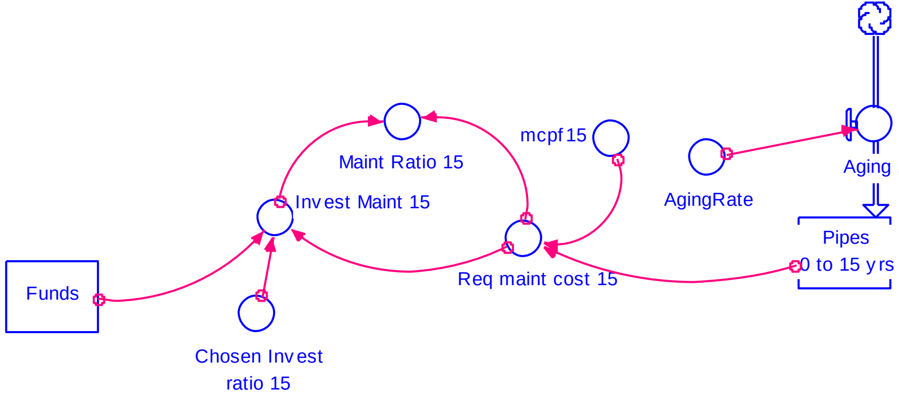
Table 3: Maintenance Cost per Foot for Each Cohort

Cohort	*Maint cost per foot*	*Achievable Accountability**	*Source*
0-15 years	$0.05/foot/year	0.85	Lane Engineering, 1999
16-30 years	0.10/foot/year	0.75	Linear interpolation
31-45 years	0.15/foot/year	0.65	Linear interpolation
45+ years	0.19/foot/year	0.45	Lane, 2007b

** This is the value for accountability when the maintenance ratio is equal to 1.*

The maintenance investment made per unit of infrastructure is based on the available funds (from the previous sector) and the required maintenance cost for each cohort of infrastructure. The required cost is simply the product of the maintenance cost per foot and the quantity of infrastructure in the corresponding cohort. See figure 14 below for the model structure.

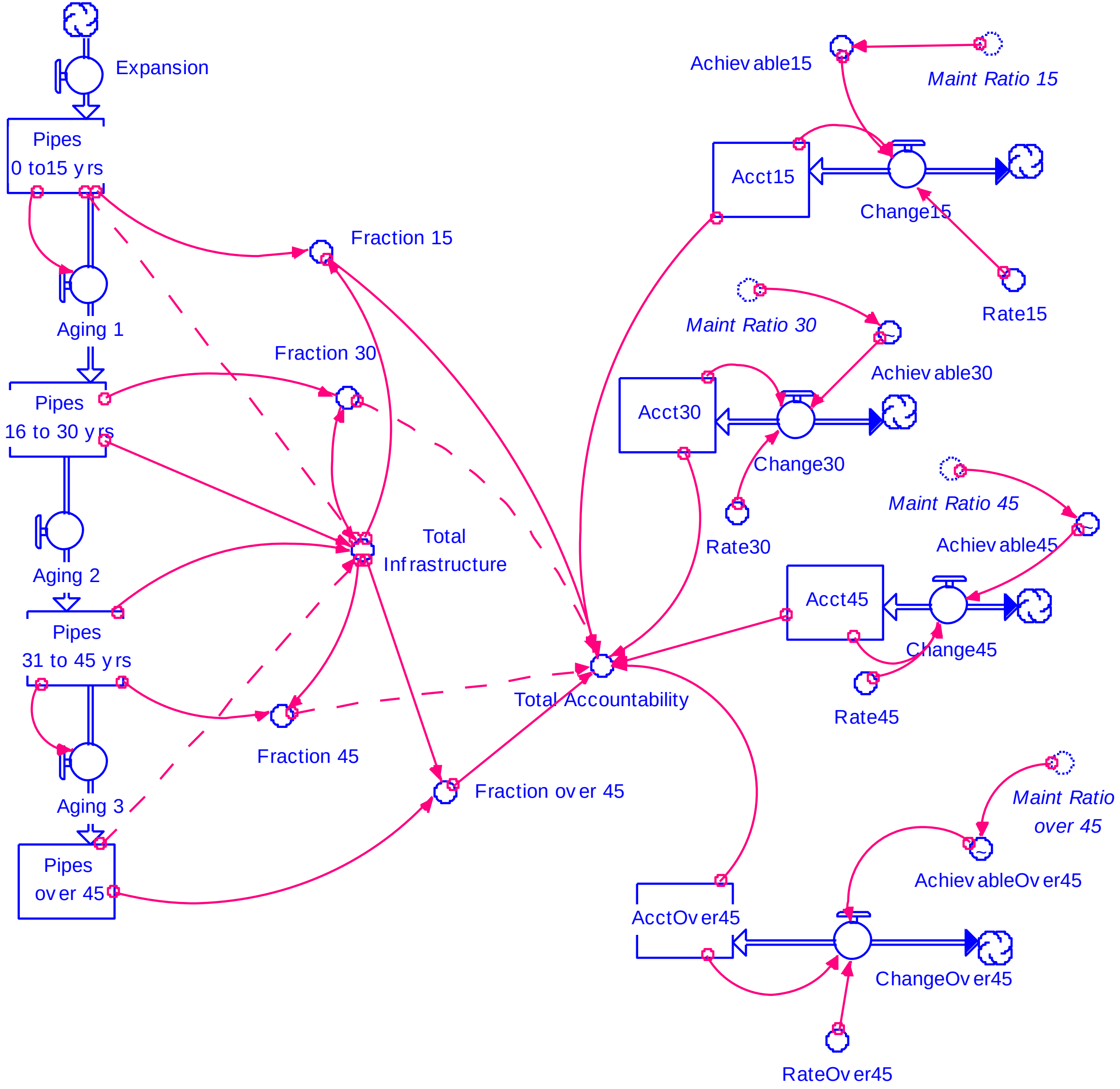
Figure 13: Required Maintenance Cost and Maintenance Ratio Structure for Each Cohort



That is, for new lines, the estimated cost for maintenance is $0.05/per foot. The value of the 0-15 pipes stock, which is initially 300,000 feet, is then multiplied by the

mcpf 15 to calculate the required cost for maintenance. The required cost for maintenance for each cohort is then calculated in the same fashion, and all of these costs are summed for the ***total required maintenance cost***. Figure 15 below shows how this logic fits together for the entire infrastructure sector. Note that in the model, the default value for the ***chosen maintenance ratio*** is 1; if the required maintenance funds are not available, then the oldest cohort is prioritized for maintenance (***pipes over 45***), then the next oldest, etc. This allows changes in water rate to have an immediate effect on maintenance spending.

Figure 14: Infrastructure sector.



The ***total accountability*** determines the ***gallons lost to leaks*** in the *water sector*, which in turn contributes to the total ***usage*** (see Figure 7). The ***usage*** then impacts the ***operating cost*** in the *funding sector* as more water is must be processed and distributed through the water system (see Figure 9).

The interactions between these sectors dictate the quantity of water available in the community over time. One of the most significant feedback loops in this system involves the level of maintenance of older infrastructure. If maintenance is neglected over time, the ***operating cost*** of the system increases. This means that more money is spent on treating and distributing water that is ultimately leaked out of the system and is not paid for by customers. Of course, this additional cost is money that could have been spent on maintenance, but is lost to leakage instead. So, ***operating costs*** increase and the funds available for maintenance decrease; therefore ***maintenance spending*** decreases. As less is invested in maintenance, accountability will decline further, increasing ***operating costs*** even more. Without a shift towards more investment in maintenance, eventually the ***operating costs*** will supersede other investments, so that maintenance is not possible without a new inflow of money. Generally, the easiest option to balance this reinforcing feedback loop is to increase water rates to fund the maintenance budget. As accountability improves, the system becomes more self-sufficient as funds are put toward maintenance and not toward wasteful operational expenses.

Chapter 3: Model Testing

Model Testing

In Chapter 2, the model assumptions, boundaries and limitations are described in detail. The next step in the modeling process is to evaluate whether the model is useful in fulfilling its defined purpose. Often the term “model validation” is used, but as a model is a simplified, limited representation of reality, a model can never be validated in an absolute sense. Instead, model testing is a process of evaluating whether the model is “good enough” for its intended purpose. In order to make this determination, we must evaluate if the model adequately addresses the system dynamics and behavior of interest in such a way as to help answer the original questions that motivated the study.

There are many established criteria for evaluating system dynamics models. These criteria are as follows (Sterman, 2001).

1. *Face validity*: Does the model employ appropriate boundaries and include variables that are relevant to its purpose? For example are variables excluded that have a significant long-term affect on water level (i.e. evaporation, for example)? If so, the model boundary should be expanded to include those variables.
2. *Structural validity*: Is the model structure logical and does it conform to basic physical laws, such as conservation of matter? Are the stock and flow structures and other relationships in the model consistent with the real-life system?
3. *Dimensional consistency*: Are the descriptions of the model variables, their numeric values, and their mathematical use consistent with the units in which they are expressed?

4. *Behavior under extreme conditions*: Is the model is appropriately sensitive to extreme conditions? Does the model respond to these conditions in a way that matches common sense? Do step changes or "spikes" in key variables propagate through the system to exhibit dynamic behaviors that are consistent with knowledge about how such a system works? For example, if precipitation is set to a 100-year flood level, does the lake fill to billions of gallons, or only within its capacity?
5. *Behavior reproduction*: How well does the model mimic relevant aspects of past behavior? Is the correspondence with past behavior sufficiently close to fulfill the purposes originally intended for the model?

The following sections elaborate on these criteria, the actual tests run, and the changes and improvements made to the model.

Face validity and structural testing

An essential aspect of model testing is the evaluation of the basic model structure. That is, do the relationships of the stocks, flows, and converters described within the model adequately represent the relationships of those variables in the real world? One method of evaluating this is through *face validity testing*, which is the qualitative analysis of the model structure against the knowledge of experts. In this case, the expert advice was provided by the Town Engineer, Bobby Lane. The first meeting regarding the model effort took place early in the modeling effort, and was primarily for the purpose of data collection and discussion of the primary variables (size of infrastructure, age, and accountability). A second meeting with the engineer regarding the model structure and outputs for the lake sector and the funding sector indicated that the behavior of the water sector logic and outputs were reasonable, but that more detail was required in the funding sector. Additional data was provided regarding the town's debt and typical reserve requirement (savings) in the budget was added to the model logic. A third meeting consisted of discussions of maintenance policies and costs with the town engineer and town manager. Examination of the current cost of maintenance combined with the expected cost for new infrastructure maintenance contributed heavily to the logic for the infrastructure sector, although this aspect of the model has not, as of this writing, been reviewed with the town engineer or manager.

