THESIS

A COST-BENEFIT ANALYSIS OF PREVENTATIVE MANAGEMENT FOR ZEBRA AND QUAGGA MUSSELS IN THE COLORADO-BIG THOMPSON SYSTEM

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY CATHERINE M. THOMAS ENTITLED A COST-BENEFIT ANALYSIS OF PREVENTATIVE MANAGEMENT FOR ZEBRA AND QUAGGA MUSSELS IN THE COLORADO-BIG THOMPSON SYSTEM BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

A COST-BENEFIT ANALYSIS OF PREVENTATIVE MANAGEMENT FOR ZEBRA AND QUAGGA MUSSELS IN THE COLORADO-BIG THOMPSON SYSTEM

The introduction of zebra mussels (*Dreissena polymorpha*) and quagga mussels (*D. bugensis*) to the western U.S. has water managers considering strategies to prevent or slow their spread. In Colorado, the Department of Wildlife (CDOW) has implemented a statewide mandatory boat inspection program. This study builds a bioeconomic model to simulate a mussel invasion and associated control costs for a connected Colorado water system, and compares the costs of the CDOW boat inspection program to the expected reduction in control costs to infrastructure. Results suggest that preventative management is effective at reducing the probability that mussels invade, but the costs may exceed the benefits of reduced control costs to infrastructure. The risk of invasion, the spatial layout of a system, the type of infrastructure, and the level of control costs associated with a system are key variables in determining net benefits of preventative management.

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INTRODUCTION

Zebra and quagga mussels are fresh water invaders that have the potential to cause severe ecological and economic damage. It is estimated that mussels cause $1 billion dollars per year in damages to water infrastructure and industries in the United States (Pimentel et al., 2004). Following their introduction to the Great Lakes in the late 1980s, mussels spread rapidly throughout the Mississippi River Basin and the Eastern U.S. The mussel invasion in the West is young. Mussels were first identified in Nevada in 2007, and have since been identified in California, Arizona, Colorado, Utah, and Texas.

Western water systems are very different from those found in the East. The rapid spread of mussels through the eastern system was facilitated by connected and navigable waterways. Western water systems are less connected and are characterized by man-made reservoirs and canals. The main vector of spread for mussels in the West is overland on recreational boats (Bossenbroek et al., 2001). In response to the invasion, many western water managers have implemented preventative management programs to slow the overland spread of mussels on recreational boats. In Colorado, the Colorado Department of Wildlife (CDOW) has implemented a mandatory boat inspection program that requires all trailered boats to be inspected before launching in any Colorado water body. The objective of this study is to analyze the costs and benefits of the CDOW boat inspection program in

Colorado, and to identify variables that affect the net benefits of preventative management.

Predicting the potential economic benefits of slowing the spread of mussels requires integrating information about mussel dispersal potential with estimates of control costs (Keller et al., 2009). Uncertainty surrounding the probabilities of establishment, the timing of invasions, and the damage costs associated with an invasion make a simulation model an excellent tool for addressing "what if" scenarios and shedding light on the net benefits of preventative management strategies. This study builds a bioeconomic simulation model to predict and compare the expected economic costs of the CDOW boat inspection program to the benefits of reduced expected control costs to water conveyance systems, hydropower generation stations, and municipal water treatment facilities. The model is based on a case study water delivery and storage system, the Colorado-Big Thompson system. The Colorado-Big Thompson system is an excellent example of water systems in the Rocky Mountain West. The system is nearly entirely man-made, with all of its reservoirs and delivery points connected via pipelines, tunnels, and canals. The structures and hydropower systems of the Colorado-Big Thompson system are common to other western water storage and delivery systems, making the methods and insight developed from this case study transferable to other western systems.

The model developed in this study contributes to the bioeconomic literature in several ways. Foremost, the model predicts the spread of dreissena mussels and associated damage costs for a connected water system in the Rocky Mountain West. Very few zebra mussel studies have focused on western water systems. Another distinguishing factor is the simultaneous consideration of spread from propagules introduced by boats and by flows. Most zebra mussel dispersal models consider boater movement patterns combined with limnological characteristics as predictors of spread. A separate set of studies have addressed mussel spread via downstream flows. To the author's knowledge, this is the first study that builds a zebra mussel spread model that specifically accounts for propagule pressure from boat introductions and from downstream flow introductions. By modeling an entire connected system, the study highlights how the spatial layout of a system, the type of infrastructure and level of control costs associated with a system, and the risk of invasion within a system affect the benefits of preventative management.

This report is presented in five chapters. The first chapter provides background information including a history of the zebra mussel invasion in the U.S. and in the West, and details about the Colorado preventative management program and the Colorado-Big Thompson system. The chapter also includes a literature review of mussel dispersal models and economic studies that address control costs and preventative management for aquatic invasive species. Chapter 2 presents the methodological approach used to analyze the costs and benefits of preventative management in the Colorado-Big Thompson system and provides details of the bioeconomic simulation model used to predict invasion patterns and the net benefits of preventative management. Results of the analysis and sensitivity testing of model parameters are presented in Chapter 3. Chapter 4 provides a summary of the analysis and conclusions. A discussion of the limitations of the model and areas for future research is presented in Chapter 5.

CHAPTER 1: BACKGROUND INFORMATION

1.1 History of the Invasion

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*) are invasive mollusks native to an area in the Ukraine and Russia near the Black and Caspian Seas. The species is believed to have been introduced to U.S. waters in the late 1980s through ballast water discharged from transatlantic freighters. Zebra mussels were first identified in Lake St. Clair and Lake Erie in 1988, and quagga mussels were discovered in 1991 (Ohio Sea Grant, 1997). Following their introduction to the Great Lakes in the late 1980s, zebra mussels rapidly expanded their North American range. By 1991, only 3 years after the discovery of zebra mussels in Lake Saint Claire, the invader had already spread throughout the Great Lakes and through much of the Mississippi River Basin.

The rapid spread of dreissena mussels is attributed to their prolific reproduction and their ability to disperse. Both species reproduce rapidly and are very successful invaders. A mature female mussel can produce as many as one million eggs per season. Eggs are fertilized in the water column and develop into young mussels within a few days. Young mussels, called veligers, are microscopic and invisible to the naked eye. In this floating larval stage, veligers can be carried by water currents, spreading to adjacent waterways. Veligers can also be carried overland in the ballast water of recreational boats or on foliage entangled in boat motors. Mature mussels generate a tuft of fibers called byssal threads that they use to attach to hard surfaces. Dreissena can attach to any non-toxic hard surface including boats and trailers, and are able to live out of water for several days (Ohio Sea Grant, 1997). Thus, zebra and quagga mussels can spread downstream to adjacent waterways in their veliger stage and can hitchhike to inland waters via transport on boats and boat trailers in their adult or veliger stages.

Since their introduction in the late 1980s, zebra and quagga mussels have spread through much of North America. However, their expansion has mostly been limited to the connected waters of the Midwest and Northeast; see Figure 1 (USGS, 2009). The spread of mussels to inland lakes and the Western U.S. has been much slower (Kraft & Johnson, 2000).

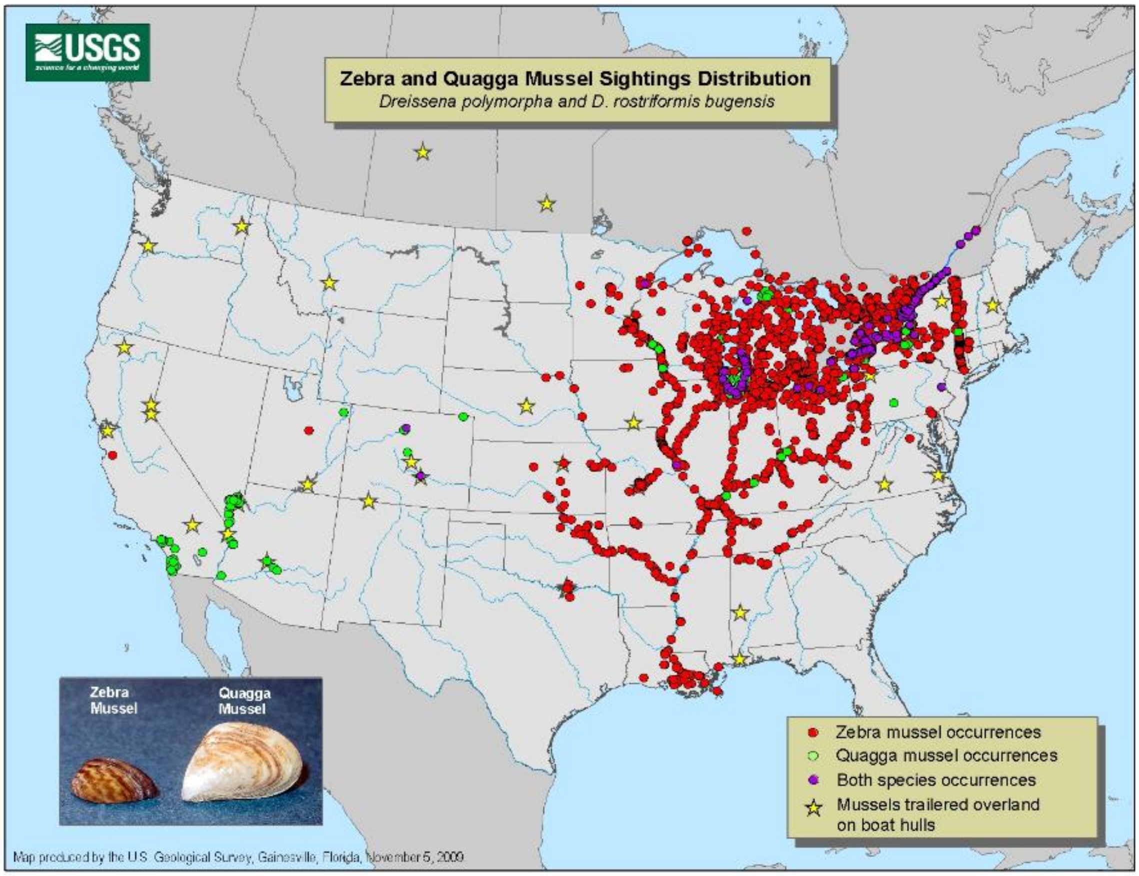

Figure 1: U.S. mussel distribution as of November 2009, USGS

Dreissena invasions can cause severe economic and ecological damage. Adult mussels attach to all types of structures and form dense mats up to one foot thick (USGS, 2000). These mats can clog water pipes and damage hydrologic infrastructure. Water-delivery structures, dams, power plants, and water treatment facilities can all incur large costs either from removing mussels from their systems or from suffering lost output (Deng, 1996). It is estimated that invasive mollusks cost the nation about $1 billion per year, mostly in damages and control costs associated with electric power plants and water supply facilities (Pimentel et al., 2004). Dreissena also affect natural ecosystems through their feeding behavior; they are filter feeders and process up to one gallon of water per mussel per day.

They remove large amounts of phytoplankton from the water, reducing the food supply for larval fish and other invertebrates (Ohio Sea Grant, 1997). The resulting increase in competition for food can have negative effects on populations of some animals and on biodiversity (USGS, 2000). The ecological effects caused by mussel invasions directly affect human enjoyment and recreational activities. Specifically, the decline of some species of fish may result in lost value for anglers who target those species. Beach recreators and lakeside homeowners may have welfare losses due to sharp shells from dead mussels that wash to shore, covering swimming areas and beaches. Mussels increase the clarity of a water body and may increase the beauty of a lake, which could be a benefit for some people.

1.2 The Invasion in Colorado

The rapid invasion of the Midwest and the East was facilitated by connected and navigable waterways. Isolated from the eastern system, western waterways were believed to be free of dreissena mussels until 2007. In 2007, Lake Mead in Nevada became the first water body west of the 100th Meridian to have a confirmed dreissena population. Although identified in 2007, quagga mussels were established in Lake Mead at least two years before they were identified (Stokstad, 2007). Within one month of finding quaggas in Lake Mead, mussels were confirmed downstream in the Colorado River and in Lake Havasu (Stokstad, 2007). Dreissena veligers were first identified in Colorado waters in January of 2008, with both zebra and quagga mussel veligers identified in Pueblo Reservoir and in Grand Lake. As of this report, Jumbo Lake, Lake Granby, Shadow Mountain Reservoir, Tarryall Reservoir, and Willow Creek Reservoir are all positive for quagga mussel veligers

(USGS, 2009). To date, no adult mussels have been identified in the state. Figure 2 shows the progression of the mussel invasion in the West (USGS, 2009).

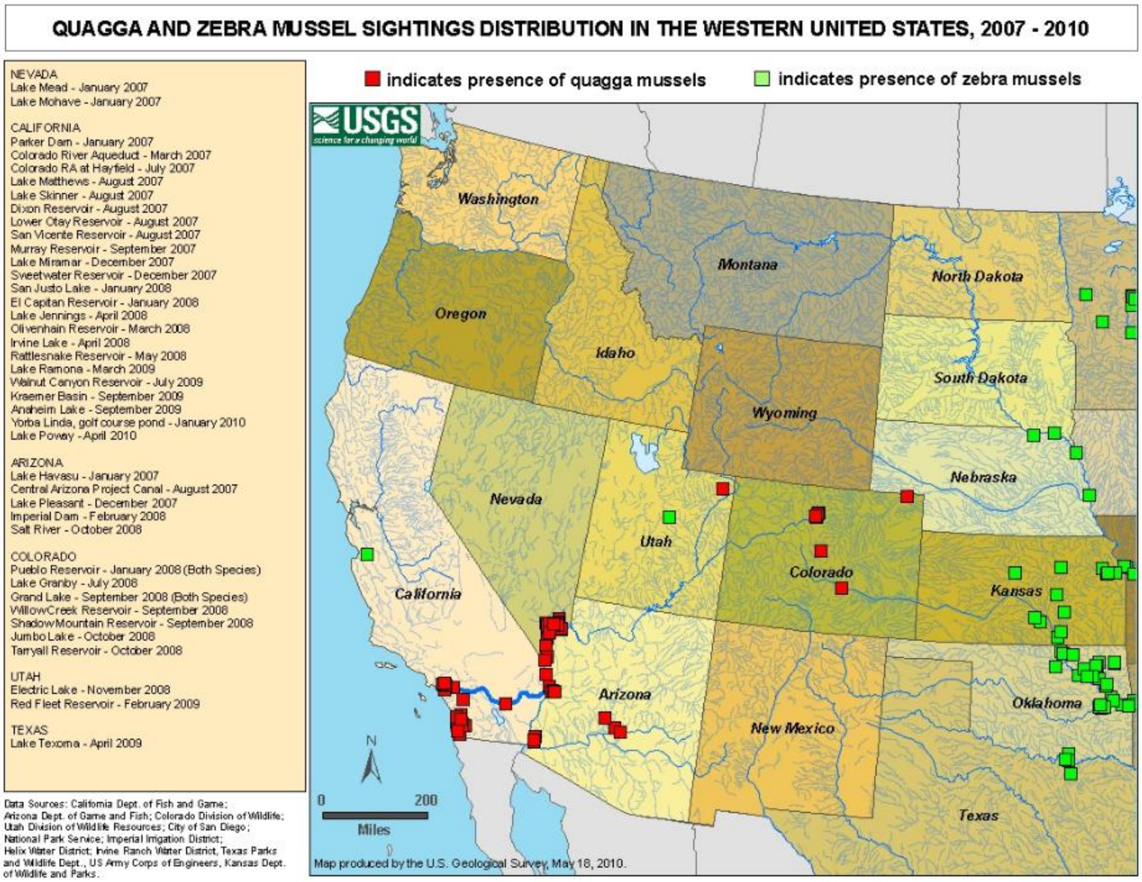

Figure 2: Western distribution of zebra and quagga mussels, USGS 2009.

1.3 Managing for Mussels in Colorado

In response to the identification of zebra and quagga mussels in the state, the Colorado Department of Wildlife (CDOW) implemented the Colorado Zebra/Quagga Mussel Management Plan (ZQM Plan) in 2009. The ZQM Plan is "a statewide collaborative effort to detect, contain, and substantially reduce the risk of spread and further infestation by zebra/quagga mussels in Colorado" (Colorado Division of

Wildlife, 2009). The ZQM Plan focuses on early detection and rapid response, containment, prevention and education/outreach. The primary component of the plan is a mandatory watercraft inspection and decontamination program to prevent the spread of mussels overland on recreational watercraft.

As of 2009, boat inspections are required prior to launch in most reservoirs and lakes in the state. Resident boaters must pass a state-certified boat inspection if they plan to launch on a reservoir where inspections are required or if they have traveled outside of the state or have launched on any of the Colorado lakes or reservoirs where mussels have been detected. Out-of-state boaters are required to pass a state-certified boat inspection before launching in any Colorado waterway. As part of the standard boat inspection, boaters are asked what state they are from and where and when they last boated. Boats that have been used out-of-state or in infested waters within the last 30 days or are dirty are considered high-risk, and are required to undergo a high-risk inspection and may be required to undergo a decontamination process. In addition to pre-launch inspections, the program also requires boats exiting dreissena positive waters to be cleaned, drained, and dried upon leaving the water.

Watercraft inspections are based on the Pacific Marine Fisheries Commission standardized watercraft inspection and decontamination training. All watercraft inspectors are required to attend a state certification course in which they learn about mussel biology, vectors of spread, methods for detecting mussels, and methods for decontaminating boats. The goal of the CDOW boat inspection program is to reduce the number of potentially infested boats that enter Colorado water bodies, thus reducing the risk of spread in the state.