Another simple model evaluation criterion is *structural testing*. The model should conform to basic physical laws, such as the conservation of matter. In this model, this would pertain to the water supply in the lake (as all the water entering the system should be accounted for), and to the infrastructure, as the "pipes" should not leave the system or "magically appear" within the system. Calculations comparing initial values to the final outputs show that physical laws are not violated, and that all material inputs and initial values are accounted for within the model. In addition to testing for conformity to physical laws, it is also important to examine the chosen boundaries and assumptions in the model. For example, monthly usage by customers was assumed to be constant in the model, and factors such as evaporation and groundwater seepage were excluded in the water sector of the model. To evaluate the effects of changing these values, the flowby outflow was doubled to examine the effects of including additional outflows such as evaporation. The values for the BCR and days supply outputs were reduced, but the overall behavior of the system did not change significantly.

Dimensional consistency

Another criterion of model validity is the *dimensional consistency* of the model. That is, the units within the equations for stocks and flows should maintain consistency in the units used. For example, if a stock contains gallons of water, then all the flows associated with that stock must be expressed as gallons per time unit. The Big Stone Gap Water Infrastructure Maintenance (WIM) model uses a monthly time step, so all the flows associated with the lake stock should be expressed in gallons per month. Similarly, this must hold true for all other stock and flow networks in the model (i.e. the total debt stock is expressed in dollars, so the flows associated with that stock must be in dollars per month). This dimensional consistency among stocks and flows propagates back through all the equations in the model and in the definitions of the units for all variables so that dimensional consistency is maintained throughout the model. This can be checked only by a careful examination of the units of each variable in the model and all the model equations. Throughout the development of the BSG-WIM model, all equations were repeatedly checked for dimensional consistency and changes were made in order to satisfy this requirement.

Extreme conditions

The final test used to evaluate the model logic and the boundaries, assumptions, and equations chosen to represent the behavior of the Big Stone Gap water system is to examine the behavior of the system using extreme values for key variables. This allows one to examine if the behavior of the model is reasonable under these conditions. Several variables were examined in this way. For example, setting the ‘runoff’ value to greater than the lake capacity over the course of the simulation results in the reservoir being filled to capacity (and not beyond that value), which would be the expected behavior. Other key variables, such as ***water rate, dist cost per gallon, proc cost per gallon, invest maint*** (for each cohort) were also tested under extreme conditions. The funding sector of the model is extremely sensitive to changes in the ***cost*** variables (maint and dist) and to the water rate value; this would be reasonable as the cost per gallon or rate charged per gallon would have large repercussions due to the fact that the model deals with millions of gallons of water and because these variables significantly impact the availability of funds for maintenance. This indicates that the values for cost-related variables must be carefully chosen; the values used in this model are based directly on Big Stone Gap budget and cost records (Lane, 2007a).

Table 4: Extreme value tests for BSG WIM model

Variable	Test	Test value	Expected Behavior	Observed Behavior
Runoff	100 year flood level	2,000,000,000 gallons	lake would stay at capacity	as expected
Population	doubled size of population	8200 connections	more frequent water shortages more funds avail	as expected
water rate	increased by 50%	$0.015	More funds available average bill increase by 50%	as expected
proc cost per gallon	increased by 50%	$0.015	Available funds would greatly decrease	as expected
dist cost per gallon	increased by 50%	$0.015	Available funds would greatly decrease	as expected
Invest maint 15	No maintenance	0.00	Accountability would rapidly decline	as expected
Invest maint 30	No maintenance	0.00	Accountability would rapidly decline	as expected
Invest maint 45	No maintenance	0.00	Accountability would rapidly decline	as expected
Invest maint over 45	No maintenance	0.00	Accountability would rapidly decline	as expected

Behavior reproduction

Once the logical soundness of the model is established, the next set of tests evaluate whether the model reproduces the known historic behavior of the system. In this model, this would include whether the water shortages shown in the model correspond with past water shortages and whether the costs in the model fit budget data provided by the town. Model outputs are compared to town data using the historic 1950-2007 data for water in the system. We begin by outlining the baseline scenario used for the behavior reproduction test and the results of that test.

Table 5: Baseline scenario values

	Baseline Scenario
	(1950-2005)
Reservoir capacity (gallons)	425,000,000
Population (number of connections)	Varies
Commercial customers (number of connections)	275
Water consumption by neighboring communities (gallons)	0
Consumer Water Rate (dollars per gallon)	0.005, 0.007
Wholesale Water Rate (dollars per gallon)	0.0035
Pipes, 0-15 years (initial value, feet)	100,000
Pipes, 15-30 years (initial value, feet)	150,000
Pipes, 30-45 years (initial value, feet)	50,000
Pipes, over 45 years (initial value, feet)	0
Initial Loan amount (dollars)	32,000,000
Loan duration* (months)	680
Total debt (dollars)	32,000,000

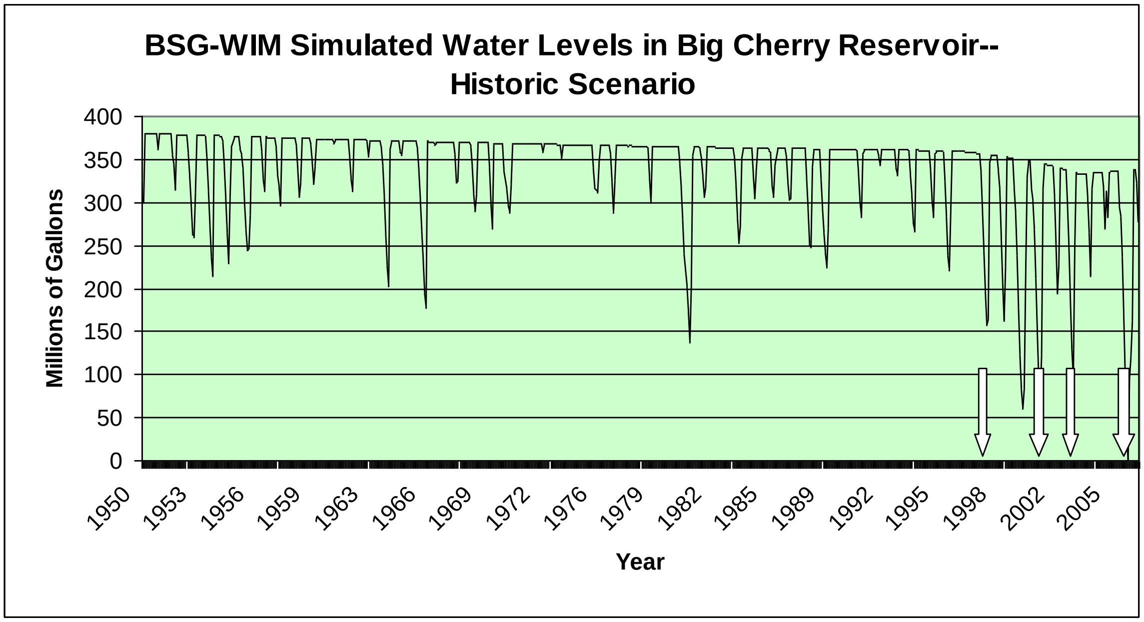
**The "loan" in the simulation assumes a baseline amount of debt for the town over the entire simulation period.*

Baseline scenario outputs were compared to historical data to evaluate whether the model effectively reproduces past system behavior. Data for the scenarios are based on several documents provided by the town. The reservoir capacity is based on the "New Big Cherry Dam, Big Stone Gap, Virginia: Technical Memoranda" (Dewberry, 2001). Data regarding the consumption of water by commercial and residential customers, and the rates charged for water sales were based on budget data provided by the town as well (Lane, 2007a, 2007b, and 2007c). The size of the infrastructure in each age cohort was back-calculated based on the current distribution of pipe (as Big Stone Gap is currently in the process of replacing all of the pipes in the town over 30 years old). The decay of infrastructure and per-foot maintenance cost in each cohort were fitted to past maintenance cost data and current data on maintenance spending to maintain the current 35% accountability.

Limited data is available regarding past water shortages and accountability. According the “Wise County Water and Sewer Study” (Dewberry, 1997), accountability was 47% in 1997. Current data provided by the town indicates that accountability was around 35% in 2006 (Hampton, 2007). Total usage outputs (including leakage) and consumption for 2006 also match the town’s current data. The town’s annual budget for 2006 also indicates that the operational cost and maintenance cost values output from the model match current values (Lane, 2007b). However, data for past loan payment amounts over the past fifty years were not available; the model operates on the assumption that the cost of the system when new would be comparable to current projects (in today’s dollars). Past expenditure data are not available, so it is assumed that the town carries a baseline amount of debt (and a baseline payment) throughout the simulation. This is why the initial loan amount is set to $32,000,000 and the loan duration was set to cover the time span covered by the simulation (i.e. just over 56 years).

The other historic measure of interest is the town’s history of water shortages. Recent data is readily available, but data prior to 1990 is not available. Water shortages occurred in Wise County, according to the Virginia Department of Emergency Management archives and data from the Big Cherry Dam technical memoranda (Dewberry, 2001), indicate water shortages in late 1998 (VDEM); late 1999 (Dewberry, 2001), February 2003 (VDEM), and October 2005 (VDEM). All of these shortages are also given in the model outputs, and are indicated with the arrows below.

Figure 15: Graph of simulation values vs. historical water shortages. ***(White arrows indicate historic records of water shortages).***



As evidenced by the above graph, the decline in accountability from 1995 until 2005 contributed to several water shortages, as drought conditions combined with the excess leakage depleted the town water supply. By comparing the simulated shortages to the water shortages indicated by the arrows in Figure 11, model outputs correspond closely to past water shortages. According to George Polly, Big Stone Gap town manager, the town has been experiencing water shortages since the early 1990's; the worst shortages were in 2000 and 2005. These dates correspond to the most severe shortages in the simulation.