1.4 Overview of the Colorado-Big Thompson System

The Colorado-Big Thompson system is a prime case study for investigating the possible implications of a mussel invasion and the effects of preventative management in Colorado. The system consists of five headwater reservoirs on the Western Slope of Colorado: Windy Gap Reservoir, Willow Creek Reservoir, Lake Granby, Shadow Mountain Reservoir, and Grand Lake. With the exception of Windy Gap Reservoir, all of these reservoirs have tested positive for dreissena veligers. Although no adult mussels have been found in any of the reservoirs, managers of the project and stakeholders that use Colorado-Big Thompson water are concerned about the implications of mussels in the system. The Colorado-Big Thompson system is comprised of the reservoirs and infrastructure that make up the Colorado-Big Thompson Project and the Windy Gap Project, and the municipal water treatment facilities that use Colorado-Big Thompson and Windy Gap water.

The Colorado-Big Thompson Project is the largest transmountain water diversion project in Colorado. Water from Colorado's Western Slope is conveyed through a series of 12 reservoirs and 5 hydropower plants on its journey across the Continental Divide. The system provides supplemental water to 30 cities and towns and over 600,000 acres of agricultural land on the Eastern Slope of the state (Northern Colorado Water Conservancy District, 2010). The Windy Gap Project pumps water from Windy Gap Reservoir to Lake Granby, where it is stored and delivered through the Colorado-Big Thompson Project reservoirs and infrastructure. The Bureau of Reclamation and the Northern Colorado Water Conservancy District each own portions of the infrastructure and jointly manage the system. Figure 3 shows a diagram of the Colorado-Big Thompson system, and highlights the major infrastructure and municipal delivery points in the system.

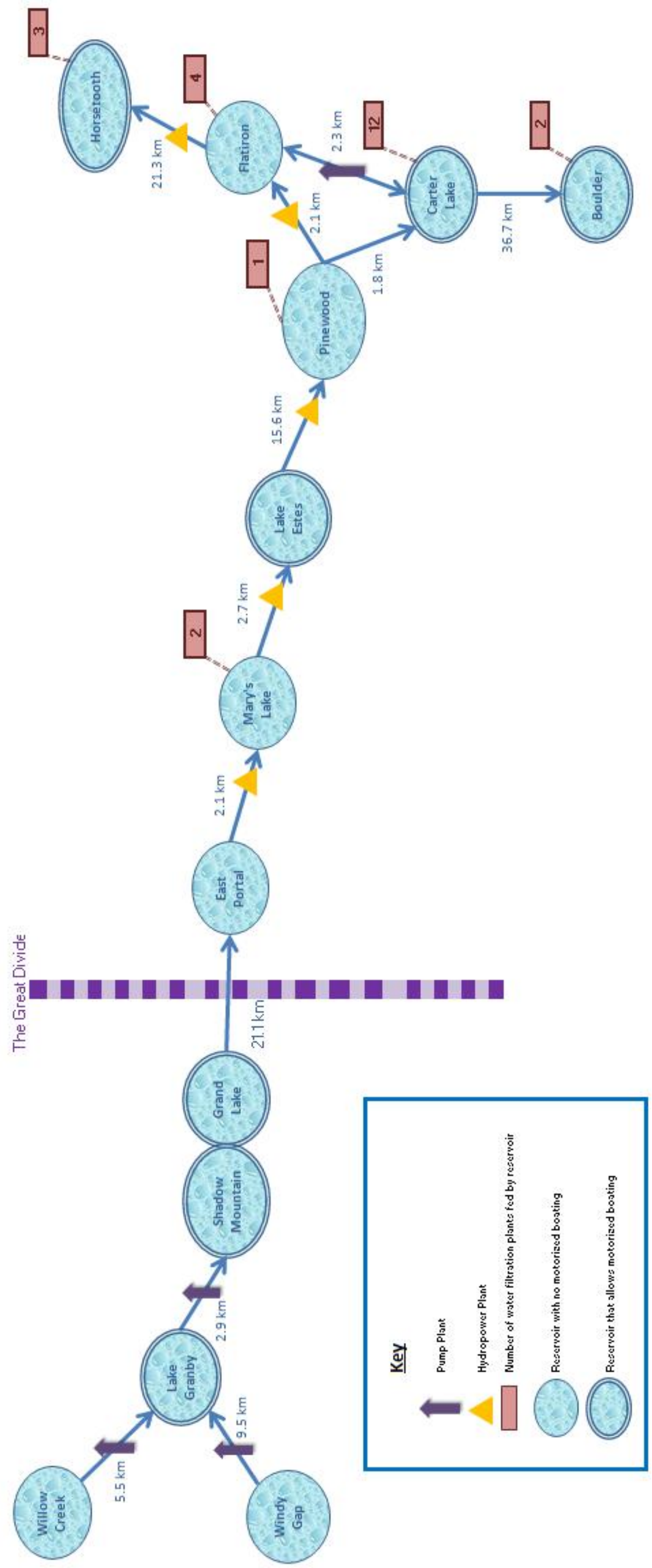

Figure 3: Schematic of the Colorado-Big Thompson system

1.4 Dreissena Dispersal Models

The large economic and ecological costs resulting from zebra mussel invasions have spurred a large field of research on the environmental limits and potential distribution of mussels. Models that predict the spread of mussels do so based on a combination of the biological and environmental requirements of dreissena and on potential vectors of spread.

1.4.1 Environmental Factors Affecting Mussel Spread

Levels of calcium, pH, alkalinity, temperature, dissolved oxygen, Secchi depth, nutrients, and available substrate have all been found to be important predictors of dreissena habitat suitability (Ramcharan et al., 1992; Mellina & Rasmussen, 1994; Cohen & Weinstein, 2001; Drake & Bossenbroek, 2004; Whittier et al., 2008; Claudi & Prescott, 2009). Several studies address the possible spread of dreissena based solely on environmental factors.

In 2004, Drake and Bossenbroek developed a model to predict the potential distribution of zebra mussels in the United States using biological and geological variables including average annual temperature, bedrock geology, elevation, flow accumulation, frost frequency, max and min temperatures, precipitation, slope, solar radiation, and surface geology. Of particular interest to this study are Drake and Bossenbroek's predictions for the Rocky Mountain region. Two of the three models developed by Drake and Bossenbroek (2004) predict that zebra mussels will not spread to the Rocky Mountain region. The third model, which includes all of the listed variables with the exception of the elevation variable, predicts the Eastern

Plains of Colorado to be at high risk of mussel infestation, but still predicts the mountainous regions of the state to have very low probabilities of infestation. At the time these models were developed, the third model was deemed the least reliable of the three, and the consensus was that the Rocky Mountain States were very unlikely candidates for mussel infestation.

Whittier et al. (2008) use calcium concentrations to assess the risk of dreissena invasions for ecoregions across the contiguous U.S. Using calcium concentration data from over 3000 stream and river sites across the nation, they define risk of dreissena invasion based on calcium concentration. Ecoregions with average calcium concentrations below 12 mg/L are defined as very low risk, 12-20 mg/L as low risk, 20-28 mg/L as moderate risk, and greater than 28 mg/L as high risk. In their assessment, the Eastern Plains of Colorado have a high risk of dreissena invasion based on calcium concentration, and the risks to the mountainous regions of the state are highly variable.

Overall, many environmental variables affect the risk of dreissena spread, and there is mixed evidence on the risk of a dreissena invasion in Colorado. Based on calcium concentrations alone, Whittier et al. (2008) find that much of the state is considered to be at high risk of a dreissena invasion. However, the study by Drake and Bossenbroek (2004) suggests that Colorado has a very low chance of invasion.

1.4.2 Boater Movement Models

Regardless of environmental suitability, in order for mussels to invade, they must first be transported to new locations. In the early years of the North American invasion, mussels were primarily transported through navigable waterways. The connected system of waterways in the Midwestern and Eastern U.S. were quickly inhabited, but the spread of mussels to inland waters and the Western U.S. has been slower and is still ongoing (Kraft & Johnson, 2000).

Overland transportation of mussels on recreational boats is believed to be the primary vector for zebra mussel dispersion into inland lakes and across large distances. A substantial number of studies attempt to predict mussel dispersal through boater movement patterns (Padilla et al., 1996; Bossenbroek et al., 2001; Leung et al., 2006; Bossenbroek et al., 2007; Leung & Mandrak, 2007; Timar & Phaneuf, 2009). Two types of boater movement models are used to predict mussel dispersal: gravity models, and random utility models (RUM models). Gravity models predict the flow of individuals that move from an origin to a destination based on the distance between the origin and the destination and the attractiveness of the destination. RUM models predict boater movement based on a boater's utility maximizing choice of one lake from a set of many lakes. Models to predict the movement of recreational boaters can be paired with biological models for habitat suitability to forecast where invasions are likely to occur (Leung et al., 2006).

Bossenbroek et al. (2001) develop a gravity model to forecast zebra mussel dispersal to inland lakes in Illinois, Indiana, Michigan, and Wisconsin. They assume that boat pressure at each lake is a function of the number of registered boaters in a county, the distance between the county and the lake, and the surface area of the lake. Their model estimates the potential for colonization based on three factors:

the probability of a boat traveling to an infested lake, the probability of that same boat traveling to an uninfested lake on a subsequent trip, and the probability that zebra mussels become established in a water body once they have been introduced. They determine that a single infested boat has a probability of 0.0000411 of establishing a zebra mussel colony, which translates to a 3.5% chance that a water body becomes established when visited by 850 infested boats. Spatially, they find that zebra mussel spread is characterized by long distance jumps and subsequent isolated centers of distribution.

Differing from the majority of gravity based boater movement models, Timar and Phaneuf (2009) use a random utility model (RUM model) to forecast boater behavior and resulting mussel spread based on utility theory. With their RUM model, Timar and Phaneuf are able to address how boaters behave, and thus how boater movement patterns change in the face of policies designed to limit the spread of aquatic invasive species. They find that explicitly accounting for behavioral responses has a dramatic effect on the predicted effectiveness of polices intended to reduce invasion threats. Overall, their findings suggest that behavioral adjustments to preventative management policies change the relative risks of invasion in a region. Boaters faced with inspections or fees may substitute to nearby water bodies that do not require inspections, thus increasing the risk of infestation of those water bodies. The boat inspection program in Colorado is statewide; therefore, boaters have very little opportunity to substitute away from lakes that require inspections. Unlike the finding by Timar and Phaneuf, behavioral adjustments are not expected to have a significant impact on the effectiveness of the CDOW boat inspection program in Colorado.

Most spread models based on boater movement use data from the Midwest. There are currently no boater movement models that predict movement within Colorado. Developing such a model is beyond the scope of this project; thus, the spread model developed for the Colorado-Big Thompson system does not specifically address boater movement patterns. Reservoirs in the system are assumed to have constant visits over time, and the percent of infested boats visiting each reservoir is assumed to be equal throughout the system. The simplifying assumptions made about boat pressure are expected to be relatively accurate, but the model could be improved by explicitly accounting for boater movement patterns with a gravity model or a RUM model.

1.4.3 Combining Boater Movement Models with Environmental Factors Affecting Mussel Spread

To predict mussel spread, boater movement models generally incorporate environmental variables that limit dreissena colonization. Dichotomous classifications of the habitability of lakes are common among models to predict the dispersal of mussels. For example, Bossenbroek et al. (2001) use calcium and pH data to determine if a lake is suitable for mussels. They develop a suitability score for each lake based on the model developed by Ramcharan et al. (1992), and deem lakes with scores below a threshold as uninhabitable.

Leung and Mandrake (2007) take a different approach and treat the habitability of a lake as a probability. Similar to Bossenbroek et al, Leung and Mandrake use a gravity model to predict boater movement from infested to uninfested lakes to develop probabilities that uninfested lakes become established. They combine these probabilities with the probability that a lake is habitable to develop joint probabilities of infestation. Leung and Mandrake's approach to modeling invasibility as a probability rather than a dichotomous choice is utilized in the model developed for the Colorado-Big Thompson system. In a dichotomous choice model, such as that used in Bossenbroek et al. (2001), many of the reservoirs in the Colorado-Big Thompson would be omitted from the set of invasible lakes based on low calcium levels. Modeling invasibility as a probability allows for a positive probability of infestation in the Colorado-Big Thompson reservoirs.

1.4.4 Downstream Flow Models

Several studies address dispersal through connected waterways. In a study of coupled lake-stream systems, Bobeldke et al. (2005) found that lakes downstream from invaded lakes were more likely to be infested than lakes downstream from non-invaded lakes and that the probability of a downstream lake becoming invaded decreases with the distance between the lakes. Specifically, they found that downstream lakes connected by streams to an upstream invaded lake were more likely to be invaded with zebra mussels (79%) than lakes upstream from an invaded lake (32%) or lakes that were not connected to an invaded lake (7%).

Bobeldke et al. (2005) also determine that a source-sink spread model is the best type of model to predict downstream spread of dreissena. Source-sink models assume that the probability of spread to a downstream lake depends on the population size in an upstream source and the likelihood of survival during transit. Source-sink dynamics also assume that mussels can settle in a stream but cannot reproduce and develop self-sustaining populations in a stream. Consistent with the source-sink model of lake-stream spread, Horvath et al. (1996) also find that mussel populations in streams are not self-sustaining and rely on an upstream source of propagules. This is an important consideration in modeling mussel movement between water bodies. Assuming source-sink dynamics, in order for mussels to invade a downstream water body, a substantial number of propagules must survive the complete journey from an upstream infested water body to a downstream uninfested water body.

Several studies address veliger mortality in transit. Horvath and Lamberti (1999) find that the percent of veligers surviving downstream passage declines exponentially with distance. Overall, findings suggest that distance downstream, turbulence, and the presence of wetlands and vegetation all affect veliger transport and mortality (Horvath & Lamberti, 1999; Rehmann et al., 2003; AMEC Earth and Environment, 2009). The spread model developed for the Colorado-Big Thompson allows for spread through flows and assumes a source-sink model of spread and exponential decay with distance traveled downstream.

1.5 Economic Studies

Relatively few studies focus on the economic implications of dreissena invasions. Many of the available economic studies are retrospective in nature, assessing the control costs that water users have incurred in the past (Hushek et al., 1995; Deng, 1996; O'Neill, 1997; Park & Hushak, 1999; Connelly et al., 2007). Several studies use available cost data to forecast potential control costs for areas that have not been invaded but may become so in the future (Rossi et al., 2004; Phillips et al., 2005). An emerging literature has taken predictive studies a step further by combining historic cost data with spread models to develop bioeconomic models to predict future economic costs and ramifications of policy alternatives (Leung et al., 2002; Lee et al., 2007; Keller et al., 2008; Warziniack et al., Draft). The model developed for the Colorado-Big Thompson system is an example of a bioeconomic model, and utilizes data from control cost surveys to intertemporally predict expected control costs based on simulated spread.

1.5.1 Control Cost Surveys

In 1995, a nationwide study of the costs to raw water dependent infrastructure was undertaken by the New York Sea Grant and the National Zebra Mussel Information Clearinghouse to estimate the economic impact of zebra mussels to North America (O'Neill, 1997). The Clearinghouse study is one of the most referenced sources of zebra mussel damage costs. Of the survey respondents, 339 facilities reported zebra mussel expenditures totaling $69,070,780 over the period 1989 through 1995, with average per facility expenditures of $205,570 for the 6-year period. Expenditures varied dramatically between and within industry categories, with expenditures on nuclear power plants accounting for over a quarter of total expenditures across all industries.

In 2004, Connelly et al. administered a follow up survey to the 1995 Clearinghouse survey (Connelly et al., 2007). This second survey focused on the two industries known to incur the greatest zebra mussel expenses: drinking water treatment facilities and electric power generation facilities. Data on the costs of implementing zebra mussel control or prevention measures was collected via a mail survey of all identifiable electric generation and drinking water treatment companies in the U.S. and Canada within the range where zebra mussels were known to be present. Forty-six percent of respondents had some zebra mussel related expenditures between 1989 and 2004, with the percentage lower for electric power generation facilities (32%) than for drinking water facilities (49%). Connelly et al. estimate total economic costs for electric generation and water treatment facilities through 2004 at $267 million with a 95% confidence interval of $161 million to $467 million. On average, per facility costs remained at about $30,000 per facility per year in the latter years, down from $44,000 per facility per year in the early years. The authors hypothesize that the decline in expenditures is likely due to increased knowledge about zebra mussels and an increased tendency to be proactive. Overall, the results of the study indicate that early predictions of the economic damages from zebra mussels were overestimates.

A 1994 survey of raw water users conducted by Deng and the Ohio Sea Grant is another oft-referenced source of zebra mussel expenditure data (Deng, 1996).

Raw water users were asked to report any costs incurred due to the presence of zebra mussels for the six-year period between 1989 and 1994. Costs include monitoring, treatment and maintenance costs, and production and revenue losses. Respondents include private utilities, public utilities, municipal water facilities, and other industries using raw water for cooling. Average reported expenditures per facility for the five-year period were $21,031 for private utilities, $13,023 for public utilities, $17,542 for municipal water treatment facilities, and $9183 for other industries.

1.5.2 Control Cost Forecasts

Rossi et al. (2004) use data from the 1995 Clearinghouse study and the 1994 Deng study to estimate the potential costs of a hypothetical zebra mussel invasion in Florida. Using data from each survey, they calculate two estimates of economic impacts to water users in Florida. The first estimate uses average zebra mussel control costs calculated from total expenditures reported in the Clearinghouse study, and the second estimate uses volume based variable and total cost values calculated by Deng. To generate a forecast of possible costs to the state, Rossi et al. multiply cost estimates for facilities by the number of facilities in the area. This assumption implies that all vulnerable facilities in the state would incur costs, and is thus an upper bound of potential control costs.