Throughout the validation process, model logic and variables were adjusted or modified to improve or address problems with the model outputs. That is, another aspect of model validation is "fine-tuning" the model to ensure satisfaction of the validation criteria. Several changes were made to the model for more accurate behaviors. Specifically, the size of the population had a significant impact on the behavior of the system over time, as population affects revenues and consumption levels, so the population was changed to fit historic trends for the region (see Figure 2). Additionally, one of the later conversations with the town manager revealed that the town had a water rate increase in 1979, which was incorporated into the model as well. Finally, the accountability ***decay rate*** was decreased within the infrastructure logic for a more realistic decline in accountability. Prior to this adjustment, poor maintenance policies (a maintenance ratio close to zero) resulted in a very rapid decay in accountability (25% in 10 years). This would be unrealistic in a relatively new system, and the affects of neglect would take at least a decade to manifest a noticeable effect on operating costs and accountability. With the adjusted ***decay rate***, the accountability declines about 16% over the first 10 years with no maintenance.

Chapter 4: Implications and conclusions

Implications of the model

Many communities in Southwestern Virginia struggle to provide citizens and businesses with a reliable, potable water supply. Issues with distance, karst terrain, and groundwater contamination have proven to be obstacles to providing water for more remote, small communities in the region. Big Stone Gap, Virginia, has also struggled with water availability; however, the water supply issues there are not as simple as an insufficient capacity. In fact, the advertised capacity of the water supply system is easily sufficient for the needs of the town, based on historic average consumption. Also, a lack of access to potable water is not an issue, as 84% of residents in the area are connected to the town water supply--one of the highest levels in the region. Nonetheless, this community has recently experienced ongoing and significant water shortages. While these shortages exist partly because of the aforementioned geographic and geologic factors, they are also the result of long-established management practices that have had accumulating effects over several decades. These accumulated effects have, in the past 20 years, had a significant, negative impact on water availability.

The simulation model developed in this thesis attempts to explore these policy issues by explicitly defining and modeling the dynamics between infrastructure expansion, maintenance, water revenues, management practices, and an aging infrastructure. That is, as the infrastructure ages it gets more expensive to maintain, so maintenance costs will increase over time. If maintenance is inadequate (due to unavailable funds or underestimation of costs), the accountability of the system will degrade and operational expenses will increase, as more water is lost to leaks. The increase in operational expense consumes available funds, which further decreases funds available for maintenance spending. This is the accountability death spiral that is addressed throughout this thesis and that explicitly modeled in the model developed herein, referred to as BSG-WIM. Without an inflow of money to improve accountability, the system will degrade considerably over time if maintenance policies are not changed.

BSG-WIM consists of three sectors: water, funds, and infrastructure. By adjusting the values for key variables in the model, managers can explore the effects of policy changes regarding water rates and maintenance, along with their long-term impact on operating costs and water availability. In this way, effective management strategies can be identified…strategies that are formulated with a long-term view of their impacts and that are based on a more complete understanding of the dynamics affecting water availability in the region.

Model Scenarios

For the purpose of policy testing for the Big Stone Gap water system, two operating environments were designed to evaluate the effects of various maintenance policies, both for water availability and for overall cost. The first environment uses data from the 1950-2005 water system, which would not include the new interconnects between other water systems, or the expanded capacity from the new dam. This will allow policymakers to examine past policy decisions and their effects, and alternate policies that may have improved water availability for the town. This historic environment will allow the user to gain understanding of how the water system came to operate at such a low accountability, and how this degradation could have been avoided.

The second environment involves the “future” operation of the system because it uses data for the newly expanded system (as of 2005), with a larger infrastructure, higher water rates, and the expanded reservoir capacity from the dam project to assist in long-term planning to reduce water shortages and to best manage the newly expanded system. Initial values for both operating environments are described in the table below.

Table 6: Initial values for BSG WIM model.

	Initial Values		
	Historic	*Future*	*Source*
	(1950-2005)	*(2005-2055)*	
Reservoir capacity (gallons)	425,000,000	610,000,000	Dewberry, 1997
Population (number of conn.)	Varies over time	4200	Lane,2007b
Commercial customers (number of conn.)	275	300	Lane,2007b
Water consumption by neighbor (gallons)	0	2,660,000	Lane,2007b
Water Rate (dollars per gallon)	Varies over time	0.011	Lane, 2007a
Sale of Water Rate (dollars per gallon)	0.0035	0.0035	Lane, 2007a
Pipes, 0-15 years (feet)	100,000	320,000	Lane, 2007c
Pipes, 15-30 years (feet)	150,000	55,000	Lane, 2007c
Pipes, 30-45 years (feet)	50,000	0	Lane, 2007c
Pipes, over 45 years (feet)	0	0	Lane, 2007c
Initial Loan amount (dollars)	32,000,000	75,000,000	Estimated from projects
Loan duration* (months)	680	680	Estimated from projects
Maintenance ratios (separately for each cohort)	Chosen by the user	Chosen by the user	1.0 ratio matches historic levels
Runoff (gallons per month)	Historical records	Same as historic	Dewberry, 1997; USGS 2007

**Loans in the model are based on estimates from the total cost of the current replacement project for the Historic Environment. The future scenario loan is the total of all recent projects not funded by grants. Additionally, the town is assumed to carry some amount of debt over the course of the simulation, so the debt is treated as one large loan.*

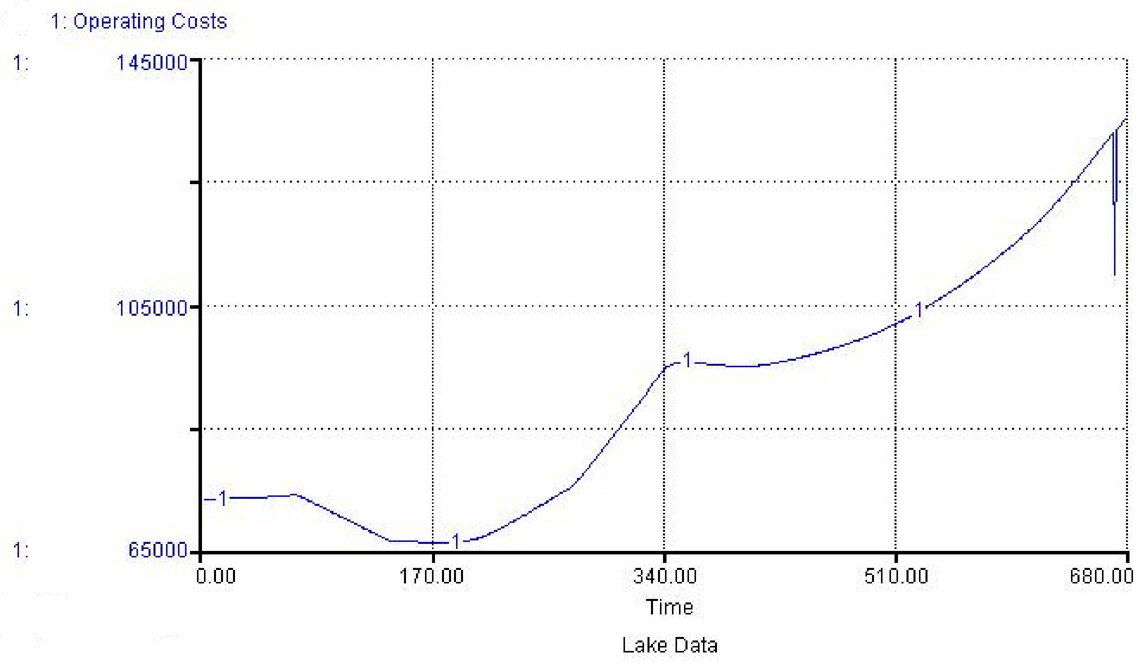
Experiment #1: Historic Environment with Current Management Practices

This experiment (also used to validate the model), sets the maintenance ratios to 1.0 throughout the simulated time window and effectively mimics the behavior of the system under the existing management practices. The results of this simulation are shown in Figure 17 (showing the system accountability over time) and Figure 18 (showing the accumulated operating costs over time). As the system grows more expensive to maintain, without an adequate increase in the consumer water rate, the town cannot afford adequate maintenance. Inadequate maintenance will lead to a decrease in accountability (Figure 17), which will increase operational costs (Figure 18). Since the water income is relatively fixed, this means that even fewer funds are available for maintenance investment. This is a result of the ***accountability death spiral*** in Figure 6.

Figure 16: Experiment #1 – Simulated Accountability under Current Management Practices

As accountability decreases, operational costs increase, as more water is treated and distributed. The town's water income varies only with population changes and with changes in water rates. A water rate increase at month 348 slows down the decline in accountability, thus creating a “kink” in the graph. The available funds for maintenance still continue to decrease, despite the water rate increase, as more and more funds are spent on processing and pumping water through the system.

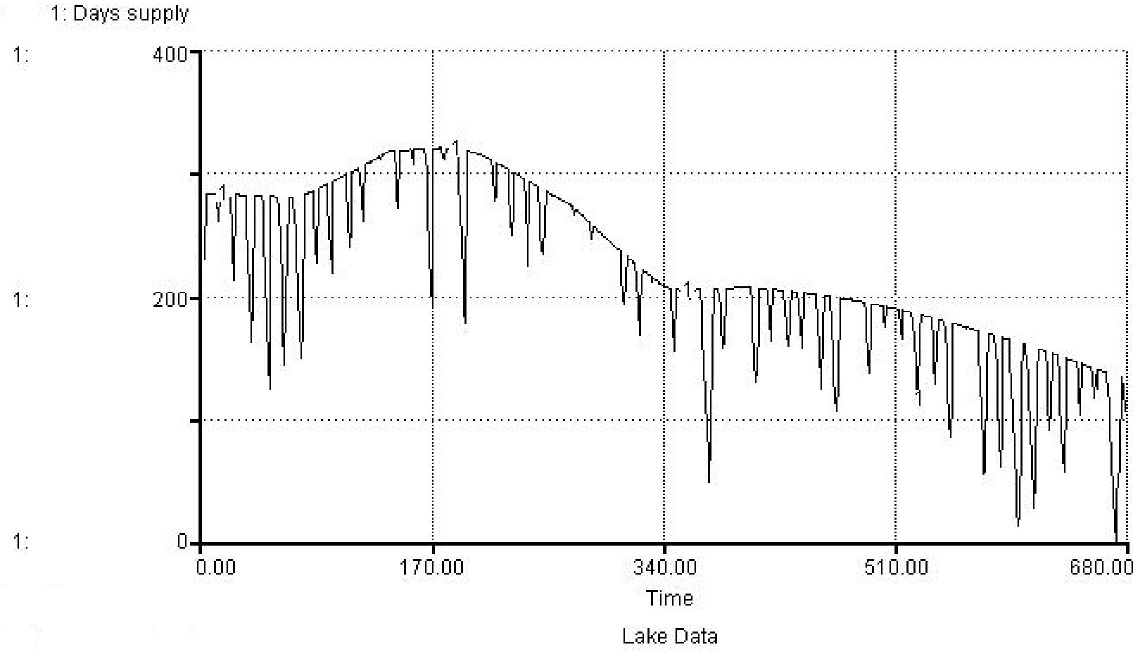
Figure 17: Experiment #1 – Simulated Accumulated Operating Costs under Current Management Practices



As the accountability of the system degrades, operational costs double by the end of the simulation. With an accountability of 33%, the town is paying to treat and distribute three times more water then when the system was new and in good repair. As a result, usage has effectively tripled with the decline in accountability. Note the fluctuations in operating costs with the decrease in population size around month 136, which indicates a large decrease in population size. Also, the operating cost increase slows down around month 348, which is when a consumer water rate increase was implemented. Lastly, a dip in operating costs occurs during a severe water shortage around month 672, as the town cannot meet its population’s needs (and is therefore not processing or pumping water).

Figure 18 shows the resulting adequacy of the water supply as accountability is decreased. The number of days the town can supply water for its customers is calculated by dividing the amount of water in the lake by usage. Under historic management practices, in the event of a drought, the reservoir can supply the town for fewer days than if the accountability is high.

Figure 18: Experiment #1 – Simulated #Days Water Supply under Current Management Practices



Experiment #2: Historic Environment with water rate increase and improved maintenance

This scenario is based on the same baseline values, except the water rate is increased to $0.007 per gallon throughout the entire simulation, and the chosen maintenance ratio is set to 1.5 for all infrastructure cohorts. This results in overall higher accumulated costs over the lifetime of the system, but also maintains an adequate water supply throughout the 56-year run.

Figure 19: Historic Experiments with Improved Maintenance – Simulated Accountability

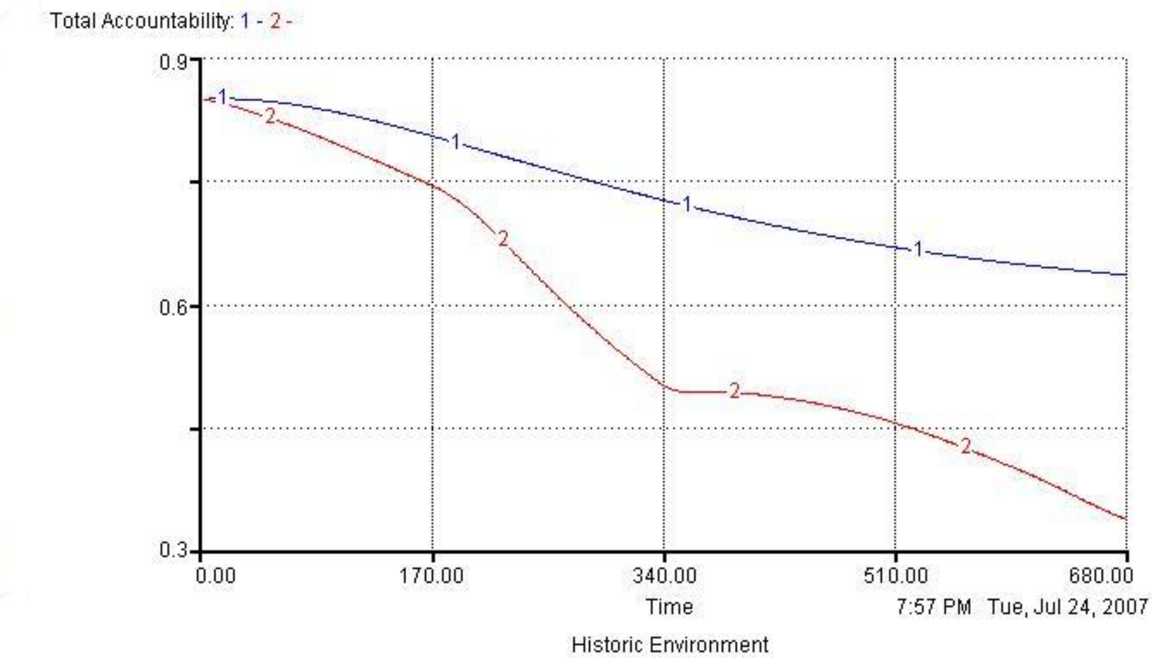
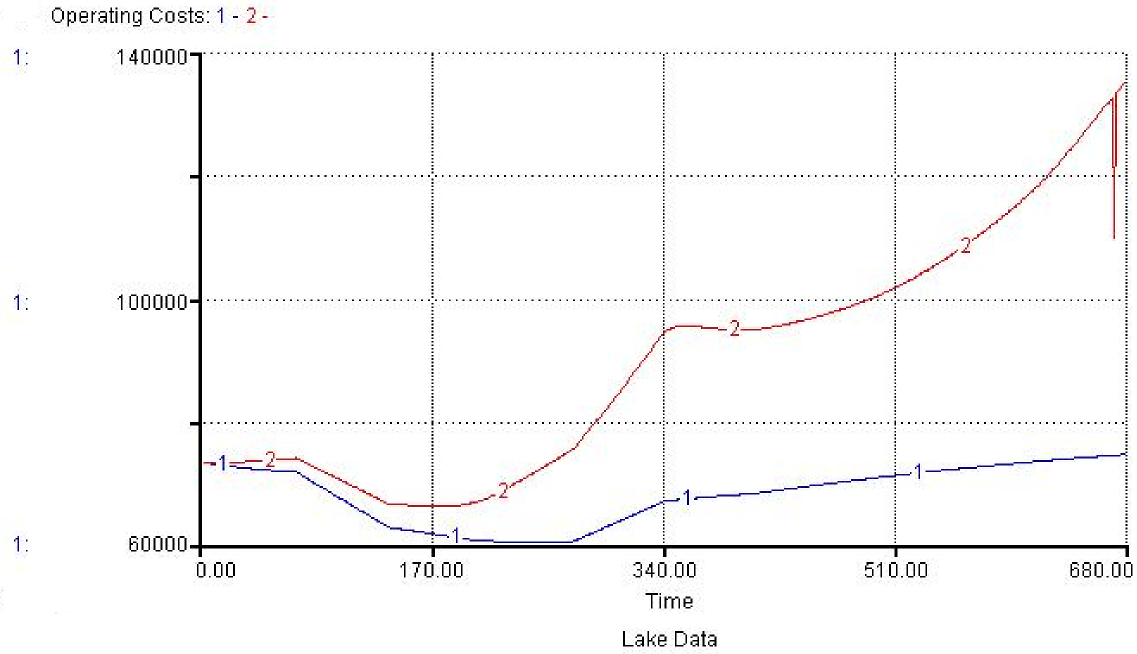


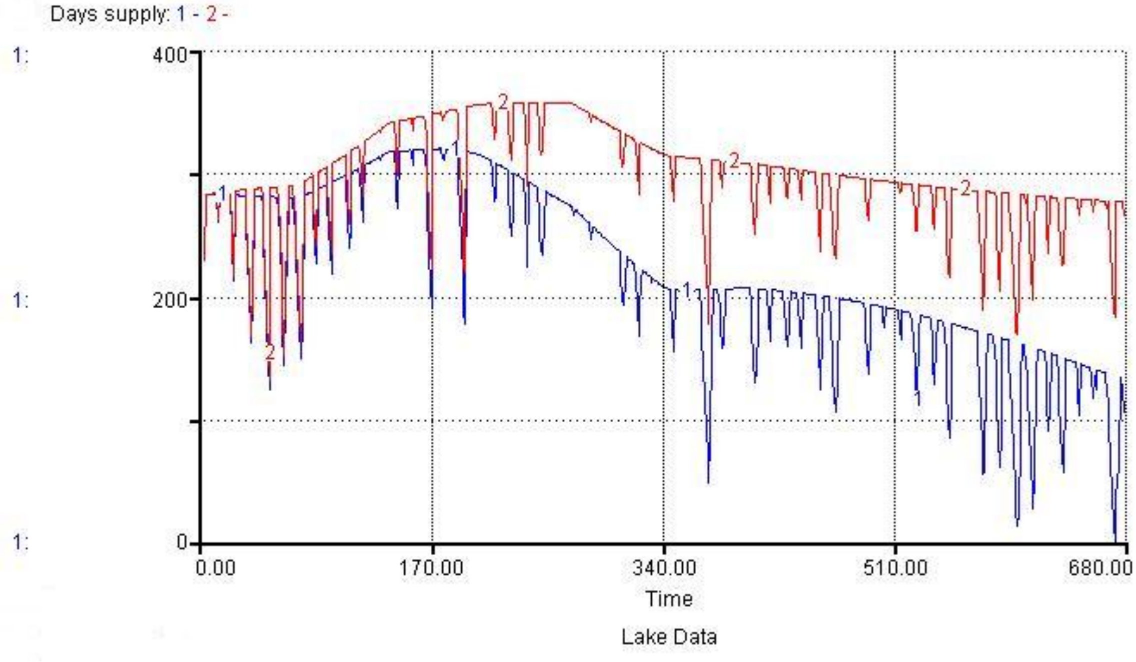
Figure 20 is a comparative graph, with the results from the previous scenario on graph 2, and improved maintenance results on line 1. Accountability is 63% for 2005 with the improved maintenance policy; this is a stark contrast to the town’s current 35% accountability.

Figure 20: Comparative Graph of Operating Costs for Improved Maintenance Policy vs. Current Management Practices Scenario



As evidenced by the above graph, operating costs (such as water processing and pumping) for the system under historical maintenance practices (line 2) is almost double the operating costs when rates are increased and the maintenance ratio is set at 1.5 (line 1). With operating costs remaining relatively stable, the funds for maintenance are also more stable, and adequate maintenance can be implemented in the town.

Figure 21: Days Supply with Improved Maintenance Policy vs. Baseline scenario



Since usage remains stable with better accountability, the reservoir can provide water for a longer period in the event of a drought. Over time, the difference in the adequacy of the water supply becomes significant with improved maintenance. For example, at month 672, instead of a *total water shortage* (which is estimated in the historic maintenance simulation, indicated by line 1 on the graph above), the town has about a six-month supply with improved maintenance (see line 2).

The most important implication of the study is that once accountability begins to decline, without a new inflow of funds to boost maintenance spending, the system will continue to degrade and will do so in at an accelerating rate as operational spending necessarily increases and maintenance spending is compromised in order to offset the higher operating costs. A small increase in the water rate as the system begins to show degradation will greatly improve the accountability of the system (assuming the additional funds go towards maintenance). The system is cumulatively more expensive with improved budgeting for maintenance, however. Ultimately, more emphasize on maintenance results in a dramatic improvement in water availability, and water shortages are mitigated by this change in policy.