Phillip's et al. (2005) use available cost data from infested hydropower facilities to forecast the potential control costs of a hypothetical mussel invasion in a system of thirteen hydropower facilities in the Columbia River Basin. Their research finds that the costs of installing zebra mussel control systems at hydroelectric facilities vary greatly from facility to facility. Phillips et al. (2005) base their estimates of cost on the assumption that hydroelectric facilities will install NaOCl (bleach) injectors and will paint their trash racks with anti-fouling paint. They estimate the average cost of installing a bleach injection system at $62,599 per generator, and the average cost of antifouling paint at $81,000 per generator. Overall, they estimate that a full invasion of the system of 13 hydropower plants in the Columbia River Basin would cost $23,621,000.

In their forecasts of control costs for a hypothetical invasion, Rossi et al. (2004) and Phillips et al. (2005) estimate costs to a region based on a full invasion of mussels. Mussel invasion are not likely to be uniform and complete across a region; thus, forecasts such as those made by Rossi and Phillips are likely to overestimate potential damage costs.

1.5.3 Bioeconomic Models

Bioeconomic models combine potential expenditure data with biological models of spread. These models are far more complex and require the interdisciplinary efforts of biologists, ecologists, economists, and mathematicians; however, expenditure forecasts developed by bioeconomic models provide a more complete picture of the possible implications of an invasion. Several current studies use a bioeconomic framework to predict possible expenditures for hypothetical mussel invasions.

Leung et al. (2002) use a bioeconomic model to assess the costs and benefits of preventative management for zebra mussels. Using a stochastic dynamic programming model, they incorporate biological variables and economic variables to quantify invasion risk and associated control costs of preventative management and reactive control. They conclude that it is optimal to spend up to $324,000 per year to prevent invasions in a single lake with a power plant.

Lee et al. (2007) develop a probabilistic bioeconomic simulation model to estimate the potential impact of zebra mussels to consumptive water users on a single lake in Florida. They characterize the lake as being in one of four possible states of nature (1) no mussels, (2) mussels introduced, (3) mussels propagating, and (4) mussels at critical mass, and assign probabilities to each of the states. Using a Markov approach, Lee et al. assess the net present values of impacts to water supply, water recreation, and wetland ecosystem services based on four management scenarios. Their results suggest that the benefits of preventative management far outweigh the costs, with an expenditure of $2.5 million on prevention over a 20-year horizon resulting in over $170 million in benefits.

Keller et al. (2008) develop a simulation model to predict the spread of rusty crayfish (*Orconectes rusticus*) through lakes in Vilas County, Wisconsin. They build their model based on data available in 1975, the initial year of the rusty crayfish invasion, and simulate the costs and benefits that varying levels of preventative management would have had in the county if a preventative management program had been in place in 1975. Rusty crayfish is an aquatic invasive species that has negative effects on native panfish populations. They are spread by anglers dumping water from bait buckets, and it is assumed that the spread of rusty crayfish can be prevented by stationing rangers on boat docks. The costs of preventative management are assumed to be equal to staffing costs for boat docks and are set at $6897 per lake per year. The benefits of preventative management are assumed to equal prevented reductions in expenditures by anglers targeting panfish and are estimated at $232.16 per hectare of lake surface area. Keller et al. assign an invasion-prediction score between 0 and 1 to each lake based on lake suitability and fishing pressure, with 0 representing a lake that is not invasible and 1 representing a lake that is very invasible. To simulate the costs and benefits of targeted preventative management, lakes with scores above a threshold are assumed to be protected and lakes with scores below the threshold are not. They find that it would have been optimal to protect lakes with invasion-prediction scores greater than 0.1 to 0.2. For the 30-year period between 1975 and 2005, an optimally targeted preventative management program could have saved $37 million in lost fishing value at a cost of $4.3 million.

Warziniack et al. (Working Paper) examine the potential economic impacts of a zebra mussel invasion into the Columbia River Basin. They develop a computable general equilibrium model (CGE model) combined with a biological model of mussel spread to estimate potential direct and indirect costs of damages and the timing of damages. Damages to irrigated agriculture, independent power producers, municipal and industrial water users, federal power generation facilities, and state and municipal power generation facilities are considered. The influence on industry costs by zebra mussels is modeled as factor productivity shocks where, following an invasion, industries respond by installing mitigation equipment and hiring additional labor to monitor and control the effects. Their results suggest that the electric generation and agricultural industries will incur significant damage costs, but that per capita market impacts will be relatively small.

1.6 An Overview of the Costs and Benefits of Preventative Management in the Colorado-Big Thompson System

1.6.1 Benefits of Preventative Management

Transport by recreational boats is considered the most important vector of spread in the West (Bossenbroek, Johnson, Peters, & Lodge, 2007). The primary benefit of the CDOW boat inspection program is a reduction in the probability that mussels will be transported overland on recreational boats. The tangible benefits of a reduced probability of introduction by boats is a decrease in the expected value of damages caused by a mussel invasion.

Mussel invasions have caused a host of damages in affected areas. These damages include ecological damages and damages to water conveyance and hydropower systems, municipal water treatment plants, water recreation, and industries and irrigators who use raw surface water (Ohio Sea Grant, 1997). This study considers damages to water conveyance systems, hydropower generation facilities, and municipal water treatment facilities. Values are not assigned to ecological damages, damages to industries and irrigators using raw surface water, or damages to water recreationists. These damages are likely to be substantial, and thus the net-benefits of the boat inspection program will be underestimated. Furthermore, this assessment only considers the effect of CDOW boat inspections within the Colorado-Big Thompson system. Reductions in the net present value of expected damage costs for facilities and structures within the Colorado-Big Thompson system are weighed against the costs of implementing the boat inspection program on reservoirs within the system. Thus, this analysis does not capture costs and benefits of the CDOW boat inspection program that are external to the system. The program is statewide, and boaters move throughout the state, thus there are interactions between Colorado-Big Thompson waters and waters throughout the rest of the state that are not captured by the model. Furthermore, by reducing the probability that Colorado waters harbor mussels, the CDOW boat inspection program provides external benefits to other western states by potentially reducing mussel sources. These external benefits are not included in this study, thus resulting in a further underestimate of the benefits of the program. In addition to slowing the spread of zebra and quagga mussels, the CDOW boat inspection program also serves to slow the spread of other aquatic nuisance species, providing additional program benefits. Table 1 provides a summary of the benefits of the CDOW boat inspection program.

Table 1: Benefits of preventative management for zebra and quagga mussels in the Colorado-Big Thompson System

Benefits of Preventative Management for Zebra and Quagga Mussels in the Colorado-Big Thompson System	
Reduced costs to infrastructure	**Possible costs to infrastructure include:**
	Costs to hydropower facilities, water treatment facilities, dams, and pump plants
	Costs to manually clean pipelines, tunnels and canals in the Colorado-Big Thompson system
Reduced control costs to industrial users	**Industrial users that could be affected include:**
	Fossil-fuel fired power plants
	Any industry using raw water as an input to production
Reduced control costs to irrigators	**Affected irrigators include:**
	Farmers using sub-irrigation or overhead sprinkler irrigation
	Parks and golf courses using raw water
Reduced ecological damages	**Possible ecological damages include:**
	Food chain depletion
	Long term negative effects to fisheries
	Severe reduction in populations of native mussels
	Noxious weed growth and associated control costs
	Algal blooms and associated control costs
Reduced human and animal health concerns	**Human and animal health concerns include:**
	Accumulation of organic pollutants that are passed up through the food chain
	Foul tastes in drinking water and associated costs to mitigate this in drinking water supplies

Benefits of Preventative Management for Zebra and Quagga Mussels in the Colorado-Big Thompson System	
Reduced recreational welfare loses	**Possible recreational welfare loses include:**
	Reduced size and weight of fish
	Reduced catch rates
	Increased fish kills due to lack of prey fish for sport fish
	Sharp shells on beaches
Reduced costs to lake homeowners	**Possible costs to lake homeowners include:**
	Control costs for treating or filtering water drawn directly from the lake
	Reduced home values
Reduced ecological and economic damages external to the Colorado-Big Thompson system	**External benefits include:**
	Reduced rate of invasion in Colorado and the West

1.6.2 Costs of Preventative Management

There are both direct and indirect costs associated with the CDOW boat inspection program. Water recreation managers, including CDOW and local recreation managers, incur direct costs of implementing the program. Direct costs include costs for training, staffing, equipment, and decontamination stations. Boaters do not pay a fee to have their boat inspected, but they do incur indirect costs associated with the inspections. All boaters are required to get their boats and trailers inspected and possibly decontaminated and thus incur time and hassle costs. For this analysis, the costs of the CDOW boat inspection program are modeled both as the direct costs alone and as the sum of the direct costs and the indirect costs together. Both measures of program costs are weighed against program benefits of reduced control costs to hydropower facilities, municipal water treatment plants, and conveyance systems.

CHAPTER 2: METHODOLOGICAL APPROACH AND DATA

The bioeconomic model developed for this study simulates a mussel invasion in the reservoirs of the Colorado-Big Thompson system over ten, thirty and fifty-year time horizons. Included in the simulation are the timing and magnitude of control costs accumulated to water conveyance structures, hydropower generation stations, and municipal water treatment facilities that draw or convey water from the Colorado-Big Thompson reservoirs. Simulations are run for two management scenarios, a base-case scenario of no preventative management, and the CDOW boat inspection preventative management scenario. The model outputs establishment patterns and the associated distributions of control costs for each scenario. Benefits of the preventative management program are measured as the difference in the net present value of control costs for the two scenarios. Net benefits of the program are measured as program benefits less program costs. Results are presented in Chapter 3 and include sensitivity analysis and "what-if" analysis to determine how sensitive results are to changes in parameter values and to determine which conditions yield benefits greater than costs.

This chapter describes the methodological approach and the data used to analyze the costs and benefits of the CDOW boat inspection program. Section 2.1 develops the cost-benefit model used to analyze the program. The cost-benefit model consists of three components: the probability of invasion, infrastructure control costs, and project costs. Infrastructure control costs are incurred only if a reservoir becomes invaded. To calculate the expected value of control costs, a simulation model is developed to predict a mussel invasion in the system and intertemporally match control costs to invaded reservoirs. The simulation model is broken into two components, a mussel dispersal component and a control costs component. Section 2.2 develops the mussel dispersal component of the simulation model and Section 2.3 develops the control costs component of the simulation model. Section 2.4 describes how the mussel dispersal component and the control cost component are combined to simulate program benefits. Project costs are assumed constant across time, and are described in Section 2.5. Each section includes an explanation of model components and a description of the data used to develop parameter values.

For all equations presented in the paper, superscripts denote differences in values for the different scenarios, with the zero superscript representing the base-case scenario of no preventative mussel management and the prime superscript representing the preventive management scenario. Many of the equations include values that vary between reservoirs and over time. For all equations presented in the paper, the subscript l represent reservoirs $l = 1, \ldots, N$, and the subscript t represent time periods $t = 0, .., T$, with a time period equal to one year. Appendix A includes a table of equations including names, descriptions, and parameter values for all of the variables used in the model.

2.1 Cost-Benefit Model

The overall objective of this project is to compare the costs and benefits of preventative management for zebra and quagga mussels in the Colorado-Big Thompson system. The net benefits of the CDOW boat inspection program are modeled as the reduction in the net present value of the expected damages to conveyance, hydropower, and municipal water structures and facilities in the Colorado-Big Thompson system, less the direct and indirect costs of implementing the program on the reservoirs within the system. Water conveyance systems, hydropower generation facilities, and municipal water treatment facilities are assumed to incur control costs if the reservoir directly above them has an established mussel population. The expected costs to structures and facilities is equal to the probability that the reservoir directly upstream has an established population of mussels multiplied by downstream facility control costs. The net present value of the net benefits of the CDOW boat inspection program is given in equation (1), and is equal to program benefits less direct and indirect program costs:

$$NPV\ of\ Net\ Benefits = (\varphi^0 - \varphi') - (\theta_D + \theta_I) \qquad (1)$$

where φ^0 and φ' are the net present values of the expected damages from mussels over the time horizon for the base-case and preventative management scenarios, and θ_D and θ_I are the net present values of the direct and indirect program costs. The following subsections describe each of the components of the net benefits equation.

2.1.1 Net Present Value of Expected Control Costs

For this analysis, mussel damages are measured as control costs incurred to dams, pump plants, hydropower facilities, and municipal water treatment facilities. The control costs to structures and facilities below reservoir l, given that reservoir l has an established population of mussels, is given as $C_{l,t}$. For each time period, reservoirs either have an established population of mussels or are unestablished. Let $E_{l,t}$ be a binary state variable with $E_{l,t} = 1$ if reservoir l is has an established population in time period t, and $E_{l,t} = 0$ if the reservoir does not have an established population. Let $P^0(E_{l,t} = 1)$ be the base-case probability that reservoir l is established in time period t, and let $P'(E_{l,t} = 1)$ be the probability that reservoir l is established in time period t under the preventative management scenario. The net present value of the expected damage costs from a mussel invasion for the base-case scenario is given in equation (2), and the net present value of the expected damage costs under the preventative management scenario is given in equation (3):

$$\varphi^0 = \sum_{t=0}^{T}\sum_{l=1}^{N}\frac{1}{(1+r)^t}C_{l,t} * P^0(E_{l,t} = 1) \qquad (2)$$

$$\varphi' = \sum_{t=0}^{T}\sum_{l=1}^{N}\frac{1}{(1+r)^t}C_{l,t} * P'(E_{l,t} = 1) \qquad (3)$$

where r is the discount rate. The benefit of the boat inspection program is equal to the reduction in the net present value of expected control costs (i.e. $Benefit = \varphi^0 - \varphi'$).

2.1.2 Net Present Value of Program Costs

The costs of the CDOW boat inspection program are equal to the sum of the direct costs to water recreation managers and the indirect costs incurred by recreational boaters. The direct costs of implementing the boat inspection program on reservoir l in time period t are given as $Z_{l,t}$. The net present value of the direct costs of implementing the program for the whole system is denoted θ_D and is given in equation (4):

$$\theta_D = \sum_{t=0}^{T}\sum_{l=1}^{N}\frac{1}{(1+r)^t}Z_{l,t} \tag{4}$$

The boat inspection program requires boaters to have their boats inspected prior to launch. Thus, boaters incur time and hassle costs associated with the boat inspection program. To model the indirect costs to boaters, welfare losses are measured based on the increased time boaters must spend waiting for boat inspections. Let $X_{l,t}$ represent lost welfare to boaters on reservoir l in time period t. The net present value of the indirect costs of the boat inspection program is denoted θ_I and is given in equation (5):

$$\theta_I = \sum_{t=0}^{T}\sum_{l=1}^{N}\frac{1}{(1+r)^t}X_{l,t} \tag{5}$$

2.2 Mussel Dispersal Component of the Simulation Model

A mussel dispersal model is built to simulate values for $P^0(E_{l,t} = 1)$ and $P'(E_{l,t} = 1)$. This section describes the mussel dispersal component of the bioeconomic simulation model and culminates with the probability that reservoir l becomes colonized by time period t.

Understanding the potential dispersal patterns of mussels is an essential first step in estimating the expected damages that mussels may cause to a system over time. Further, understanding how preventative management programs, like the CDOW boat inspection program, change the dispersal patterns and timings of invasions is an important key to estimating the benefits of such programs. Two factors drive the probability of an invasion by an invasive species: (1) the suitability of the receiving environment, and (2) the ability of the species to reach the receiving environment (Bossenbroek et al., 2001; Leung & Mandrak, 2007). Dreissena mussels can be transported to new environments on boats or via downstream flows. The number of invaders that reach a new location via these pathways determines propagule pressure, which is an important predictor of invasion success (Leung et al., 2004; Keller et al., 2009). However, propagule pressure alone is not enough to predict an invasion; once veligers are introduced to a new environment, their ability to persist depends on the suitability of the new environment for survival. Thus, simulating an invasion in the Colorado-Big Thompson system requires knowledge of the pathways by which mussels can enter the system, the environmental qualities of the habitat that the system provides, and the associated probabilities of colonization. Leung and Mandrak describe an environment as invasible if a species can survive and reproduce at that site, and suggest that the probability of colonization is jointly determined by propagule pressure and invasibility (Leung & Mandrak, 2007). They derive the joint probability of colonization as the product of the probability that a location is invasible and the risk due to propagule pressure. The joint probability of colonization is the key component in the mussel dispersal model, and determines the likelihood of invasion for each reservoir in each time period.

The mussel dispersal model has three main components: the probability that a reservoir is invasible, the probability of establishment given invasibility, and the joint probability of colonization. Section 2.2.1 describes the environmental suitability of the Colorado-Big Thompson reservoirs for mussel colonization and develops the probability of invasibility; Section 2.2.2 describes measures of propagule pressure from boats and from flows in the Colorado-Big Thompson system and relates propagule pressure to the probability of establishment; and Section 2.2.3 describes the joint probability of colonization.

2.2.1 Environmental Suitability of the Colorado-Big Thompson Reservoirs for Mussel Colonization and the Probability of Invasibility

In order for an environment to be invasible, the environmental conditions of the location must be such that introduced propagules can successfully reproduce and form an established colony (Bossenbroek et al., 2001; Leung & Mandrak, 2007). A number of water quality and limnological characteristics have been found to be correlated with mussel survival and density. The most common parameters used to assess mussel habitat suitability, in order from most predictive to least predictive, are calcium content, alkalinity, pH, nutrients, Secchi depth, dissolved oxygen, mean annual temperature, and conductivity (Claudi & Prescott, 2009). Calcium is a key indicator. Dreissena need calcium to form their shells, and without sufficient calcium, all of the other parameters become insignificant (Claudi & Prescott, 2009). Table 2 contains a summary of value ranges and associated dreissenid levels for the major dreissenid indicators.