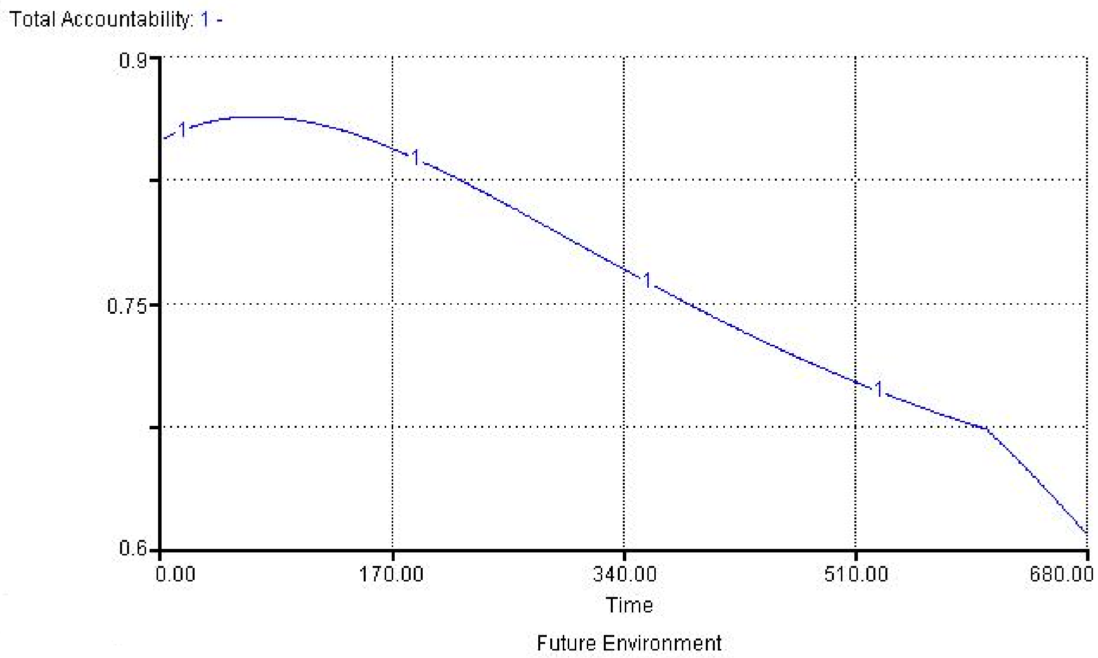
Future Environment

Examining the management of the Big Stone Gap newly-expanded and replaced system with the current (larger) debt load will be invaluable to identifying management practices to mitigate future water shortages. Now that the dynamics of past management practices are understood, that knowledge can be exploited to explore management options for the newly expanded system. To this end, a second simulation environment and user interface was created to simulate the behavior of the system for a 50-year period, beginning in 2005. See Table 5 for the values defining this future simulation environment.

Within this simulation environment, two experiments were developed that examine the affect of a water rate increase, assuming additional funds are spent towards maintenance.

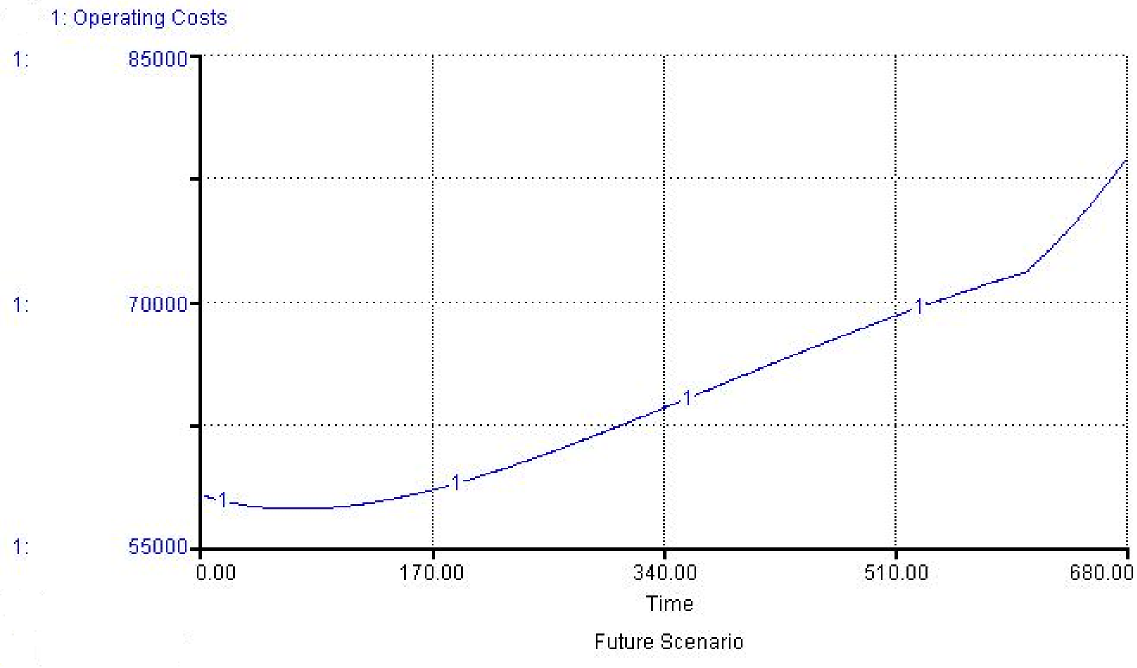
Experiment #3: Aggressive maintenance Practices with Current Water Rate Increase

Figure 22: Accountability, Future Environment, with Current Consumer Water Rate and Aggressive Management Practices.



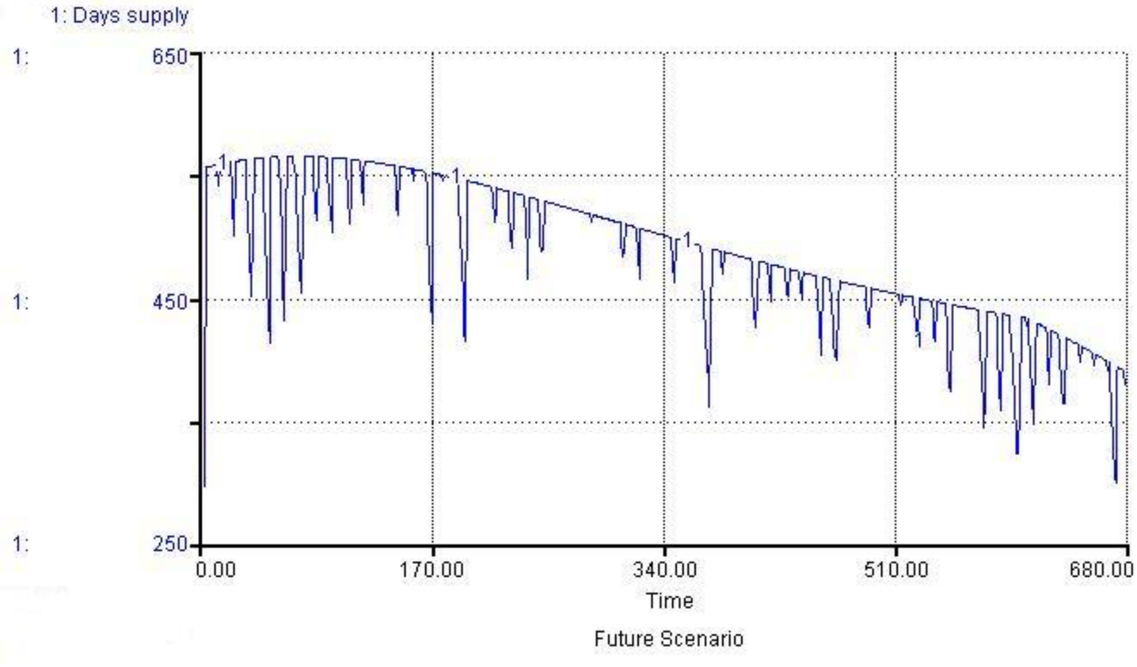
The future environment simulation here was run with an aggressive maintenance policy, where the town spent 1.5 times more per foot on maintenance than their past maintenance policies (a ***maintenance ratio*** of 1.5). This keeps accountability of the system well over 50% over the course of fifty years.

Figure 23: Operating Costs, Future Environment, with Current Consumer Water Rate and Aggressive Management Practices.



With more aggressive maintenance, operating costs for the town, even with the added demand and expense of wholesale customers and additional connections, are not significantly greater than historic values.

Figure 24: Days Supply, Future Environment with Current Water Rate Experiment



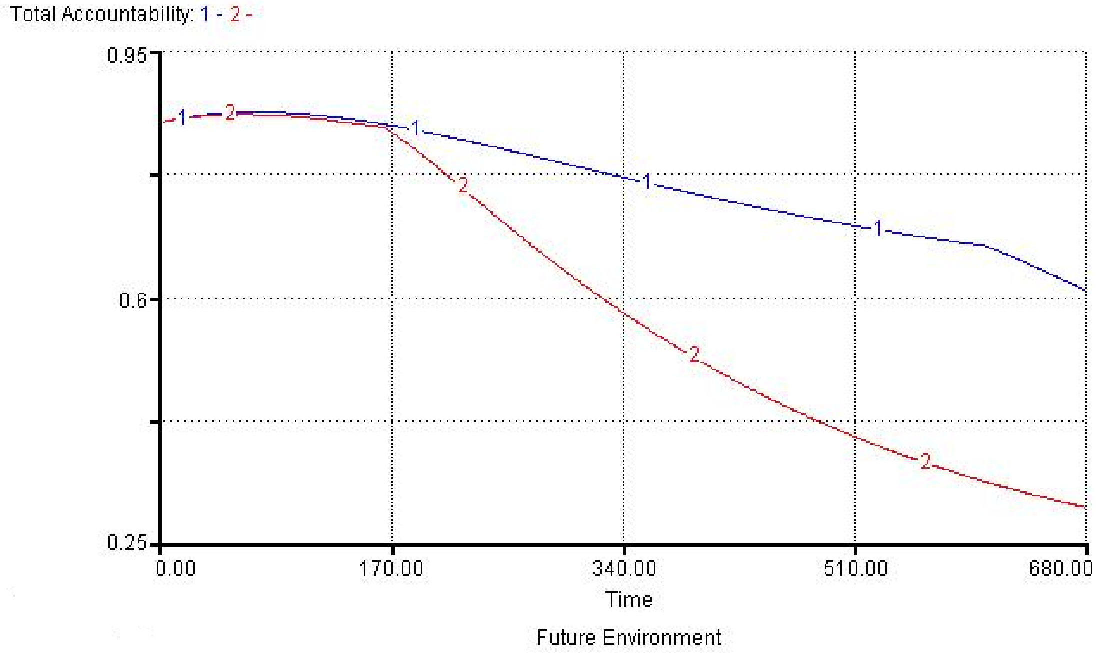
With the expanded capacity of the new reservoir, the town has almost a year's supply of water storage if they implement aggressive maintenance policies with the new system.

However, the ability to implement an aggressive maintenance policy depends entirely on having an appropriate water rate.

Experiment #4: Aggressive Maintenance Practices with a Smaller Water Rate Increase.

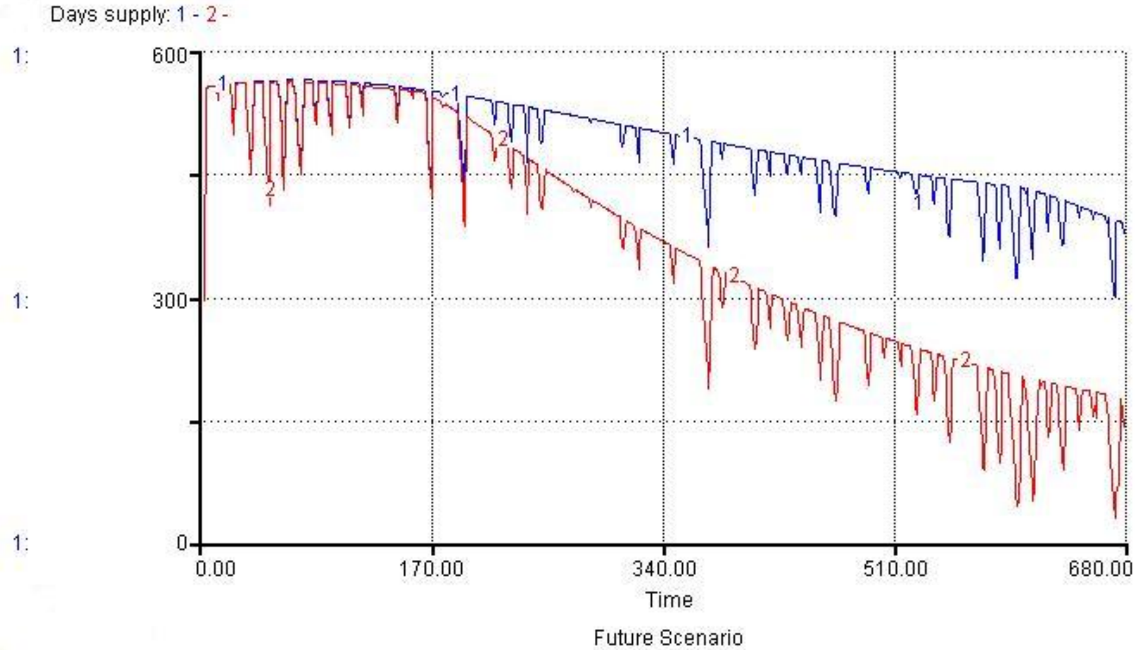
There is currently considerable controversy in the town of Big Stone Gap over their recent water rate increase. With the high level of poverty in the region, there is considerable pressure to keep water rates affordable, which has also contributed to the inadequate rate structure and related infrastructure decline. The new water rate is approximately $11.00/1000 gallons of water, which will give an average water bill of $45, considering average per capita usage. The following graphs examine the behavior of the system with a water rate of $9.00/1000 gallons, which is still a $2.00 increase over the water rate charged from 1979-2006.

Figure 25: Accountability, Future Scenario with Inadequate Water Rate Increase



The future experiment with current water rates result is indicated by line 1 in the graph above. Line 2 represents accountability with a smaller water rate increase ($9.00/1000 gallons). Based on this simulation, we can see that the town can support aggressive management for a few years with a lower rate, but would need to implement the increase to the new rate within 10 years (around month 170, specifically), in order to provide adequate maintenance. Otherwise, the system will again fall to an extremely low accountability within 50 years.

Figure 26: Days Supply, Future Scenario with Inadequate Water Rate Increase



Without an appropriate water rate, the system will again fall to a poor accountability within 50 years, and the town will again be faced with severe water shortages (see line 2 in figure 26).. In this simulation, the town has approximately a one-month supply during the driest period (around month 672). This supply is a stark contrast to the 10-month supply available with aggressive maintenance (line 1 above).

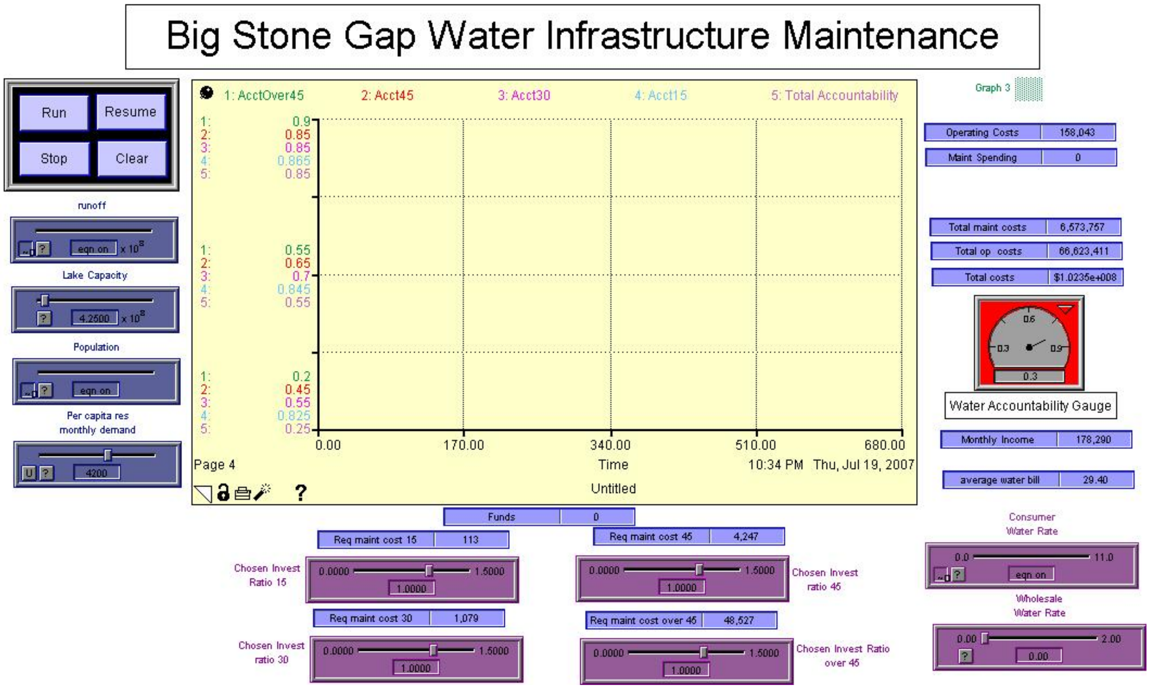
Benefits and applications for model

While the model is designed for the Big Stone Gap water infrastructure (in terms of rate of accountability decay and cost for maintenance), the overall logic is applicable to other communities in the Appalachian region. That is, as the rough terrain and long distances of pipe contribute to the greater expense for maintenance and the accelerated rate of decay, the same dynamics affecting the BSG water infrastructure will be present in other communities in the region. Only the values of several variables will need to be changed to better match the unique characteristics of the other community. Moreover, the model can be used to illustrate the affect of poor maintenance over time; the affects of an inadequate water rate on system sustainability; and the difficulty in funding improvements once operational costs begin to increase due to excessive leakage without a water rate increase or securing additional funds through loans or grants.

Implications

Using the 2005-2055 scenario data, the recent increase in water rates may be sufficient to maintain the newly expanded infrastructure for acceptable levels of accountability. Assuming limited growth in the region, even with the previously inadequate maintenance policies in place, the town can operate effectively with as low as 50% accountability in 50 years and offer an adequate water supply with the new water rate. However, continued degradation beyond that point will result in continued problems. Additionally, increased budgeting for maintenance as the system ages will allow the system to operate at a more typical accountability (around 80%) without greatly increasing the overall costs of the system. Figure 28 below is an image of the decision support tool followed by a brief explanation of how to use the tool. Also note that there are two versions of the model, one with the future scenario values and one with historic values. The interface is the same, but initial values are set to those in table 6 for the respective environment.

Figure 27: Dashboard for BSG-WIM Model



runoff: eqn on x 10^8

Lake Capacity: 4.2500 x 10^8

Population: eqn on

Per capita res monthly demand: 4200

Operating Costs 158,043

Maint Spending 0

Total maint costs 6,573,757

Total op costs 66,623,411

Total costs $1.0235e+008

Water Accountability Gauge: 0.3

Monthly Income 178,290

average water bill 29.40

Funds 0

Req maint cost 15 113

Chosen Invest Ratio 15: 1.0000

Req maint cost 30 1,079

Chosen Invest ratio 30: 1.0000

Req maint cost 45 4,247

Chosen Invest ratio 45: 1.0000

Req maint cost over 45 48,527

Chosen Invest Ratio over 45: 1.0000

Consumer Water Rate: eqn on

Wholesale Water Rate: 0.00

Figure 27 is a screenshot of the user interface for the BSG-WIM model. The model offers user-adjustable sliders for several key variables. Specifically, the user can turn off the historic data for runoff and examine the behavior of the system during extending droughts, as well as examining the affect of changes in population or per capita usage (conservation policies). All other user adjustments relate to decisions around maintenance and water rates charged to customers. The sliders at the bottom of the screen allow the user to decide whether to spend the recommended amount on each cohort of infrastructure. Above each of those sliders is a "digital readout" of the recommended maintenance investment. To the right of the maintenance sliders are the rate sliders that allow the user to implement a water rate increase.

On the right-hand side of the interface, there are several other numeric outputs pertaining to the cost of the system. The top two outputs describe the operational expense and maintenance expense each month of the simulation; the next three numeric displays provide the total cost over the simulation for operational cost, maintenance cost, and the total cost of the system including debt.

Below the “digital displays” is the water accountability gauge. This shows the accountability of the system over time, and generates a “warning” with a suggestion to increase the water rate when the accountability begins to decline (approaches 50%). Below this gauge is a digital readout that gives monthly income and another display with the average bill for a residential customer.