Table 2: Dreissena indicators and associated densities

Parameter	None	Low Density	Moderate Density	High Density
Calcium mg/L	<10	<16	16-24	≥24
Alkalinity mg CaCO3/L	<35	35-45	45-89	>90
Total Hardness mg CaCO3/L	<40	40-44	45-90	≥90
pH	<7.2	7.2-7.5	7.5-8.0 or 8.7-9.0	8.0-8.6
Mean Summer Temperature °F	<64	64-68 or >83	68-72 or 77-83	72-75
Dissolved Oxygen mg/L (% saturation)	<6 (25%)	6-7 (25-50%)	7-8 (50-75%)	≥8 (>75%)
Conductivity μS/cm	<30	<30-37	37-84	≥85
Salinity mg/L	>10	8-10	5-10	<5
Secchi depth m	<0.1	0.1-0.2 or >2.5	0.2-0.4	0.4-2.5
Chlorophyll a μ/L	<2.5 or >25	2.0-2.5 or 20-25	8-20	2.5-8
Total phosphorous μg/L	<5 or >35	5-10 or 30-35	15-30	10-15
Total Nitrogen μg/L	<200	200-250	250-300	300-500

Source: (Claudi & Prescott, 2009)

The literature provides mixed reviews on dreissena survivability and reproduction potential in low calcium waters. Cohen and Weinstein (2001) reviewed the literature on calcium thresholds for zebra mussel survival and growth, and found thirteen studies that experimentally tested aspects of dreissena survival and growth in waters with different calcium concentrations. These studies report mixed results for calcium levels below 15 mg/L, with some experiments concluding that adult mussels can survive in waters with calcium levels as low as 4 mg/L; however, most studies found poor reproduction at low calcium levels. Mussels have been reported in Lake Champlain which has a calcium concentration of 13-14 mg/L, and have also been reported in four inland lakes with mean calcium levels between 4 and 11 mg/L; however, it is not clear if these are established populations. There is very little research on dreissena survival in waters with calcium levels between 15 and 20 mg/L. Experiments indicate that calcium concentrations greater than 20 mg/L can support good adult survival and reproduction, and calcium levels greater than 28 mg/L can support abundant populations (Cohen & Weinstein, 2001). There is mixed evidence and a general lack of research on zebra and quagga mussel marginal habitats in the West (Claudi & Prescott, 2009).

In a series of reports prepared for the Bureau of Reclamation, RNT Consultants deem the calcium levels in the Colorado-Big Thompson reservoirs to be below those likely needed to support dreissenid survival, and conclude that there is a very low risk of mussels establishing reproducing populations in the calcium-poor reservoirs of the system (Claudi & Prescott, 2009). Many experts would agree with this assessment, and most mussel dispersal models would exclude the possibility of mussels establishing populations in the Colorado-Big Thompson waters. Mussel have, however, been identified in the low calcium headwaters of the system. In 2008, multiple samples tested by multiple agencies positively identified dreissena veligers in Willow Creek Reservoir, Lake Granby, Shadow Mountain Reservoir, and Grand Lake. However, no evidence of veligers was found in any of these reservoirs in 2009. This data spurs several questions: Were these reservoirs supporting a small population of reproducing veligers that went extinct? Are the reservoirs currently supporting reproducing populations that were missed in 2009 sampling efforts? Were the veligers that were found in the reservoirs isolated individuals, independent of a reproducing population? The answers to these questions are unknown at this time.

Table 3 contains the available calcium data for the reservoirs in the Colorado-Big Thompson system. Reservoirs are classified as having very low, low, moderate, or high levels of risk based on classifications suggested by Whittier et al. (2008). Reservoirs with average calcium levels less than 12 mg/L are classified as very low risk, between 12 and 20 mg/L as low risk, between 20 and 28 mg/L as moderate risk, and greater than 28 mg/L as high risk. Based on available calcium data, Boulder Reservoir is the only reservoir in the system that is at high risk of a dreissena invasion. Windy Gap Reservoir, Willow Creek Reservoir, Lake Granby, Shadow Mountain Reservoir, Grand Lake, Horsetooth Reservoir and Carter Lake all have calcium levels in the low or very low ranges. Two sources of calcium data for Mary's Lake give conflicting evidence of the calcium levels in the lake. Samples taken by the Northern Colorado Water Conservancy District of discharge water from Mary's Lake indicate that calcium levels in the lake are very low, whereas sampling by the Town of Estes water quality lab suggests that calcium levels in Mary's Lake fall in the moderate range. There is no calcium data available for East Portal Reservoir, Lake Estes, Pinewood Reservoir, or Flatiron Reservoir. As part of the sensitivity testing of the model, calcium levels in these reservoirs and in Mary's Lake are modeled as very low, low and moderate.

Table 3: Calcium levels in the reservoirs of the Colorado-Big Thompson system

Reservoir	Average Ca (mg/L)	Low Ca (mg/L)	High Ca (mg/L)	Calcium Classification
Windy Gap Reservoir	15	12.5	17.4	Low
Willow Creek Reservoir	15.2	8.9	24.3	Low
Lake Granby	8.7	7.6	10.3	Very Low
Shadow Mountain Reservoir	8.2	3.8	9.7	Very Low
Grand Lake	6.9	3.7	9	Very Low
East Portal Reservoir	not available			Unknown
Mary's Lake*	5.6	2.5	8.9	Unknown
Lake Estes	not available			Unknown
Pinewood Reservoir	not available			Unknown
Flatiron Reservoir	not available			Unknown
Horsetooth Reservoir	9.2	7.6	10.8	Very Low
Carter Lake	9.2	7.4	10.2	Very Low
Boulder Reservoir	30.6	14.0	42.0	High

**Sampling by the Town of Estes water quality lab suggests that Ca levels in Mary's Lake may be higher. The Town of Estes draws water from Mary's Lake and reports average Ca levels ranging from 20-25 mg/L.*

The Probability of Invasibility

To model the invasibility of the Colorado-Big Thompson reservoirs, let I represent the state in which a reservoir is invasible and let x_l be the water quality characteristics of reservoir l. The probability that reservoir l is invasible, denoted ϕ_l, is given in equation (6):

$$\phi_l = P(I|x_l) \tag{6}$$

Parameter Values for the Probability of Invasibility

The probability that a reservoir is invasible is a function of many variables, some known and some unknown. For the simulation of invasion in the Colorado-Big

Thompson system, parameter estimates for the probability of invasibility are assigned based on the calcium risk level for each reservoir. The assumption made in this study is that ϕ_l is small but greater than zero for all of the reservoirs in the system. Although ϕ_l may be zero in the calcium-poor reservoirs of the Colorado-Big Thompson Project, it is reasonable to assume that the probability of invasibility is likely to be small but non-zero for the reservoirs in the very low and low calcium categories. Available literature assigns risk qualitatively, which makes assigning quantitative parameter values challenging. The chosen parameter values are subjective, making this an important variable to consider as part of the sensitivity analysis. The table presented in Appendix A gives the range of values for ϕ_l used in simulating invasions in the Colorado-Big Thompson reservoirs.

2.2.2 Pathways of Invasion and the Probability of Establishment

The introduction of mussels to an environmentally suitable lake does not guarantee that mussels will colonize the lake. In fact, it is likely that introductions by multiple boats will be necessary for successful colonization of a water body (Bossenbroek et al., 2001). Likewise, lakes downstream from infested water bodies are not guaranteed to become infested. The distance downstream and the level of turbulence in the stream have both been found to affect the mortality of mussel veligers and their likelihood of establishing downstream colonies (Horvath & Lamberti, 1999; Rehmann et al., 2003). Propagule pressure, a measure of the number of propagules released into a region, is a key determinant of the probability that an environmentally suitable water body becomes established (Keller et al., 2009). In this section, measures of propagule pressure from boats and from downstream flows are developed and related to the probability of establishment.

2.2.2(a) Propagule Pressure from Boats

In order to estimate the probability that a reservoir develops an established colony of mussels from propagules introduced by boats, an estimate of the propagule pressure from boats is required. Propagule pressure from boats is assumed to be well estimated by the number of potentially infested boats visiting each reservoir each year (Leung & Mandrak, 2007). The model developed in this study assumes that the number of potentially infested boats visiting each reservoir in the system is equal to a percent of total boat visits to each reservoir and is equal across reservoirs. The number of invaded lakes and reservoirs in the western states is expected to increase each year as the western invasion progresses. Consequently, as the number of mussel sources increase, the percent of potentially infested boats visiting the Colorado-Big Thompson reservoirs is also expected to increase. Thus, propagule pressure from boats is expected to increase over time.

Boat Visits to the Colorado-Big Thompson Reservoirs

The first step in estimating propagule pressure from boats is to estimate the total number of boat visits to each reservoir. Seven of the twelve reservoirs in the Colorado-Big Thompson system allow motorized boating, including Lake Granby, Shadow Mountain Reservoir, Grand Lake, Lake Estes, Horsetooth Reservoir, Carter Lake, and Boulder Reservoir. Reservoirs that allow motorized boating are highlighted in Figure 3 on page 13 with doubled borders[1]. CDOW inspection data from the 2009 boating season is used to approximate the average annual number of boat visits to each reservoir (CDOW, 2009)[2]. There is no dedicated monitoring station for Lake Estes. Boats at Lake Estes are monitored by roving patrol; thus, inspection data for Lake Estes does not provide valid estimates of seasonal boat visits. Annual trailered boat visits to Lake Estes are estimated by the Estes Valley Parks and Recreation marina based on daily permit sales (Estes Valley Parks and Recreation, 2010).

To model total boat visits, let $B^0_{l,t}$ represent average yearly trailered boat trips to reservoir l in time period t for the base-case scenario, and let $B'_{l,t}$ represent average yearly trailered boat trips for the preventative management scenario. Values for $B'_{l,t}$ are set equal to the number of boat inspections on reservoir l in 2009. Total boat visits may differ between scenarios. Although there is no fee for boat inspections, the time and effort that boaters must spend to get their boats inspected represents a time cost. The requirement of boat inspections may cause some boaters to reduce the number of trips taken within the system. Boaters may substitute out of the system and boat on non-Colorado waters, or they may simply take fewer boat trips. Let ρ represent the percent decline in the number of boat

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[1] Motorized boating was previously allowed in Willow Creek Reservoir, but the reservoir has been closed to motorized boating as part of the Colorado ZQM Plan. The reservoir may re-open to boating. This scenario is not considered in the model, but would be an easy adaptation.

[2] The 2009 data may provide under estimates of average yearly boat visits, as the 2009 boating season was exceptionally rainy. Despite this concern, the 2009 boat inspection data is the best available data for estimating yearly boat visits to each reservoir.

visits attributable to the boat inspection program. Values for $B^0_{l,t}$ are estimated by backing out 2009 inspection numbers as in equation (7) :

$$B^0_{l,t} = B'_{l,t}/(1-\rho) \tag{7}$$

Parameter Values for the Percent Decline in Boat Visits

A survey conducted by CDOW in 2008 provides some idea of how boaters may behave when faced with mandatory boat inspections. The survey was conducted prior to the mandatory boat inspection program, and asks boaters:

> Q12: In 2007, about how many days did you use your boat in Colorado?
>
> Q27: The average time for an aquatic nuisance species (ANS) boat inspection is 3 minutes. There is currently no fee for an ANS inspection in Colorado. If an inspection found or suspected an ANS attached to your boat, you would have to go through the decontamination process before putting in at that water body. Decontamination would depend on the size of your boat but may take 20 minutes. After reading the text above, how likely would you be to avoid water bodies which require the inspection process?

A major limit to using question 27 to address boater behavior when faced with the CDOW boat inspection program, is that question 27 asks what a boater would do if their favorite water body required inspections. Thus, question 27 implies that boaters could substitute away from inspections by boating at other Colorado water bodies. The CDOW boat inspection program is statewide, which greatly reduces substitute options. Boater behavior when faced with statewide inspections may differ from that reported in question 27. For the purpose of this analysis, it is assumed that boaters who answered "very likely" or "likely" to question 27 may reduce the number of boat trips they take within Colorado. A total of 1811 respondents answered both questions 12 and 27. Of those respondents, a total of 30,631 Colorado boat trips were reported. Questions 12 and 27 are used to estimate a low, base, and high percent reduction in the number of Colorado boat trips. The high estimate of ρ assumes that respondents who answered "very likely" to question 27 and respondents who answered "likely" will reduce their Colorado trips by 20% and 10%, respectively. This assumption results in a 3% reduction in the number of boat trips taken in the state. To estimate the base value of ρ, a 10% reduction in Colorado trips is assumed for respondents who answered "very likely", with a 0% reduction in trips for all other respondents. This assumption results in a 1% reduction in the number of boat trips taken in the state. The low estimate of ρ assumes perfectly inelastic demand for recreational boating, resulting in a 0% reduction in boat trips.

Total Boat Visits to the Colorado-Big Thompson Reservoirs Under the Base-Case Scenario and the Preventative Management Scenario

Table 4 gives average yearly boat visit values used in the simulation model. Values for $B^0_{l,t}$ are given for the low, base, and high parameter values for ρ.

Table 4: Total number of trailered boat visits by reservoir

Reservoir	$B_{l,t}$	$B^0_{l,t}, \rho = 0$	$B^0_{l,t}, \rho = .01$	$B^0_{l,t}, \rho = .03$
Windy Gap Reservoir	0	0	0	0
Willow Creek Reservoir	0	0	0	0
Lake Granby	7404	7404	7479	7633
Shadow Mountain Reservoir	3562	3562	3598	3672
Grand Lake	3263	3263	3296	3364
East Portal Reservoir	0	0	0	0
Mary's Lake	0	0	0	0
Lake Estes	420	420	424	433
Pinewood Reservoir	0	0	0	0
Flatiron Reservoir	0	0	0	0
Horsetooth Reservoir	48,518	48,518	49,008	50,019
Carter Lake	7982	7982	8063	8229
Boulder Reservoir	1700	1700	1717	1753

The Percent of Potentially Infested Boats

The previous section considered the total number of boats visiting the system for the base-case and preventative management scenarios. The next step in estimating propagule pressure from boats is to estimate the percent of those boats that are potentially infested with mussels. The percent of potentially infested boats is expected to increase over time as a greater number of water bodies become mussel sources. An increasing random-walk method, similar to that used by Leung et al. (2004), is utilized to model an increasing percent of potentially infested boats over time. Each year, the percent of potentially infested boats increases by a random value, R, where R is chosen from a uniform distribution bounded by 0 and R_{max}. Let p_0 be the percent of visiting boats that are potentially infested in year 0 (i.e. 2009), and let R_{max} represent the maximum rate at which the percent of potentially infested boats can increase in each period. The percent of potentially infested boats will be limited by the extent of the mussel infestation in the region. Thus, p_t^0 is bounded by a maximum value, p_{max}. Equation (8) gives the percent of potentially infested boats in period t for the base-case scenario:

$$p_t^0 = \begin{cases} p_{t-1}^0 + R & if\ p_{t-1}^0 + R \leq p_{max} \\ p_{max} & if\ p_{t-1}^0 + R > p_{max} \end{cases} \tag{8}$$

$$where\ R \sim U[0, R_{max}]$$

The difference between the percent of potentially infested boats that enter Colorado-Big Thompson waters for the preventative management scenario versus the base-case scenario captures the main effect of the CDOW boat inspection program. The boat inspection program affects the percent of potentially infested boats in two ways: (1) it will slow the rate of invasion in the region, and (2) inspectors will catch and clean a percent of potentially infested boats that visit the system. Let β be the percent reduction in the rate of invasion attributable to the boat inspection program. Equation (9) gives the percent of potentially infested boats entering the system in year t for the preventative management scenario:

$$p'_t = p'_{t-1} + R - \beta R \tag{9}$$

The percent of boats caught and cleaned by boat inspections is assumed to be constant over time and across reservoirs, and is denoted γ. Equation (10) gives p_t'', the percent of potentially infested boats entering Colorado-Big Thompson waters after being inspected (i.e. the percent of potentially infested boats that are missed by boat inspectors):

$$p_t'' = (1 - \gamma)p_t' \tag{10}$$

Propagule Pressure from Boats

Propagule pressure from boats is derived by multiplying total boat visits with the percent of potentially infested boats. Propagule pressure from boat introductions in reservoir l in time period t for the base-case scenario is denoted $N_{l,t}^{B^0}$ and is given in equation (11):

$$N_{l,t}^{B^0} = B_{l,t}^0 * p_t^0 \tag{11}$$

Propagule pressure from boat introductions for the preventative management scenario is denoted $N_{l,t}^{B'}$ and is given in equation (12):

$$N_{l,t}^{B'} = B_{l,t}' * p_t'' \tag{12}$$

Parameter Values for the Percent of Potentially Infested Boats

Mussel veligers and adult mussels can be difficult to find, so boat inspectors cannot be sure of the reliability of their inspections. Thus, the value of γ is unknown. Parameter estimates of γ are set to range between .8 and 1, with $\gamma = 1$

representing perfect efficacy of boat inspections. The value of β is also unknown. Parameter estimates of β are set to range between .25 and .75.

CDOW inspection data are used to develop a range of values for the parameter p_0. A total of 305,622 entrance inspections were conducted in the state in 2009. Of these, 5647 inspections were high-risk inspections, and 3364 resulted in decontamination. Boats that have traveled from reservoirs that are known to be infested or from high-risk states are subjected to a high-risk inspection or decontamination; thus, the percent of inspections that were high-risk or resulted in decontamination should be a good proxy for the percent of potentially infested boats. To model the initial percent of potentially infested boats, the base value of p_0 is set equal to 1.8%, the percent of high-risk inspections conducted in 2009. The low value is set equal to 1.1%, the percent of decontaminations, and the high value is set equal to 2.9%, the percent of entrance inspections that were high risk or resulted in decontamination.

The parameter range for R_{max} is based on the possible rate of infestation for the region. The rate by which the mussel invasion in the West will occur is unknown, but is likely to be slower than the initial U.S. invasion in the Midwest and Northeast (Bossenbroek et al., 2007). To allow for differing rates of invasion, a range of values for R_{max} are tested in the model. Parameter values for R_{max} are based on two studies of mussel infestation rates. Kraft and Johnson (2000) investigate zebra mussel colonization rates in a four-state region adjacent to the Great Lakes from 1995 to 1997. They tested for the presence of zebra mussel veligers each year from a sample of environmentally suitable lakes. For the period 1995-1996, the annual infestation rate was 4.6%. For the period 1996-1997, the annual infestation rate increased to 5.6%, with annual infestation rates higher in Indiana (11-12%) and Michigan (5-12%) than in Wisconsin (0%). These results suggest that rates of inland colonization vary by region. Regional differences may be attributed to differences in habitat suitability between regions or to differences in the patterns and efficiency of dispersal vectors. Evidence from a 2004 study by Johnson et al. (2006) suggest that the invasion of inland lakes is occurring slowly, thus lower estimates of R_{max} seem most appropriate. Using the infestation rates found by Kraft and Johnson (2000), values for R_{max} are set to range between 0% and 5.6%; however, the base value of R_{max} is set low (.5%) to reflect the finding by Johnson et al (2006) that the invasion of inland lakes is happening very slowly.

Parameter values for p_{max} are chosen based on national risk assessments provided by Whittier et al. (2008). Using regional water calcium levels, Whittier et al. classify 58.9% of U.S. ecoregions as being at high risk of dreissena invasion, and an additional 19.8% as having highly variable risk. Evidence from the ongoing U.S. invasion suggests that only a small portion of water bodies that are suitable habitat for dreissena will become invaded. As of 2004, only in Michigan and Indiana were more than 10% of suitable lakes invaded (Johnson et al., 2006). To reflect this, the low value of p_{max} is set at 2.95%, five percent of the percent of high-risk ecoregions, and the base value is set at 5.89%, ten percent of the percent of high-risk ecoregions. The high value is set at 58.9%. There is much uncertainty in the values for R_{max} and p_{max}, making sensitivity analysis of these parameters important.

3.2.2 (b) Propagule Pressure from Flows

To model the invasion in the Colorado-Big Thompson reservoirs, source-sink dynamics are assumed. There are two main criteria for a downstream sink to become colonized from an upstream source: (1) the population in the upstream source must be sufficiently large, and (2) a sufficiently large percentage of veligers must survive transport (Bobeldke et al., 2005). To account for both of these criteria, propagule pressure from flows is modeled as the density of veligers who survive downstream transport.

Density of the Upstream Reservoir

Estimating the potential densities of mussels in the reservoirs of the Colorado-Big Thompson system is beyond the scope of this project; however, mussel density is an important component in the simulation. In the model, the probability of establishment from downstream flows is a function of mussel density in the upstream reservoir and distance downstream. Upstream population densities are dependent on a number of factors including water chemistry and other limnological characteristics. Population densities can also change over time.

Ramcharan et al. (1992) develop models to predict the occurrence and density of dreissena mussels in lakes based on limnological characteristics. They find that both occurrence and average density of mussels are highly correlated with the water chemistry of a lake. In their data set (a total of 278 European lakes), no mussels were found in lakes with average pH values below 7.3 or calcium concentrations below 28.3 mg/L. The variables pH and Ca were found to be important for distinguishing lakes without dreissena from those with low densities, and the variables PO_4 and NO_3 were found important for distinguishing lakes with low densities from lakes with high densities. Overall, Ramcharan et al. (1992) find that calcium and pH levels are important indicators of the presence or absence of dreissena, but that other variables are more important for predicting the density of mussels in an established water body.

Mellina and Rasmussen (1994) also find that calcium levels set a threshold for the presence of zebra mussels, but are a poor predictor of abundance. They find that the size distribution of the available substrate (i.e. boulders, gravel, sand, mud) is a better determinate of mussel density, with larger substrates supporting denser populations. Burlakove et al. (2006) find the major factors affecting the size of a mussel population are the time since initial colonization, the relative abundance of substrates for mussels to attach to, and limnological characteristics.

Overall, the density of zebra mussels in an established water body can vary dramatically. In their study of mussel densities in European lakes, Ramcharan et al. (1992) found densities ranging from a low of 22 individuals/m^2 to a high of 7500 individuals/m^2, with mean densities of just over 800 individuals/m^2. Reported densities of zebra mussels in the United States range from a low of 55 individuals/m^2 in the Tennessee River to a high of 250,000 individuals/m^2 in Lake Michigan (Bossenbroek et al., 2007).

Casagrandi et al. (2007) model temporal patterns in mussel density based on lifecycle and reproductive characteristics of zebra mussels and on predation.

They find that the density of zebra mussel populations can be described by a boom-bust cycle of high densities followed by low densities, and that equilibrium population densities can only be reached if veliger survival is very low. In contrast, Burlakova et al. (2006) track population densities and biomass for three lakes in Belarus over a 12-year period following initial colonization, and find that mussel populations remain constant after reaching a maximum density.

For this model, it is assumed that population densities increase over an initial period and then remain constant over time. It is further assumed that upstream reservoirs only become potential sources for downstream infestation after reaching their maximum population density following a lag time of m years. Consequently, reservoirs that are colonized at time t become sources of propagules at time $t + m$.

Mussel Density Parameter Values

The density of an established and homogeneous population of mussels in reservoir l is denoted D_l, with parameter values of D_l set at 22, 800, and 7500 individuals/m^2, as described in Ramcharan et al. (1992). Although calcium is a relatively poor predictor of population density, it is the only data available to calibrate the base densities for the reservoirs in the Colorado-Big Thompson system. Base parameter values are set at 22 individuals/m^2 for very low and low calcium reservoirs, 800 individuals/m^2 for moderate calcium reservoirs, and 7500 individuals/m^2 for high calcium reservoirs. The effects of different levels of mussel densities in the system are tested as part of the sensitivity analysis.

It is difficult to determine the exact timing of an invasion, so most estimates of lag time are based on the time from initial detection. A substantial difference may exist between the time of initial introduction and the time of detection. When populations grow exponentially or logistically, there is an initial period were growth is very slow. This period may last for several years (Ricciardi, 2003). Data from Europe and North America suggest that zebra mussels reach maximum density about 2-3 years after detection. Burlakova et al. (2006) estimate that it takes 7-12 years for zebra mussels to reach maximum population density after the time of initial invasion (2006). The time following initial invasion is the most appropriate for this model. The estimates by Burlakova et al. (2006) seem on the high end, so low, base, and high parameter values of m are set equal to 6, 8, and 10 years, respectively.

Veliger Survival in Downstream Transport

The density of veligers that survive downstream transport is also a function of veliger survival in transit. Distance downstream, turbulence, and the presence of wetlands and vegetation all affect veliger transport and mortality (AMEC Earth and Environment, 2009). The Colorado-Big Thompson Project is nearly entirely connected via pipelines, tunnels, and canals, with no wetlands or vegetation present to slow or hinder veliger transport. Therefore, the possibility of veliger transport between reservoirs comes down to the ability of veligers to survive the distances and turbulence encountered in the system. Little is currently know about how veligers will fair passage through the man-made conduits and the turbulent hydropower plants of the Colorado-Big Thompson Project. Unlike natural rivers, the canals and pipelines in the project are operated at hydraulic velocities that are more conducive to transport of viable veligers; the conduits also provide an ideal surface for settlement and growth (Claudi & Prescott, 2009; Clark, 2010). This suggests that veligers may be able to travel further in the Colorado-Big Thompson conduits than is suggested by studies of veliger mortality conducted in natural rivers. Aside from a smoother ride in the pipelines and canals, in many stretches of the system, veligers will be subject to a trip through a turbulent hydroelectric power plant. These confounding characteristics provide added uncertainty to the viable transport of mussels from upstream sources to downstream sinks in the Colorado-Big Thompson system. Despite these unique and confounding characteristics, information gathered from other systems is the best information available to understand how mussel veligers may pass through the Colorado-Big Thompson system.

In their study of connected lake-stream systems in the St. Joseph River Basin in Michigan, Bobeldke et al. (2005) found that lakes greater than 20 km from an upstream source had a lower chance of being invaded. The longest connections in the Colorado-Big Thompson system are between Carter Lake and Boulder Reservoir (36.7 km), between Grand Lake and East Portal Reservoir (21.1 km), and between Flatiron Reservoir and Horsetooth Reservoir (21.3 km); see Figure 3 on page 13. The remaining conduits in the system are all less than 20 km in length.

Horvath and Lamberti (1999) found that the percent of veligers that survive downstream transport declines exponentially with distance traveled downstream (1999). For the stretch of river tested, the percent of veligers that survived downstream transport was found to be well estimated by the equation: $percent\ live = 80.1e^{-0.5x}$, where x is the distance downstream, measured in kilometers. The stretch of river used in their study is considered turbulent, and the authors' findings suggest that exposure to turbulence or shear during transport negatively affects veliger survival.

Incorporating turbulence, among other variables, AMEC Earth and Environment (2009) built a particle tracking simulation model to assess the possible transport of mussel veligers between two Colorado reservoirs connected by over 50 km of natural river. Results of their model indicate that turbulence plays a very large role in the fate of veligers in the system, with all simulations resulting in 100% veliger mortality within a short distance downstream from the upstream reservoir.

In laboratory experiments, Rehmann et al. (2003) test the effects of turbulence on the mortality of zebra mussel veligers. They conclude that turbulence in streams can increase mortality rates, but the magnitude of the effect depends on the size distribution of veligers and the relative importance of acute and chronic exposure to turbulence. Their experiment was motivated by the possibility of using bubbler barriers as a preventative control to block the passage of mussel veligers in streams. They conclude that bubble barriers could be effective if mortality is a result of acute exposure to turbulence, but would be impractical if veliger mortality is a result of chronic exposure to turbulence. This finding is useful in evaluating the potential mortality of mussels passing through hydropower plants. If mortality is a result of acute effects caused by damage during short periods of high turbulence, then it is reasonable to assume that veligers will not survive passage though hydropower plants. However, if mortality is a result of chronic exposure to turbulence, mussel veligers may have a greater chance of surviving passage through hydropower penstocks and turbines.

Evidence from the Hoover Dam suggests that mussels can successfully pass through hydropower facilities. In 2007, shortly after the discovery of mussels in Lake Mead, Bureau of Reclamation divers identified quagga mussels on the intake tower upstream of Hoover Dam and on the spillway outlet below the dam, indicating that mussels had successfully passed through the hydroelectric facility (Bureau of Reclamation, 2007).

In 2010, the Bureau of Reclamation began work on a project to assess the viability of mussel veligers in Bureau of Reclamation conveyance structures. With the exception of the Bureau of Reclamation study, there are currently no studies that specifically address how mussel veligers will survive in a system like the Colorado-Big Thompson Project; however, findings from other systems suggest that it is likely that mussels can survive transport through the conduits and hydropower facilities of the project.

In order to estimate propagule pressure from propagules introduced via downstream flows, several assumptions are made about how veliger densities are impacted by passage through the Colorado-Big Thompson system. It is assumed that veliger densities will decline exponentially with distance traveled, as found by Horvath and Lamberti (1999). It is also assumed that the presence of a hydropower facility along a stretch does not affect the overall percentage of veligers that survive passage. In order to make this assumption, the underlying assumption is that veliger mortality is more dependent on chronic exposure to turbulence than on acute exposure.

To model propagule pressure from downstream flows from infested upstream sources, maximum upstream population densities are multiplied by the percent of veligers that survive downstream passage. Propagule pressure from flows that reach reservoir l in time period t are denoted $N_{l,t}^{F}$, and are given in equation (13):

$$N_{l,t}^{F} = D_{l^{up}} * Ae^{-b*x_l} \qquad (13)$$

where $D_{l^{up}}$ is the maximum population density in the reservoir directly upstream from reservoir l, A is an intercept parameter, b is a decay parameter, and x_l is the distance between reservoir l and the upstream infested reservoir.

Parameter Values for Propagule Pressure From Flows

The intercept value of $A = 80.1$ found in the Horvath and Lamberti (1999) study is unlikely to differ across systems. This value represents the percent of veligers that survive without passing any distance. The value for b estimated in the

Horvath and Lamberti (1999) study characterizes veliger decay in a natural, turbulent stream system. The value of *b* for the Colorado-Big Thompson system is likely different from the one found for the natural stream system. Low, base, and high parameter values for *b* are set based on densities falling to 0.1% after 10, 15, and 20 km, respectively. These values are graphed in Figure 4, and show that downstream mortality declines more slowly for smaller values of *b*.

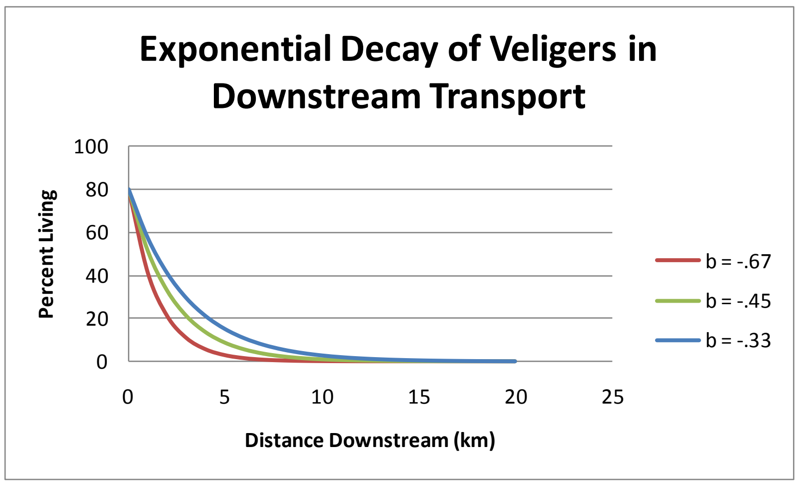

Figure 4: Veliger decay in downstream transport

3.2.2 (c) Relating Propagule Pressure to the Risk of Establishment

The probability that reservoir l becomes established in time period t is a function of propagule pressure. This section develops equations for the probability of establishment from propagules introduced by boats and by flows.

Leung et al. (2004) develop a model that relates the probability of population establishment to propagule pressure. They test two functional forms to predict the probability of establishment as a function of propagule pressure. The first functional form assumes that each propagule has an independent chance of establishment, and the second assumes the presence of an Allee effect. An Allee effect describes population reproduction for small populations were the reproduction and survival rates of individual propagules increases with population density. With an Allee effect, the probability of propagules successfully reproducing and forming an established colony is disproportionately small for propagule numbers below a threshold, and then grows with larger numbers of propagules (Leung et al., 2004). For the case of independence, the probability of establishment is the complement of the probability that no propagules successfully establish. For this case, the probability of establishment as a function of propagule pressure is given as: $E\left(N_{l,t}\right) = 1 - (1-p)^{N_{l,t}} = 1 - e^{-(\alpha N_{l,t})}$, where p is the probability of a single propagule establishing a colony, $N_{l,t}$ is the number of propagules arriving at location l at time t, and α is a shape coefficient. The second functional form accounts for an Allee effect. In this form, the curve contains an inflection point. Below the inflection point threshold, the probability of establishment is disproportionately smaller. The function is similar to the one used for the independent case, but includes an additional shape parameter, c: $E\left(N_{l,t}\right) = 1 - e^{-(\alpha N_{l,t})^{c}}$. Values of c greater than one indicate the presence of an Allee effect, whereas c equal to one indicates independence. Leung et al. (2004) use boater registration data and zebra mussel presence/absence data from Michigan to develop estimates of propagule pressure and to fit parameter values to the models. They assume recreational boat movement is the primary vector for zebra mussel dispersal, and do not consider propagule pressure from upstream sources. They estimate propagule pressure using a production constrained gravity model, as in Bossenbroek et al. (2001), where $N_{l,t}$ is the number of potentially infested boats that visit location l in time period t. To consider changes to propagule pressure over time, Leung et al. (2004) assume that as the invasion progresses and more locations become invaded, propagule pressure will increase over time. They incorporate this into their model using the formula, $N_{l,t+1} = N_{l,t} + R$, where R is randomly chosen from a uniform distribution between 0 and 10. Using observed invasion data from Michigan lakes, Leung et al. (2004) estimate values for the model parameters α and c and find a significant Allee effect (c is found to be statistically significantly larger than one). For the Allee model, the estimated parameter values are $\alpha = 1.03 \times 10^{-4}$ and $c = 1.86$.

For the Colorado-Big Thompson dispersal model, the methods developed by Leung et al. (2004) are used to establish relationships between the probability of establishment and propagule pressure from boats and flows. Using the Allee effect functional form developed by Leung et al. (2004), measures of propagule pressure from boats and from upstream flows for the Colorado-Big Thompson system are converted to probabilities of establishment. For the following equations, the superscripts and subscripts B and F represent differences in equations for propagules introduced by boats and by flows, respectively.