For future research (potential for model refinement and extension):

There are several options available to further expand the model to examine additional policies. For example, adding infrastructure replacement as an intervention with known costs per foot for replacement projects would be a useful addition. This would allow easy comparison of replacement versus maintenance costs, as there is likely a “tipping point” where it would be more economic to replace pipeline than to repair it.

There are also several simplifying assumptions made in the model that could be refined to provide more accurate model outputs. Many variables are “fixed” within the current version that could be implemented as a graphical function whose value changes over time. This is especially true in the *funding sector*. For example, the *funding sector* uses values in today’s dollars, and assumes that costs have been fixed, and that any changes in costs on paper are due to inflation. The system is very sensitive to operational costs per gallon, so any change in these values can have large repercussions throughout the system. Specifically, if operational costs such as the cost of water treatment (***proc cost per gallon***), or other costs increase, a corresponding increase in water rates would be necessary to avoid maintenance neglect. Incorporating rate increases and more accurate operational and maintenance cost data would allow more useful cost-benefit or financial analysis that is currently outside the scope of this model. Additionally, a water rate increase has no affect on demand within the model; in fact, many customers may conserve water after an increase in water rates. Adding a relationship between water rates and demand would also improve the accuracy of the model, and would better exhibit the effect of a water rate change to generate funds.

Another limitation of the model is that the policies and accountability outputs only address Big Stone Gap's responsibility for the connections to other reservoirs. In fact, if the neighboring counties do not adequately maintain their part of the pipeline, the water supply of Big Stone Gap can be adversely affected as well. Water loss due to "neighbor neglect" could also be added to the model in a future iteration.

Appendix A: Table for Runoff calculation, 1950-2006 (streamflow gauge readings)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	3.17	8.93	5.96	6.48	4.18	4.6	11.07	2.91	4.27	0.94	3.21	3.3
1957	8.02	6.07	2	4.17	1.65	5.48	3.07	1.89	5.93	1.06	4.67	5.23
1958	2.63	3.95	2.9	6.17	4.16	4.22	7.19	7.89	1.29	1.08	2.26	2.75
1959	3.16	2.68	4.36	4.91	4.88	3.07	4	3.61	2.88	4.74	4.71	3.59
1960	2.49	4.16	3.67	2.01	2.83	4.47	6.75	5.13	3.89	2.51	2.28	2.5
1961	3.34	6.39	4.4	4.86	3.21	3.57	6.49	2.77	1.13	3.23	2.6	5.36
1962	5.46	5.43	2.98	3.46	4.55	4.86	5	2.68	5.43	2.74	4.44	2.49
1963	2.66	2.3	10.78	1.45	5.16	1.67	3.31	4.06	1.47	0.03	4.56	1.17
1964	3.57	3.6	4.51	4.79	3.25	5.5	2.58	3.82	5.58	4.87	3.54	4.13
1965	3.95	2.87	6.37	3.97	4.59	2.63	6.97	2.91	1.92	2.48	2.15	0.42
1966	2.24	3.82	3.21	5.28	1.98	2.58	8.19	7.8	7.08	2.69	4.46	3.63
1967	2.39	2.8	5.55	4.08	5.19	3.01	8.31	2.86	1.68	2.03	3.28	5.47
1968	2.59	0.62	5.21	4.23	6.63	4.27	3.82	4.48	2.23	2.47	2.8	2.69
1969	2.15	3.32	2.09	3.17	2.49	5.45	5.23	4.99	0.87	1.41	3.09	6.65
1970	2	2.88	3.27	5.75	3.13	1.53	4.1	4.89	3.25	3.02	3.2	3.29
1971	3.54	3.16	2.44	3.35	6.31	5.45	6.36	2.21	4.4	5.36	2.08	2.49
1972	8.47	0	2.64	5.01	3.34	4.37	5.52	0.33	3.82	3.99	3.49	6.04
1973	1.43	2.49	6.85	4.45	0	4.19	5.83	1.81	2.77	4.82	6.38	4.79
1974	6.04	3.36	5.87	2.96	6.03	5.54	1.05	6.05	2.11	2.81	3.1	2.04
1975	4.17	3.59	10.34	3.23	8.49	3.19	2.12	3.37	6.98	3.97	2.55	3.55
1976	2.33	2.76	5.43	1	2.98	3.2	3.78	3.32	5.23	5.99	1.59	2.86
1977	1.13	1.77	2.81	9.59	1.98	5.24	3.2	3.41	2.12	6.58	5.98	2.75
1978	0	1.34	2.6	3.55	5.94	3.42	5.3	3.5	1.71	1.56	3.83	6.64
1979	7.41	3.88	3.42	4.13	5.74	4.73	6.2	3.81	3.47	2.89	5.67	1.81
1980	0	1.15	4.32	4.03	2.88	1.37	7.85	3.82	0	1.25	2.79	1.07
1981	1.16	3.74	2.72	4.56	3.82	3.89	5.14	7.96	3.98	4.13	1.38	2.74
1982	5.73	4.95	4.17	1.83	2.11	7.16	4.1	5.55	5.55	1.63	4.76	2.55
1983	1.76	3.62	1.96	4.35	7.13	2.95	3.75	4.2	1.47	3.09	2.51	3.94
1984	2.21	4.99	4.16	3.55	7.28	2.43	0	1.98	2.91	4.39	4.47	2.46
1985	2.67	3.93	2.17	2.57	3.6	3.04	4.82	6.41	0	2.11	5.52	1.56
1986	1.6	5.41	1.94	1.07	3.56	0.72	0	0	3.49	3.17	5.33	4.16
1987	3.89	3.61	3.32	6.32	2.62	3.17	4.2	4.12	5.82	1.1	2.07	4.87
1988	2.66	2.29	2.38	3.06	2.67	2.32	4.97	2.27	4.56	1.88	4.77	3.25
1989	3.69	5.01	3.31	3.41	6.64	11.61	6.42	7.29	7.52	4.73	4.19	2.33
1990	3.14	5.12	3.59	4.06	6.17	3.7	4.21	3.55	3.05	3.59	1.56	6.34
1991	4	3.91	7.42	2.47	3.16	4.72	7.37	4.13	3.1	1.39	4.17	7.22
1992	2.87	2.29	4.28	2.64	3.9	3.67	7.02	2.97	1.12	2.27	3.29	3.99
1993	2.58	5.06	6.33	4.31	5.28	3.49	4.08	2.98	4.17	3.56	3.52	5.35
1994	4.39	7.84	10.29	4.79	3.04	4.83	6.18	6.55	1.58	2.1	1.91	1.44
1995	6.3	4.94	3.28	2.62	6.27	4.13	1.31	3.66	3.03	3.12	5.52	2.94
1996	7.08	4.57	5.93	3.77	5.7	3.85	5.48	3.97	5.89	2.68	6.16	4.34
1997	4.07	3.43	6.34	3.64	4.04	2.88	2.6	1.24	4.6	1.56	2.84	2.86
1998	5.89	3.67	4.1	9.24	5.04	7.2	3.56	3.3	1.81	1.46	1.63	5.67
1999	5.18	3.34	3.25	3.54	2.87	2.24	4.38	1.7	1.89	2.25	3.41	2.15
2000	3.43	2.45	4.01	5.16	2.17	3.94	8.73	4.25	3.41	0.5	1.61	2.89
2001	3.17	3.7	3.62	2.23	6.02	6.39	6.68	3.95	2.66	1.69	1.17	3.21
2002	5.74	1.37	8.78	2.9	4.07	2.54	7.65	5.19	3.73	3.73	4.63	4.04
2003	1.97	9.82	1.8	8.16	5.75	5.52	6.27	4.43	2.94	1.96	5.75	3.48
2004	4.33	2.5	4.22	3.52	8.75	7.05	3.19	3.56	8.15	2.67	4.35	5.09
2005	2.8	2.83	3.06	7.03	2.61	3.65	8.65	2.88	1.04	1.66	2.68	2.76
2006	3.93	1.89	2.31	6.05	5.46	0	0	0	0	0	0	0

Appendix B: Model equations

```
Debt_total(t) = Debt_total(t - dt) + (Debt__repayment) * dt
INIT Debt_total = 0
Debt__repayment = IF(Total__Debt>0)THEN(Loan_Payment)ELSE(0)
Funds(t) = Funds(t - dt) + (Monthly_Income - Operating_Costs - Debt__repayment -
Maint_Spending - Saving) * dt
INIT Funds = 200000
Monthly_Income = water__revenue
Operating_Costs =
(Usage*Proc_cost_per_gallon)+Admin_costs+(Usage*Dist_cost__per_gal)
Debt__repayment = IF(Total__Debt>0)THEN(Loan_Payment)ELSE(0)
Maint_Spending =
IF(Funds>=(Invest_Maint_15+Invest_Maint_30+Invest_Maint_45+Invest_Maint__over_
45))
THEN(Invest_Maint_15+Invest_Maint_30+Invest_Maint_45+Invest_Maint__over_45)
ELSE(IF(Funds>=Invest_Maint__over_45)THEN(Invest_Maint__over_45)
ELSE(IF(Funds>=Invest_Maint_45)THEN(Invest_Maint_45)
ELSE(IF(Funds>=Invest_Maint_30)THEN(Invest_Maint_30)
ELSE(IF(Funds>=Invest_Maint_15)THEN(Invest_Maint_15)
ELSE(0)))))
Saving =
IF(Maint_Spending=0)THEN(Short_term__assets)ELSE(0.0416*(Maint_Spending+Oper
ating_Costs)+Short_term__assets)
Reserves(t) = Reserves(t - dt) + (Saving - Addl_spending) * dt
INIT Reserves = Saving
Saving =
IF(Maint_Spending=0)THEN(Short_term__assets)ELSE(0.0416*(Maint_Spending+Oper
ating_Costs)+Short_term__assets)
Addl_spending = Reserves/12
Total__Debt(t) = Total__Debt(t - dt) + (Interest - Payoff) * dt
INIT Total__Debt = 30000000
Interest =
IF(Total__Debt>0)THEN((Initial_Loan__Amount*Interest__Rate)/Loan__Duration)ELS
E(0)
Payoff = IF(Total__Debt=0)THEN(0)ELSE(Debt__repayment)
Total_maint_costs(t) = Total_maint_costs(t - dt) + (Maint_Spending) * dt
INIT Total_maint_costs = 0
Maint_Spending =
IF(Funds>=(Invest_Maint_15+Invest_Maint_30+Invest_Maint_45+Invest_Maint__over_
45))
THEN(Invest_Maint_15+Invest_Maint_30+Invest_Maint_45+Invest_Maint__over_45)
ELSE(IF(Funds>=Invest_Maint__over_45)THEN(Invest_Maint__over_45)
ELSE(IF(Funds>=Invest_Maint_45)THEN(Invest_Maint_45)
ELSE(IF(Funds>=Invest_Maint_30)THEN(Invest_Maint_30)
ELSE(IF(Funds>=Invest_Maint_15)THEN(Invest_Maint_15)
```

```
ELSE(0)))))
Total_op__costs(t) = Total_op__costs(t - dt) + (Operating_Costs) * dt
INIT Total_op__costs = 0
Operating_Costs =
(Usage*Proc_cost_per_gallon)+Admin_costs+(Usage*Dist_cost__per_gal)
Admin_costs = 6250
average_water_bill = Per_capita_res_monthly_demand*Water_Rate
Dist_cost__per_gal = 0.0008
Initial_Loan__Amount = 32000000
Interest__Rate = 0.055
Loan__Duration = 680
Loan_Payment =
(Initial_Loan__Amount+(Initial_Loan__Amount*Interest__Rate))/Loan__Duration
Proc_cost_per_gallon = 0.0009
Short_term__assets = 5000
Total_costs = Debt_total+Reserves+Total_op__costs+Total_maint_costs
water__revenue = ((Gallons_consumed-
Water_consumption_by_neighbor)*Water_Rate)+(Water_consumption_by_neighbor*Sal
e_of__Water_Rate)
Sale_of__Water_Rate = GRAPH(TIME)
(0.00, 0.00), (68.0, 0.00), (136, 0.00), (204, 0.00), (272, 0.00), (340, 0.00), (408, 0.00),
(476, 0.00), (544, 0.00), (612, 0.00), (680, 0.00)
Water_Rate = GRAPH(TIME)
(0.00, 0.005), (68.0, 0.005), (136, 0.005), (204, 0.005), (272, 0.005), (340, 0.007), (408,
0.007), (476, 0.007), (544, 0.007), (612, 0.007), (680, 0.007)
Acct15(t) = Acct15(t - dt) + (Change15) * dt
INIT Acct15 = 0.85
Change15 = (Achievable15-Acct15)*Rate15
Acct30(t) = Acct30(t - dt) + (Change30) * dt
INIT Acct30 = Acct15
Change30 = (Achievable30-Acct30)*Rate30
```