Probability of Establishment from Boats

Propagule pressure from boats for reservoir l in time period t for the base-case scenario is denoted $N_{l,t}^{B^0}$ and is measured as the number of potentially infested boats visiting reservoir l in time period t. The formula for $N_{l,t}^{B^0}$ is given in equation (11), and the associated probability of establishment is given in equation (14):

$$E\left(N_{l,t}^{B^0}\right) = 1 - e^{-\left(\alpha_B N_{l,t}^{B^0}\right)^{c_B}} \tag{14}$$

For the preventative management scenario, propagule pressure from boats for reservoir l in time period t is denoted $N_{l,t}^{B'}$ and is measured as the number of potentially infested boats visiting reservoir l in the time period t that are still infested after being inspected. The formula for $N_{l,t}^{B'}$ is given in equation (12), and the associated probability of establishment is given in equation (15):

$$E\left(N_{l,t}^{B'}\right) = 1 - e^{-\left(\alpha_B N_{l,t}^{B'}\right)^{c_B}} \tag{15}$$

Parameter Values for the Probability of Establishment by Boats

Values for the parameters α_B and c_B are equal in equations (14) and (15), because propagules introduced by boats face the same biological conditions regardless of the CDOW boat inspection program. Parameter values for α_B and c_B in equations (14) and (15) are assumed to be similar to those estimated for α and c in the Leung et al. (2004) study, because the same measure of propagule pressure is used. Figure 5 shows a graph of the probability of establishment as a function of the number of potentially infested boats, with $c_B = 1.86$, as found in Leung et al. (2004), and α_B ranging between low, base, and high values of .00005, .000103, and .0005. The base value for α_B is equal to the α value found by Leung et al. (2004), and the low and high values are chosen subjectively.

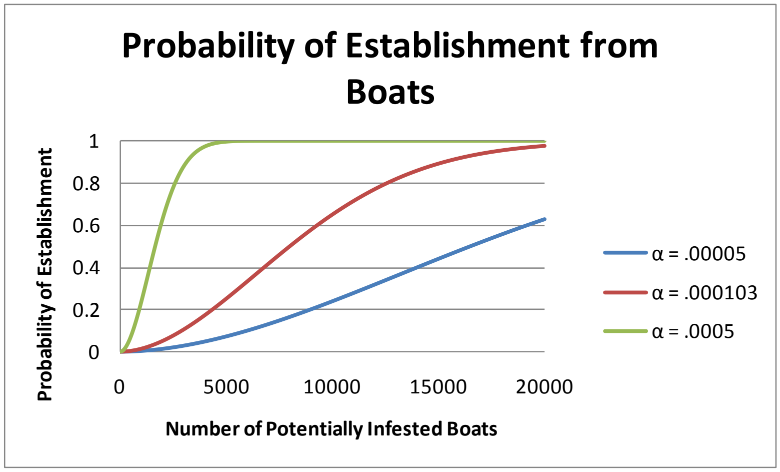

Figure 5: The probability of establishment as a function of the number of potentially infested boats

Probability of Establishment from Flows

Propagule pressure from downstream flows for reservoir l in time period t is measured as the density of propagules surviving downstream passage and is given in equation (13). Upstream reservoirs become a source of propagules following a lag time of m years; thus, the probability of establishment from flows is a step-wise function with the probability equal to zero prior to the completion of the lag time, and a function of $N_{l,t}^{F}$ following the lag time. The probability of establishment from propagules introduced from downstream flows is given in equation (16):

$$E\left(N_{l,t}^{F}\right) = \begin{cases} 0 & if\ t < t_{e_l^{up}} + m \\ 1 - e^{-\left(\alpha_F N_{l,t}^{F}\right)^{c_F}} & if\ t \geq t_{e_l^{up}} + m \end{cases} \qquad (16)$$

where $t_{e_l^{up}}$ is the time period in which the reservoir directly upstream from reservoir l becomes established.

Parameter Values for the Probability of Establishment from Flows

Values for the parameters α_F and c_F are expected to be substantially different from those estimated in the Leung et al. (2004) study, because the measure of propagule pressure is different. There is very little information available about how veligers will survive in conveyance structures like those in the Colorado-Big Thompson Project; thus, there is little data available to calibrate the α_F and c_F parameter values. Figure 6 demonstrates how different values of α_F and c_F and upstream densities affect the probability of establishment from downstream flows as a function of distance downstream. The base decay rate of $b = -.45$ is used for all of the graphs. In general, the probability of establishment from flows increases with upstream density and with α_F. The c_F parameter affects how quickly the probability of establishment drops off with distance downstream. For $c_F = 1.86$, the probability of establishment remains close to 100% for short distances and then quickly drops to 0%; whereas for $c_F = 1$, the probability of establishment drops more gradually as the distance downstream increases.

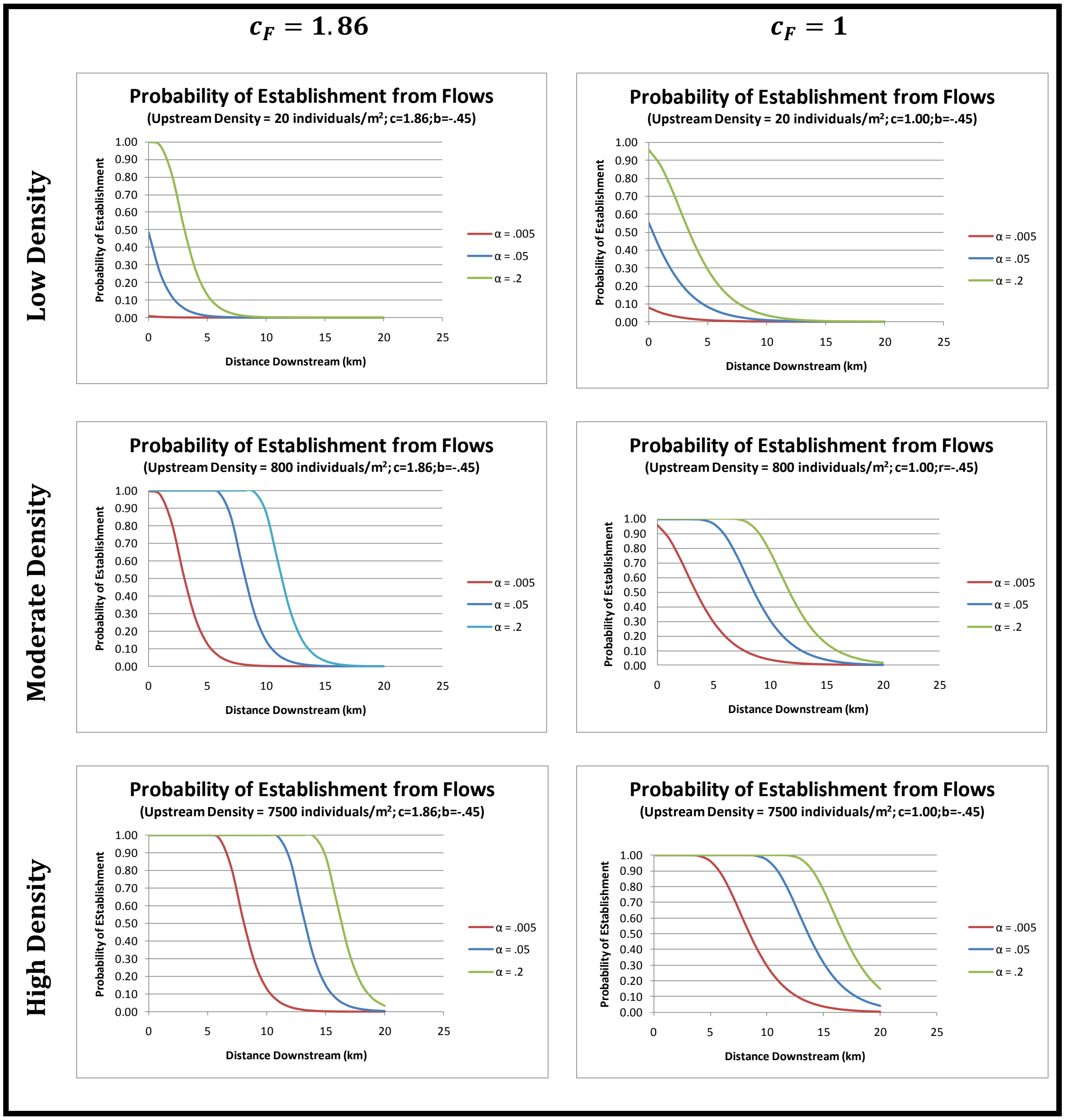

Figure 6: The probability of establishment from flows

2.2.3 Combining the Probability of Invasibility and the Probability of Establishment: The Joint Probability of Colonization

This section combines the probability of establishment with the probability of invasibility to develop the joint probability that reservoir l becomes colonized by time period s. Joint probabilities of colonization are developed for propagules introduced by boats and propagules introduced by flows. These probabilities are the key components that determine establishment in the simulation model.

Leung and Mandrak (2007) derive the joint probability of colonization as the product of the probability that a location is invasible and the probability of establishment as a function of propagule pressure over time. Given that a reservoir is invasible, the probability that reservoir l becomes established in year t can be described by a binomial distribution. Let $P(E|N_{l,t})$ be the probability that reservoir l becomes established in year t, given propagule pressure in reservoir l in year t. Then the probability that reservoir l remains unestablished in year t is equal to $1 - P(E|N_{l,t})$. The overall probability that reservoir l remains unestablished by year s is the product of the probabilities that the reservoir remains unestablished in each year t up to year s. The probability that reservoir l is established by year s, denoted $\vartheta_{l,s}$, is the compliment of the probability that it is not established by year s and is given in equation (17):

$$\vartheta_{l,s} = 1 - \prod_{t=1}^{s}(1 - P(E|N_{l,t})) \qquad (17)$$

Multiplying the probability of invasibility from equation (6) with the probability of establishment from equation (17) gives the joint probability of colonization. The joint probability that reservoir l becomes established by year s, denoted $\psi_{l,s}$, is given in equation (18):

$$\psi_{l,s} = \phi_l * \vartheta_{l,s} \quad (18)$$

Let $\psi_{l,s}^{B^0}$ and $\psi_{l,s}^{B'}$ represent the joint probabilities of colonization in reservoir l by time period s from propagules introduced by boats in the base-case scenario and the preventative management scenario, respectively. Let $\psi_{l,s}^{F}$ represent the joint probability of colonization in reservoir l by time period s from propagules introduced from an upstream infested reservoir.

2.3 Control Costs Component of the Simulation Model

The previous section described the derivation of the joint probability of colonization from boats and from flows. These probabilities are used to simulate a mussel invasion in the Colorado-Big Thompson system. Following the colonization of a reservoir, structures directly downstream from that reservoir become vulnerable to mussel biofouling and may incur mussel control costs. This section describes the development of control cost schedules for the structures and facilities in the Colorado-Big Thompson system and explains how control costs are spatially and intertemporally matched to invasion patterns. Section 2.3.1 explains how control cost schedules are matched to establishment patterns to simulate benefits of the preventative management program; Section 2.3.2 explains how capital expenditures and variable costs are handled in the model; and Section 2.3.3 describes the data used to develop control cost schedules.

2.3.1 Simulating Net Benefits

As described in the mussel dispersal component of the model, population densities in newly established reservoirs are very small, and it can take as many as 6 to 12 years before a newly established colony grows to its maximum density (Burlakova et al., 2006). To model damage costs to facilities and structures, it is assumed that all structures directly downstream from an invaded water body will incur control costs after a lag time of n years following the establishment of the source reservoir. Low, base, and high parameter values of n are set equal to 6, 8, and 10 years, respectively (Burlakova et al., 2006). To match control costs to establishment patterns, control costs for facilities directly below an infested reservoir are scheduled to begin n years following the establishment of the reservoir. Once facility control cost schedules are matched to colonized reservoirs, control costs for the entire system are summed across time and discounted. Let $\tau = 1,2,3, \dots$ be an index for control cost schedules, where $\tau = 1$ represents costs incurred in the first year mussels settle in a facility. Let $C^0_{l,t}$ and $C'_{l,t}$ be the control costs incurred by facilities under reservoir l in time period t for each scenario. Equations (19) and (20) give incurred control costs for the base-case and preventative management scenarios, respectively:

$$C^0_{l,t} = \begin{cases} 0 & if\ t < t^0_{e^l} + n \\ \sum_{s=1}^{S_l} C_{s,t+1-\tau} & if\ t \geq t^0_{e^l} + n \end{cases} \tag{19}$$

$$where\ \tau = 1\ in\ year\ t^0_{e^l} + n$$

$$C'_{l,t} = \begin{cases} 0 & if\ t < t'_{e^l} + n \\ \sum_{s=1}^{S_l} C_{s,t+1-\tau} & if\ t \geq t'_{e^l} + n \end{cases} \tag{20}$$

$$where\ \tau = 1\ in\ year\ t'_{e^l} + n$$

where $t^0_{e^l}$ and t'_{e^l} represent the first year that reservoir l is established for the base-case scenario and the preventative management scenario, respectively, S_l is the total number of structures under reservoir l, and $C_{s,t+1-\tau}$ is the incurred cost of control for structure s in year t. Let $\emptyset^0$ be the simulated net present value of control costs incurred under the base-case scenario, and let $\emptyset'$ be the simulated net present value of control costs incurred under the preventative management scenario. Equations (21) and (22) give the simulated net present value of control costs for the entire system for the base-case scenario and the preventative management scenario, respectively:

$$\emptyset^0 = \sum_{t=0}^{T} \sum_{l=1}^{N} \frac{1}{(1+r)^t} C_{l,t}{}^0 \tag{21}$$

$$\emptyset' = \sum_{t=0}^{T} \sum_{l=1}^{N} \frac{1}{(1+r)^t} C_{l,t}{}' \tag{22}$$

where N is the number of reservoirs in the system, T is the length of the time horizon, and r is the discount rate. The simulated benefits of the program are equal to the difference in the simulated net present value of incurred control costs between the base-case scenario and the preventative management scenario (i.e. $Simulated\ Benefit = \emptyset^0 - \emptyset'$). By incorporating the results of the dispersal model, $\emptyset^0$ and $\emptyset'$ integrate the probability of establishment and the costs of control. These simulated expected control costs are analogous to equations (2) and (3) in the cost-benefit model.

Choosing the Discount Rate

Choosing an appropriate discount rate for the case of preventing or slowing a dreissena invasion involves discounting benefits that may happen far in the future. Furthermore, the event of a dreissena invasion is irreversible and may cause irreversible damages such as loss of biodiversity. Discount rates for social projects are generally based on a discount factor of .95 to .99, which corresponds to discount rates between .01 and .053. Weitzman (1998) argues that the lowest discount rate possible should be used for discounting the far distant future in long-term environmental projects. Discount rates between 0 and .053 are tested as part of the sensitivity analysis to determine how sensitive results are to discounting.

2.3.2 Capital Expenditures and Variable Costs

Appendix B includes a list of all major structures and facilities associated with the Colorado-Big Thompson system. For each structure type, damage costs are split into capital expenditures and yearly variable costs. It is assumed that funds for capital expenditures are borrowed, and that funds for yearly variable costs are incorporated into yearly budgets. Control costs schedules are constructed by summing yearly variable costs with principal and interest payments for the capital expenditure loan. Principal and interest payments are calculated using the amortization formula given in equation (23):

$$P = P_0 * \frac{i(1+i)^{\omega}}{(1+i)^{\omega} - 1} \tag{23}$$

where P is the principal and interest payment, P_0 is the amount of the loan, i is the interest rate, and ω is the term length of the loan, in years.

Parameter Values for Capital Expenditure Loans

Low, base, and high interest rate values ranging between 4% and 5% are chosen based on the median and quartiles of a sample of 100 bond trades posted on the EMMA (Electronic Municipal Market Access) website in June of 2010 (MSRB, 2010). Low, base, and high loan term lengths are set at 15, 20, and 30 years, respectively.

2.3.3 Control Cost Schedules

This section details the data and methods used to develop control costs schedules for the major structures and facilities in the Colorado-Big Thompson system. Forecasting specific control costs for water systems and facilities prior to an invasion is difficult, because control costs depend on the severity of the invasion and can vary drastically from facility to facility. Control cost schedules are estimated for the major infrastructure in the Colorado-Big Thompson system using the best data available. It is important to warn that the data available to make these estimates is sparse and in many cases dated. In addition, some of the infrastructure in the system is unique, resulting in a lack of transferable cost data. Control cost schedules only account for mussel related costs incurred by facilities experiencing settling mussels, and facility costs are assumed to be zero prior to settling. Some facilities may monitor for mussels before mussels begin to settle in their facility. Proactive monitoring costs are not included in this analysis for two reasons: (1) conversations with municipalities in the Colorado-Big Thompson system suggest that the majority of municipalities in the system are not proactively monitoring for mussels, and (2) this analysis is focused on the reduction in control costs attributable to the CDOW boat inspection program. If facilities are proactively monitoring for mussels then they would likely do so with or without the presence of the boat inspection program, making the reduction in proactive monitoring costs a wash. All dollar values have been converted to 2009 dollars using the Bureau of Labor Statistics Consumer Price Index inflation calculator (Bureau of Labor Statistics).

A vulnerability report prepared by RNT Consultants (2009) for the Bureau of Reclamation assesses the vulnerability of Colorado-Big Thompson infrastructure, and finds that mussels could foul gauging stations, intake structures such as trash racks, screens, grates, and intake towers, and water conveyance structures such as piping, siphons, and parts of canals. Fouling of these structures could reduce performance and additional cleaning and inspection may be necessary. RNT also identifies minor risks to system pumping plants and power plants (Claudi & Prescott, 2009). Municipal water treatment facilities that use Colorado-Big Thompson water are also at risk of mussel fouling.