References

Abrams, Len, 2000. “The Water Page: Sustainability.” Water Web Management Ltd, Surrey, UK. http://www.africanwater.org/sustainability.htm. (accessed April 3, 2007).

Appalachian Regional Commission. n.d. “Online Resource Center: Appalachian Regional Commission.” www.arc.gov (accessed February 5, 2007).

Carriker, Roy. 2000. “Water Wars: Water Allocation Law and the Apalachicola-Chattahoochee-Flint River Basin.” *Department of Food and Resource Economics, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences.* University of Florida. http://edis.ifas.ufl.edu/ (accessed April 4, 2007).

Cox, William; Shabman, Leonard. 1985. “A Proposal for Improved Management of Interjurisdictional Water Transfer.” *Virginia Water Resources Research Center*, Virginia Polytechnic Institute and State University. Blacksburg, Virginia. http://www.vwrrc.vt.edu/pdf/sr19.pdf

Department of Sustainable Development. 2006. Organization of American States. http://www.oas.org/dsd/environmentlaw/trade/waterpolicy.htm (accessed March 23, 2007).

Dewberry and Davis.

> 1997. “Wise County Water and Sewer Study.” Lenowisco Planning District Commission, Duffield, Virginia. http://www.lenowisco.org/PDF%20Files/Wise%20County%20604b.pdf (accessed January 27, 2007).
>
> 2001. “New Big Cherry Dam, Big Stone Gap, Virginia: Technical Memoranda.” GEI Consultants, Englewood Colorado.

Gleick, Peter. 1998. “Water in Crisis: Paths to Sustainable Water Use.” *Ecological Applications*, Vol. 8, No. 3. (Aug., 1998), pp. 571-579. http://links.jstor.org/sici?sici=1051-0761%28199808%298%3A3%3C571%3AWICPTS%3E2.0.CO (accessed February 13, 2007).

Halich, Greg; Stephenson, Kurt. “The Effectiveness of Drought Management Programs in Reducing Residential Water-Use in Virginia.” *Virginia Water Resources Research Center*, Virginia Polytechnic Institute. Blacksburg, Virginia.

Hampton, Gary. “Big Stone Gap Accountability” Excel spreadsheet. April 20, 2007, 4:13 P.M. Personal Communication.

Iglesias, Eva; Garrido, Alberto; and Gomez-Ramos. 2007. "Economic drought management index to evaluate water institutions' performance under uncertainty." *The Australian Journal of Agricultural and Resource Economics.* 51: 17-38.

Lane, Bobby.

"BSG All System Use and Income, New Rates," Excel Spreadsheet. May 1, 2007, 12:59 PM. Personal Communication.

"BSG Presentation Workshop," Excel Spreadsheet, December 5, 2006. May 1, 2007, 12:59 PM. Personal Communication.

"Project Planning and Cost Estimate," Excel Spreadsheet. May 1, 2007, 12:59 PM. Personal Communication.

Lane Engineering.

2007. "Big Stone Gap Preliminary Engineering Report, BRL revision." Town of Big Stone Gap, Big Stone Gap, Virginia.

2004. "Big Stone Gap-Norton Water System Interconnection Preliminary Engineering Report." Town of Big Stone Gap, Big Stone Gap, Virginia.

2001. "Eastern Lee Water System Preliminary Engineering Report." Lee County Public Service Authority. Jonesville, Virginia.

1999. "Jasper Community Water System Preliminary Engineering Report." Lee Public Service Authority. Jonesville, Virginia.

Passell, Howard; Tidwell, Vincent; Conrad, Stephen; Thomas, Richard; and Roach, Jessee. 2003. "Cooperative Water Resources Modeling in the Middle Rio Grande Basin." *Sandia National Laboratories*, Albuquerque, NM. http://www.sandia.gov/water/docs/ModelingSANDrprtFINAL.pdf (accessed March 12, 2007).

Pimentel, David; Houser, James; Preiss, Erika; White, Omar; Fang, Hope; Mesnick, Leslie; Barsky, Troy; Tariche, Stephanie; Schreck, Jerrod; and Alpert, Sharon. 1997. **"**Water Resources: Agriculture, the Environment, and Society". *BioScience*, 47:2. 97-106. American Institute of Biological Sciences. http://links.jstor.org/sici?sici=0006-3568%28199702%2947%3A2%3C97%3AWRATEA%3E2.0.CO%3B2-D (accessed April 4, 2007).

Raucher, Robert; Harrod, Megan; and Hagenstad, Marca. 2004. "Consolidation for Small Water Systems: What are the Pros and Cons?" *Rural Water Partnership Fund White Paper*, NRWA (National Rural Water Association). www.nrwa.org (accessed April 3, 2007).

Sandia Corporation. 2005. “Sandia National Laboratories Water Portal: A Collaborative Water Monitoring, Modeling and Management Environment.” Sandia National Laboratories online. https://waterportal.sandia.gov/demo.html (accessed October 1, 2006).

Shabman, Leonard; Younos, Tamim; and Poff, Judy. 1996. “Proceedings of Southwest Virginia Water Symposium, 1996.” *Virginia Water Resources Research Center*. Virginia Polytechnic Institute and State University, Blacksburg, Virginia. http://www.vwrrc.vt.edu/publications/swvawatersym96.htm#swtoc. (accessed May 19, 2007).

Sterman, John. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World.* McGraw-Hill, Lexington MA.

Southeast Regional Climate Center. n.d. “Wise, Virginia monthly climate summary.” http://cirrus.dnr.state.sc.us/cgi-bin/sercc/cliMAIN.pl?va9215 (accessed October 12, 2005).

Town of Big Stone Gap. 2005. “Town Meeting Minutes.” http://www.bigstonegap.org/twngovt/minutes.htm. (accessed October 23, 2005).

Thompson and Litton Engineers, Architects, and Planners. “Virginia Coalfields Regional Water Study.” Lenowisco Planning District. November 1998. http://www.lenowisco.org/PDF%20Files/Coalfieldwater.PDF

United States Geological Survey. 2006.

> 2006.”USGS Washington Water Science Center.” http://wa.water.usgs.gov/outreach/rain.htm. (accessed February 5, 2007).
>
> 2006. “USGS Surface Water Monthly Statistics for the Nation.” Water gauge number USGS 03531500 Powell River near Jonesville, Virginia, monthly discharge in cubic feet per second, 1931-2006. (accessed February 5, 2007).

Water Resources Management Program, University of Wisconsin. 2000. “Dam Repair or Removal: A Decision-Making Guide.” University of Wisconsin—Madison. http://www.ies.wisc.edu/research/wrm00/eductime.htm. (accessed February 2, 2007).

Wise County Clerk of Court. n.d. Wise County, Virginia Interactive Geographic Information System. http://arcims2.webgis.net/wise/default.asp. (accessed February 7, 2007).

Virginia Department of Health. 2006. “Remote Area Medical Media Kit.” Virginia Department of Health newsroom website. http://www.vdh.state.va.us/news/RAM_Visit_Media_Kit/ (accessed May 19, 2007).

Young, Micki Melinda. 2002. “Cooperative Infrastructures for Small Water Systems: A Case Study.” *Virginia Water Resources Research Center*, Virginia Polytechnic Institute and State University. Blacksburg, Virginia. http://www.vwrrc.vt.edu/publications/Young%20Special%20Report.pdf

Younos, Tamim; Bohdan, Rebecca; Anderson, Eric; Ramsey, Kelly; Cook, Nicole; Ross, Blake; Dillaha, Theo. 1998. “Evaluation of Rooftop Rainfall Collection—Cistern Storage Systems in Southwest Virginia.” *Virginia Water Resources Research Center*, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. http://www.vwrrc.vt.edu/pdf/sp3-1998.pdf

Younos, Tamim; Wright, Benjamen; Reaves, Dixie. 1999. “The Potential for Developing Mine Cavity Water for Water Supplies: Institutional and Water Quality Issues.” *Virginia Water Resources Research Center*, Virginia Polytechnic Institute and State University. Blacksburg, Virginia. http://www.vwrrc.vt.edu/publications/Special%20Report%2012-1999.pdf