The Colorado-Big Thompson system contains 5 hydroelectric power plants, 4 pump plants, 14 dams, 24 water treatment plants, and nearly 400 km of pipelines, tunnels, and canals. Appendix B lists all of the facilities and structures considered in this analysis and their location in the system. Control cost schedules are developed for all of the water treatment plants, hydropower facilities, dams and pump plants in the system. Other system infrastructure such as pipelines, tunnels, canals, and gauging stations are also likely to incur minor damage costs if mussels are present. A description of the possible damages to these structures is included in the report; however, due to a lack of data, damage costs for these structures are not included in the analysis.

Water Treatment Facilities

Chlorine treatment is the most commonly used method for controlling mussels in water treatment facilities. Most water treatment facilities already use chlorine as part of their normal operations, so the main control costs for water treatment facilities are for retrofitting facilities to move chlorine injectors to the water intake (Deng, 1996). In general, the pattern for water treatment facilities suggests that facilities have relatively constant yearly expenditures on monitoring and control costs, and incur the greatest costs in a one-time retrofit of their facility.

Three zebra mussel control cost surveys provide data on zebra mussel related costs to water treatment facilities: the 1994 survey of raw surface water users drawing Great Lakes water conducted by Deng (1996), the 1995 National Zebra Mussel Clearinghouse survey conducted by O'Neill (1997), and the 2004

Clearinghouse follow-up survey conducted by Connelly et al. (2007). The Connelly survey is used to develop cost schedules for the water treatment facilities in the Colorado-Big Thompson system, because it provides the most recent data on zebra mussels control costs in water treatment facilities.

A fourth study by the City of Westminster provides an alternative estimate of control costs to water treatment facilities. In preparation for the possibility of an invasion in their source reservoir, the City of Westminster, near Denver Colorado, hired HDR consultants to develop a zebra and quagga mussel management plan (City of Westminster, 2010). The plan assesses the vulnerability of the City's source reservoir, Standley Lake, and develops options for controlling mussels if Standley Lake becomes infested. The control cost estimates developed in the City of Westminster report are much larger than those reported in the Connelly et al. (2007) study. This adds additional uncertainty to the potential control costs in the Colorado-Big Thompson system. To account for the possibility of larger control costs to municipalities, the model developed for the Colorado-Big Thompson system gives the option of using control cost values from the Connelly et al. (2007) study, or a combination of control cost values from the Connelly et al. (2007) study and the City of Westminster (2010) study.

Water Treatment Control Cost Estimates Based on Values from Connelly et al. (2007)

Connelly et al. (2007) find that expenditures are correlated with facility capacity, and provide summary statistics for expenditures split by capacity. Table 5 shows average per facility expenditures for the period 1989 to 2004, split by facility capacity, and Table 6 gives capacities of the water treatment facilities in the Colorado-Big Thompson system, measured in millions of gallons per day (MGD).

Table 5: Average expenditures per facility per period for the period 1989-2004; data from Connelly et al, 2007

	Average Expenditures per facility per period		
Expenditure Category	**≤ 1 MGD**	**2-10 MGD**	**≥ 11 MGD**
Prevention efforts	$17,078	$59,144	$152,468
Lost production and revenues	$0	$1,453	$0
Chemical treatment	$26,618	$21,981	$64,736
Planning, design, and engineering	$17,429	$13,140	$85,934
Retrofit and/or reconstruction	$20,989	$30,283	$53,916
Filtration or other mechanical exclusion	$2,893	$2,906	$47,352
Monitoring and inspection	$17,615	$11,387	$27,388
Mechanical removal	$2,956	$4,567	$19,179
Nonchemical treatment	$211	$0	$0
Research and development	$11	$0	$8,173
Personnel training	$911	$1,780	$3,036
Customer education	$3,571	$94	$3,443
Other	$0	$0	$39,836
Total	**$110,282**	**$146,735**	**$505,461**

Dollar values are listed as reported in Connelly et al. (2007), and are not adjusted for inflation.
MGD=Millions of Gallons per Day

Table 6: Water treatment facility capacities in the Colorado-Big Thompson system

Water Treatment Facility	Capacity (MGD)
Town of Estes	4
Mary's Lake (Town)	2
Newell Warnock	<1
City of Loveland	30
Emissaries of Divine Light	<1
Eden Valley	<1
Spring Canyon	0.25
Fort Collins	87
Soldier Canyon	50
Greeley	21
Carter Lake Filter Plant 1	20
Carter Lake Filter Plant 2	20
Town of Berthoud	4
City of Longmont 1	32
City of Longmont 2	15
Louisville 1	8
Superior	5.5
Town of Erie	12.3
Broomfield	20
City of Fort Lupton	5
City of Fort Morgan	10
City of Boulder	16
City of Lafayette	13
Louisville 2	5

Several of the categories listed in Table 5 represent one-time capital expenditures, whereas other expenditure categories represent yearly costs. It is assumed that planning, design, engineering, and retrofit/reconstruction expenditures are one-time capital expenditures that must be paid in the first year mussels start settling in the facility. The remainder of the expenditure categories, with the exception of prevention efforts, are assumed to be ongoing yearly expenses. Expenses for prevention efforts are omitted. Table 7 breaks expenditures into capital expenditures and average yearly variable costs. The values reported for the Connelly survey are aggregated over the period 1989 to 2004, thus it is difficult to adjust these values for inflation. The values in Table 7 have been adjusted to 2009 dollars based on a base year of 1997 (the mid-point between 1989 and 2004).

Table 7: Capital expenditures and yearly variable costs for water treatment facilities; based on data from Connelly et al, 2007

	Average Expenditures per facility		
	≤ 1 MGD	**2-10 MGD**	**≥ 11 MGD**
Capital Expenditures			
Planning, design, and engineering	\$23,297	\$17,564	\$114,866
Retrofit and/or reconstruction	\$28,056	\$40,479	\$72,068
Total Capital Expenditures	**\$51,353**	**\$58,043**	**\$186,934**
Yearly Principal and Interest Payment*	**\$4034**	**\$4559**	**\$14,684**
Variable Costs (average yearly values)			
Lost production and revenues	\$0	\$121	\$0
Chemical treatment	\$2,224	\$1,837	\$5,408
Filtration or other mechanical exclusion	\$242	\$243	\$3,957
Monitoring and inspection	\$1,472	\$952	\$2,288
Mechanical removal	\$247	\$381	\$1,603
Nonchemical treatment	\$17	\$0	\$0
Research and development	\$1	\$0	\$683
Personnel training	\$76	\$148	\$254
Customer education	\$298	\$8	\$287
Other	\$0	\$0	\$3,328
Total Average Yearly Variable Costs	**\$4,577**	**\$3,690**	**\$17,808**

Dollar values have been adjusted to 2009 dollars using a base year of 1997.
**Based on the base interest rate of 4.75% and loan term length of 20 years.*

Based on these values, with a base interest rate of 4.75% and a term length of 20 years for capital expenditure loans, control costs for water treatment facilities with capacities less than 1 MGD are projected to be \$8611 for $\tau = 1\ to\ \omega$, and \$4577 for $\tau > \omega$. Control costs for water treatment facilities with capacities between 2 and

10 MGD are projected to be \$8249 for $\tau = 1\ to\ \omega$, and \$3690 for $\tau > \omega$; and for facilities with capacities greater than or equal to 11 MGD, control costs are projected to be \$32,492 for $\tau = 1\ to\ \omega$, and \$17,808 for $\tau > \omega$.

Water Treatment Control Cost Estimates Based on a combination of values from Connelly et al. (2007) and the City of Westminster (2010)

Standley Lake is the source of drinking water for four water providers: the cities of Westminster, Thornton, and Northglenn, and the Farmers Reservoir and Irrigation Company (FRICO). From an intake at Standley Lake, water is delivered to the four entities via a system of pipelines totaling over 30 km in length. This type of delivery system is common along the Front Range of Colorado. In the Colorado-Big Thompson system, water is piped from Boulder Reservoir, Horsetooth Reservoir, and Carter Lake to two, three, and ten water treatment facilities, respectively. These piping systems are at risk of becoming clogged and could require expensive cleaning methods such as pigging. Although some of the municipalities in the Connelly et al. (2007) study may have incurred similar costs, it is not known if these costs are explicitly accounted for in the Connelly expenditure values. One of the options developed by the City of Westminster (2010) is to install a chlorine injection system at the intake from Standley Reservoir. This method of control would chlorinate the water in the pipelines and would prevent mussels from surviving and settling in the pipelines. A similar control strategy could be implemented at Boulder Reservoir, Horsetooth Reservoir, and Carter Lake in the Colorado-Big Thompson system.

To account for the possibility of higher costs to the cities below Boulder Reservoir, Horsetooth Reservoir, and Carter Lake, the estimated control costs developed by the City of Westminster (2010) to install a chlorine injection system at the Standley Reservoir intake are applied to these three reservoirs[3]. The remainder of the municipalities in the Colorado-Big Thompson system are assigned control cost schedules based on the per facility values reported in Connelly et al. (2007)[4]. Table 8 gives the estimated costs of installing a chlorine injection system at the intake of Standley Reservoir, and Table 9 gives alternative control cost schedules for the water treatment facilities in the Colorado-Big Thompson system.

Table 8: Estimated Expenditures to Control Mussels at the Intake of Standley Reservoir

Estimated Expenditures to Control Mussels at Intake of Standley Reservoir	
Capital Expenditures	
Chemical Feed System to Supply Oxidizing Agent at Intake	$3,200,000
Coat Existing Trash Racks (2)	$250,000
Redundant Feed System at Discharge Facility to Big Dry Creek	$2,250,000
Cathodic Protection of Valves	$200,000
Administration and Engineering	$2,360,000
Total Capital Expenditures	**$8,260,000**
Yearly Principal and Interest Payment*	**$648,827**
Variable Costs (average yearly values)	
Chloramination of Total Flow	$2,100,000
Breakpoint Chlorination of Municipal Water Supply Flow	$400,000
Total Yearly Variable Costs	**$2,500,000**

Source: (City of Westminster, 2010)
**Based on the base interest rate of 4.75% and loan term length of 20 years.*

[3] The number of municipalities served and the length of the pipeline systems for each of these reservoirs differs greatly. Thus, control costs to install a chlorine injection system are unique to each reservoir and delivery system. Individual studies of each reservoir and associated city delivery systems would be necessary to accurately account for the expected costs to install a chlorine injection system at each of these reservoirs.
[4] The Carter Lake filter plants are assumed to incur per facility costs, because they draw water directly from Carter Lake. Treated water from the Carter Lake filter plants is delivered to the Central Weld County and Little Thompson Water Districts. The remainder of the cities below Carter Lake have raw water delivered through The Northern Integrated Supply Project pipeline, which consists of over 170 km of pipeline. Expenditure costs for these cities are captured in the cost of installing a chlorine injection system at the pipeline intake at Carter Lake.

Table 9: Control cost schedules using per intake values from The City of Westminster (2010) and per facility values from Connelly et al. (2007)

Intake Reservoir	Control Costs (Per Intake)	Time Period
Boulder Reservoir	$3,148,827	$\tau \leq w$
Filter Plants Below Boulder Reservoir:	$2,500,000	$\tau > w$
City of Boulder		
City of Laffeyette		
Horsetooth Reservoir	$3,148,827	$\tau \leq w$
Filter Plants Below Horsetooth Reservoir:	$2,500,000	$\tau > w$
Fort Collins		
Soldier Canyon		
Greeley		
Carter Lake	$3,148,827	$\tau \leq w$
Filter Plants Below Carter Lake:	$2,500,000	$\tau > w$
Town of Berthoud		
City of Longmont 1		
City of Longmont 2		
Louisville 1		
Louisville 2		
Superior		
Town of Erie		
Broomfield		
City of Fort Lupton		
City of Fort Morgan		
Other Water Treatment Facilities	**Control Costs (Per Facility)**	**Time Period**
Town of Estes	$8,611	$\tau \leq w$
	$4,577	$\tau > w$
Mary's Lake (Town)	$8,611	$\tau \leq w$
	$4,577	$\tau > w$
Newell Warnock	$8,611	$\tau \leq w$
	$4,577	$\tau > w$
City of Loveland	$32,492	$\tau \leq w$
	$17,808	$\tau > w$
Emissaries of Divine Light	$8,611	$\tau \leq w$
	$4,577	$\tau > w$
Eden Valley	$8,611	$\tau \leq w$
	$4,577	$\tau > w$
Spring Canyon	$8,611	$\tau \leq w$
	$4,577	$\tau > w$
Carter Lake Filter Plant 1	$32,492	$\tau \leq w$
	$17,808	$\tau > w$
Carter Lake Filter Plant 2	$32,492	$\tau \leq w$
	$17,808	$\tau > w$

Hydropower Facilities

Retrofit and control costs for hydropower facilities can vary dramatically, as each facility is unique. Three sources provide estimates of mussel related control costs for hydropower facilities: the 1995 National Zebra Mussel Clearinghouse survey by O'Neill (1997), an estimation study conducted by Phillips et al. (2005), and an estimate by Leonard Willett, the quagga mussel cordinator for the Hoover Dam (2010).

Twenty-three hydropower facilities responded to the 1995 National Zebra Mussel Clearinghouse survey and reported spending a total of $1,759,000 over the period from 1989-1995, with a mean expenditure of $79,950 per facility. Thirteen of the twenty-three facilities were infested with zebra mussels at the time of the survey. Infested facilities had a mean expenditure of $122,154 for the period and non-infested facilities had a mean expenditure of $17,100 for the period. The largest hydropower expense was for chemical control, with an average expenditure of $34,380 per facility. The second greatest expense was for planning and engineering, with a mean expenditure of $17,865 per facility (O'Neill, 1997).

Philips et al. (2005) estimate the costs of a hypothetical zebra mussel invasion to thirteen Federal hydropower facilities in the Columbia River Basin. To develop their estimates, they use actual expenditure data from five invaded eastern hydroelectric facilities. Based on controls implemented at these facilities, they assume that the Columbia River Basin facilities will adopt NaOCL (bleach) injection and anti-fouling paint mitigation strategies. Philips et al. (2005) estimate the cost of a NaOCL injection system to be $62,599 per generator, and the cost of anti-fouling paint for trash racks to be $81,000 per generator.

Using information from industry sources, Leonard Willett (2010), the quagga mussel coordinator for the Hoover Dam, estimates that retrofit costs at dams with hydropower plants can range between $1,000 and $2,000 per megawatt of generation capacity. Retrofit costs include costs to purchase and install equipment or modify systems to protect the various generator cooling water, fire water, domestic water supply, turbine seal water, and transformer cooling water functions. Willett also estimates annual operation and maintenance costs will increase by $50 to $100 per megawatt of generation capacity. These costs do not include impacts to the dams themselves.

Table 10 lists the five hydropower facilities in the Colorado-Big Thompson Project, along with number of generators and megawatts of generation capacity for each facility. Table 11 gives capital expenditure and yearly variable cost estimates for each facility based on the three available sources. All values in Table 11 are in 2009 dollars.

Table 10: Hydropower facilities in the Colorado-Big Thompson Project

Hydropower Facility	Number of Generators	Megawatts of Generation
Mary's Lake Hydropower Plant	1	8.1
Estes Hydropower Plant	3	45
Pole Hill Hydropower Plant	1	38.2
Flatiron Hydropower Plant	2	94.5
Big Thompson Hydropower Plant	1	4.5

Table 11: Capital expenditure and yearly control cost estimates for hydropower facilities in the Colorado-Big Thompson Project

	O'Neill	Phillips	Willett*
Mary's Lake Hydropower Plant			
Capital expenditures	$25,149	$157,743	$12,150
Increase in annual operating expenditures	$8,066		$608
Estes Hydropower Plant			
Capital expenditures	$25,149	$473,230	$67,500
Increase in annual operating expenditures	$8,066		$3,375
Pole Hill Hydropower Plant			
Capital expenditures	$25,149	$157,743	$57,300
Increase in annual operating expenditures	$8,066		$2,865
Flatiron Hydropower Plant			
Capital expenditures	$25,149	$315,487	$141,750
Increase in annual operating expenditures	$8,066		$7,088
Big Thompson Hydropower Plant			
Capital expenditures	$25,149	$157,743	$6,750
Increase in annual operating expenditures	$8,066		$338

**Per megawatt values are set at the mean value provided by Willet (2010): capital costs=$1500 per megawatt of generation, yearly costs=$150 per megawatt of generation.*

The Willett (2010) estimates are chosen to develop control cost schedules for the Colorado-Big Thompson hydropower facilities based on two factors. The first is the relative magnitude of the estimates. The vulnerability report prepared by RNT Consultants states that the hydropower plants in the Colorado-Big Thompson system are expected to only face minor damages (Claudi & Prescott, 2009). The cost estimates developed by Phillips et al. (2005) are much larger than those estimated from the other studies, and thus seem unrealistic for the Colorado-Big Thompson hydropower facilities. The Willett (2010) estimates and the O'Neill (1997) estimates are similar in magnitude, but the Willett estimates offer greater differentiation between large and small power plants. The second factor that supports using the Willett (2010) estimates is that the other two estimates are based on facilities using chemical controls, whereas the Willett estimates are more general. RNT consultants comment on the potential control methods that may be used to treat mussels in affected hydropower facilities in the Colorado-Big Thompson system. Although chemical treatments are among the most commonly used control methods for zebra mussels, RNT does not believe that chemical treatment methods to protect hydropower facilities in the Colorado-Big Thompson will be acceptable due to sport fishing activities in the area. They suggest small-pore self-cleaning filters or UV systems as possible alternatives. The cost estimates produced by Phillips et al. (2005) are based on bleach injection systems, and the major control methods for the hydropower facilities surveyed in the O'Neill (1997) study are chemical controls.

Control cost schedules based on the Willett estimates are listed in Table 12. Per megawatt values are set at the mean value provided by Willet (2010), with capital costs set at $1500 per megawatt of generation and yearly increases in annual operating expenditure set at $150 per megawatt of generation.

Table 12: Control cost schedules for hydropower facilities in the Colorado-Big Thompson Project

Hydropower Facility	Control Costs
Mary's Lake Hydropower Plant	
Capital expenditures	$12,150
Yearly principal and interest payment*	$956
Increase in annual operating expenditures	$608
Total costs incurred for $\tau < \omega$	$1,564
Total costs incurred for $\tau \geq \omega$	$608
Estes Hydropower Plant	
Capital expenditures	$67,500
Yearly principal and interest payment*	$5,310
Increase in annual operating expenditures	$3,375
Total costs incurred for $\tau \leq \omega$	$8,685
Total costs incurred for $\tau > \omega$	$3,375
Pole Hill Hydropower Plant	
Capital expenditures	$57,300
Yearly principal and interest payment*	$4,508
Increase in annual operating expenditures	$2,865
Total costs incurred for $\tau \leq \omega$	$7,373
Total costs incurred for $\tau > \omega$	$2,865
Flatiron Hydropower Plant	
Capital expenditures	$141,750
Yearly principal and interest payment*	$11,151
Increase in annual operating expenditures	$7,088
Total costs incurred for $\tau \leq \omega$	$18,239
Total costs incurred for $\tau > \omega$	$7,088
Big Thompson Hydropower Plant	
Capital expenditures	$6,750
Yearly principal and interest payment*	$338
Increase in annual operating expenditures	$531
Total costs incurred for $\tau \leq \omega$	$869
Total costs incurred for $\tau > \omega$	$338

Per megawatt values are set at the mean value provided by Willet (2010): capital costs=$1500 per megawatt of generation, yearly costs=$150 per megawatt of generation.
**Based on the base interest rate of 4.75% and loan term length of 20 years.*

Dams

The only specific data available for dams is from the 1995 Clearinghouse study (O'Neill, 1997). Nine impoundments and reservoirs responded to the survey, but none of these facilities were infested at the time of the survey. They reported combined monitoring costs of $27,100 from 1991 through 1995, with a mean expenditure per facility of $3,010, a minimum expenditure of $1000, and a maximum expenditure of $17,500. This data is not appropriate for this study, because cost schedules in this study are based on control costs for infested facilities.

In assessing the vulnerability of dams in the Colorado-Big Thompson Project, RNT Consultants (Claudi & Prescott, 2009) find that dam trash racks are especially at risk of biofouling. In the case of infestation, RNT recommends that the inspection cycle for trash racks be increased from once every 5-years to quarterly. They also suggest that trash racks can be painted with anti-fouling paint if frequent cleaning is required. Beyond the potential for trash rack fouling, each of the dams in the system have unique issues that could result from a mussel infestation. Some may have issues with pitting corrosion of metal gates, spillway fouling, or pipe fouling. In general, the potential damages to dams reported by RNT appear to range from none to moderate. The potential for biofouling of trash racks is common across many of the dams in the system, and estimates of the costs of painting trash racks are available from the City of Westminster (2010) study. Using this information, control cost schedules for dams are based on the cost of painting dam trash racks with anti-fouling paint. Information from the City of Westminster (2010) study suggests that the cost of painting trash racks with anti-fouling paint is about $25,000 per trash rack for the coating application and about $100,000 per trash rack to hire divers to remove and replace the trash racks. Table 13 gives the number of trash racks for each of the dams in the Colorado-Big Thompson Project.

Table 13: Dams in the Colorado-Big Thompson Project

Dams	Number of Trash Racks
Willow Creek Dam	1
Granby Dam	1
Shadow Mountain Dam	0
East Portal Reservoir	1
Olympus Dam	1
Rattlesnake Dam	1
Flatiron Dam	1
Horsetooth Dam	1
Soldier Dam	1
Dixon Dam	0
Spring Canyon Dam	0
Carter Lake Dam 1	1
Carter Lake Dam 2	0
Carter Lake Dam 3	0

Control costs schedules for dams are built based on a 5-year useful life of paint. Thus, costs for dams are equal to $0 in every year for dams with no trash racks, and equal to $125,000 every fifth year for dams that have one trash rack. The Adams Tunnel also has trash racks that are vulnerable to mussel fouling (Claudi & Prescott, 2009). The trash racks at the intake to the Adams Tunnel are large, and it is assumed that the cost to paint the Adams Tunnel trash racks are twice the cost of painting dam trash racks.

Pump Plants

No information was found on the control costs for pump plants. According to the RNT vulnerability assessment, pump plants that are dry for more than one month each year should have very few mussel related issues. Any settled mussels would die of desiccation over the winter when the pump plant was dry, and summer growth would result in little to no effect on the piping, flow capacity, or pump systems (Claudi & Prescott, 2009). Table 14 lists all of the pump plants in the system and shows if they are dry for at least one month each year. Control costs for pump plants that are dry for at least one month each year are assumed to be zero.

Table 14: Pump plants in the Colorado-Big Thompson Project

Pump Plants	Dry for at least one month?
Windy Gap Pump Plant	no
Willow Creek Pump Plant	yes
Farr Pumping Plant	no
Flatiron Reversible Pump	yes
West Longmont Pumping Plant	no
Louisville/Superior Pumping Plant	no

For lack of better information, the remainder of the pump plants are assumed to incur costs similar to a mid-sized hydropower facility. Capital expenditures and yearly variable costs for the Windy Gap, Farr, West Longmont, and Louisville/Superior pump plants are set equal to those for the Estes Hydropower Plant.

Other Infrastructure

According to the RNT vulnerability report (Claudi & Prescott, 2009), gauging stations, intake towers, and conveyance structures such as piping, siphons, and parts of canals are vulnerable to mussel fouling. Fouling of these structures could reduce performance and additional cleaning and inspection may be necessary. No cost information was found on control costs for these structures, and potential costs to these structures have not been included in the analysis. In a conversation with Fred Nibling of the of the Bureau of Reclamation, he explained that costs for cleaning and inspecting these types of infrastructure are already incurred and that it is often difficult to separate costs of other maintenance activities from those resulting from mussel fouling (Nibling, May 14, 2010). Difficulty in separating mussel related costs was also reported in the Phillips and Connelly studies (Phillips et al., 2005; Connelly et al., 2007). The addition of mussels to the Colorado-Big Thompson system would likely increase the frequency and possible duration of regular maintenance and inspections, but this value is difficult to quantify. Thus, estimates for control costs in the system should be considered a lower bound.

Other Affected Industries

Industrial facilities and fossil fuel-fired electric generating facilities that use raw water as part of their operations have been found to incur large damage costs from zebra mussel infestations (O'Neill, 1997; Deng, 1996). The extent of these types of industrial activities using raw Colorado-Big Thompson water is unknown, but believed to be small. Colorado-Big Thompson water is managed and sold by the

Northern Colorado Water Conservancy District, and almost all of their clients are municipalities and irrigators. Therefore, unless municipalities sell raw Colorado-Big Thompson water to industrial users, industries using Colorado-Big Thompson water are not likely to incur mussel control costs.

The Platte River Power Authority (PRPA) is a Windy Gap client (Emsley, June 28, 2010). PRPA cools their fossil-fuel fired power plant with raw water from Hamilton Reservoir. The majority of the water used to fill Hamilton Reservoir is effluent from the City of Fort Collins Waste Water Treatment Plant. A small portion of the water in the reservoir comes from Horsetooth Reservoir. Therefore, if Horsetooth were to become infested, PRPA would likely incur control costs. The PRPA power plant is not included in the analysis.

Raw water is often used to irrigate parks and golf courses. In the case of a mussel infestation, these users would either need to install filtration systems or switch to purchasing treated water. The cost of filtration systems can be large, and it is expected that these users would likely switch to purchasing treated water. Increased water costs to park and golf course irrigators are not included in the analysis.

If faced with a mussel infestation, irrigators using micro-irrigation systems and overhead systems may encounter problems. Both irrigation systems involve pipes that may become clogged by mussels. For these irrigators, sand filters or mechanical filters at the surface water source may be the best option for controlling mussels. However, these filtration systems are very expensive, which could lead farmers to substitute away from sprinkler irrigation (Michigan Sea Grant College Program, 1993). Potential control costs to irrigators are not included in the analysis.

2.4 Colorado-Big Thompson Zebra and Quagga Mussel Dispersal and Damage Cost Simulation Model

This section describes the bioeconomic simulation model developed for the Colorado-Big Thompson system, and explains how the dispersal component of the model is paired with the control cost component of the model to simulate the net benefits of the preventative management program. The Colorado-Big Thompson zebra and quagga mussel dispersal and damage cost simulation model is developed in Microsoft Excel 2007 using Visual Basic 6.5. The Visual Basic code used to run the model is reproduced in Appendix D. The model simulates a mussel invasion in the Colorado-Big Thompson system starting with a base year of 2009 and extending for a ten, thirty, or fifty year time horizon. The base-case scenario and the preventative management scenario are run simultaneously for 1000 iterations, and the model outputs a distribution of establishment patterns and associated control costs for each scenario. An Excel-based interface allows users to easily change parameter values to test how parameters affect establishment patterns and control costs in the system.

To develop establishment patterns, the joint probability of colonization from propagules introduced by boats and the joint probability of colonization from propagules introduced by downstream flows are calculated for each reservoir in each year for each scenario. Joint probabilities are functions of propagule pressure from boats and from flows, the invasibility of the reservoir, and the state of the environment in previous years.

The probability of establishment from downstream flows is dependent on upstream relationships and flow distances, so the probability of colonization from downstream flows requires information about how the reservoirs in the system are connected. Figure 3 on page 13 shows directions of flow and distances between reservoirs. Windy Gap Reservoir and Willow Creek Reservoir are at the head of the system, and are considered to have no upstream water bodies. This implies that these reservoirs are not vulnerable to establishment from upstream water bodies, which makes the strong assumption that the system cannot receive veligers flowing from waters outside of the Colorado-Big Thompson system. Flow between Flatiron Reservoir and Carter Lake is reversible, making each of these reservoirs potentially upstream from one another. The majority of the reservoirs in the system have one upstream water body. Lake Granby, Flatiron Reservoir, and Carter Lake all have two upstream water bodies. To accommodate for the possibility of two upstream water bodies, two values for propagule pressure from an upstream water body are calculated for each reservoir. Let $\psi_{l,s}^{F^1}$ and $\psi_{l,s}^{F^2}$ be the joint probabilities of colonization from propagules introduced by flows from upstream water body 1 and upstream water body 2, respectively, and let $\psi_{l,s}^{B^0}$, and $\psi_{l,s}^{B'}$ be the joint probabilities of colonization from propagules introduced by boats under the base case scenario and under the preventative management scenario, respectively.

Using the joint probabilities of colonization, establishment patterns are determined through a series of Bernoulli trials. In each year and for each scenario, three Bernouill trials are conducted for each water body (Bossenbroek et al., 2001). The first trial is based on the joint probability of colonization from propagules introduced by boats ($\psi_{l,s}^{B^0}$ for the base-case scenario, and $\psi_{l,s}^{B'}$ for the preventative management scenario), the second trial is based on the joint probability of colonization from propagules introduced from upstream water body 1, $\psi_{l,s}^{F_1}$, and the third is based on the joint probability of colonization from propagules introduced from upstream water body 2, $\psi_{l,s}^{F_2}$. A water body is deemed established if at least one of the Bernoulli Trials results in establishment[5]. Established upstream water bodies become possible sources of invasion m years after establishment, and once a water body is established, it remains established in all subsequent years.

To simulate total control costs in the system, structures and facilities directly downstream from invaded reservoirs are assumed to incur control costs n years after the reservoir directly upstream becomes established. Let t_{e^l} be the first year that reservoir l becomes established. Control cost schedules for each of the structures directly below reservoir l are matched in time such that $\tau = 1$ in year $t = t_{e^l} + n$. Control costs are summed over all reservoirs and all years and then discounted to find the net present value of incurred costs. The model outputs the

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[5] A shortcoming of this method is that it does not allow for a mix in propagule pressure from boat introductions and from flow introductions. The units used to measure propagule pressure from boats and propagule pressure from downstream flows are not compatible; however, it is possible that propagules introduced by boats could interact with propagules introduced by flows to increase the overall propagule pressure in a reservoir. This would serve to increase the probability that propagules establish a colony.

net present value of incurred costs for each scenario and the difference in costs between each scenario to provide a distribution of benefits of the preventative management program. Net benefits are calculated as program benefits less program costs.

2.5 Boat Inspection Program Costs

The costs of the CDOW boat inspection program are equal to the sum of the direct costs to water recreation managers and the indirect costs incurred by recreational boaters. Water recreation managers, including CDOW and local recreation managers, incur direct costs of implementing the boat inspection program. These direct costs include inspector training costs, administrative costs, and costs to build and service inspection stations. Boaters do not pay a fee to have their boats inspected, but they do incur indirect costs associated with the inspections. All boaters are required to get their boats and trailers inspected and possibly decontaminated and thus incur time and hassle costs.

2.5.1 Direct Costs of the Boat Inspection Program

The direct costs of the CDOW boat inspection program are estimated using 2009 and 2010 budgets and expenditure information. The largest costs of the program are for staffing, followed by decontamination units, equipment and materials, and training. Costs of capital are interest free and are calculated using straight-line depreciation. The life of the asset is assumed to be equal to the term length of capital expenditure loans. Total yearly variable costs for implementing the program in the Colorado-Big Thompson system are $827,206 per year, and yearly payments towards the cost of capital are $4656 per year.

Direct costs of implementing the boat inspection program on Horsetooth Reservoir and Carter Lake

Inspections at Horsetooth Reservoir and Carter Lake are managed by Larimer County, and CDOW compensates the County for the costs of the inspections. Inspection costs for Horsetooth Reservoir and Carter Lake are based on the 2010 Aquatic Nuisance Species (ANS) Inspection budget contract between CDOW and Larimer County and are listed in Table 15 (Brown, June 21, 2010).

Table 15: Direct costs of implementing the boat inspection program on Horsetooth Reservoir and Carter Lake

Horsetooth Reservoir and Carter Lake	
Capital Expenditures	
Decontamination Units (4 at $8000 each)	$32,000
Yearly Principal Payment (Interest Free)	**$1,600**
Yearly Variable Costs	
Training	$3,682
Staffing	$299,313
Equipment	$18,990
Forms	$3,000
Brochures	$2,500
Total Yearly Variable Costs	**$327,485**

Direct costs of implementing the boat inspection program on the Grand County Reservoirs

CDOW manages inspections at the Grand County Reservoirs (Lake Grandby, Shadow Mountain Reservoir, and Grand Lake). Inspection costs for the Grand County reservoirs are based on the 2009 CDOW ANS Inspection budget and are listed in Table 16 (Brown, June 21, 2010).

Table 16: Direct costs of implementing the boat inspection program on the Grand County reservoirs

Grand County Reservoirs	
Capital Expenditures	
Decontamination Units (6 at $6500 each)	$39,000
Equipment	$22,118
Yearly Principal Payment (Interest Free)	**$3,056**
Yearly Variable Costs	
Training	$1,458
Staffing	$370,400
Operating Expenditures (including brochures, signs, equipment, supplies, travel, per diem, equipment repair, building materials, road materials, equipment repair and maintenance, uniforms, training materials, gas, etc)	$22,118
Vehicle Lease ($1400/month x 5 months)	$7,000
Travel and Mileage (1000 miles/month x 5 months x $.45/mile)	$2,250
Total Yearly Variable Costs	**$403,226**

Direct costs of implementing the boat inspection program on Boulder Reservoir

The City of Boulder owns and manages Boulder Reservoir, and is responsible for boat inspections on the reservoir. Inspection costs for Boulder Reservoir are based on 2009 expenditures. In 2009, inspections were only conducted for three-quarters of the boating season. To project full season costs for inspection on

Boulder Reservoir, 2009 expenditures are multiplied by four-thirds (Cole, April 8, 2010). Projected costs for implementing the boat inspection program on Boulder Reservoir are listed in Table 17.

Table 17: Direct costs of implementing the boat inspection program on Boulder Reservoir

Boulder Reservoir	
Yearly Variable Costs	
Staffing	$88,461
Signage	$1,333
Materials	$6,700
Total Yearly Variable Costs	**$96,495**

2.5.2 Indirect Costs of the Boat Inspection Program

This section describes the methods used to estimate the indirect costs that boaters face as a result of the boat inspection program. Indirect costs to boaters are measured as reduced consumer surplus to boaters. As described in the cost-benefit model, $X_{l,t}$ represents reduced welfare to boaters on reservoir l in time period t. Let W be the average consumer surplus per boater per boating day for the base-case scenario. The added time costs incurred as a result of boat inspections may induce some boaters to stay home. The percent reduction in boat trips is given as ρ and is described in Section 2.2.2(a). For boaters that stay home, the entire value of W is charged to the indirect costs. For the remainder of boaters who continue to boat as frequently as in the base-case scenario, a fraction of W, equal to the portion of an average boater day that is spent getting a boat inspection, is charged to the indirect costs. Let $Q_{l,t}$ represent the number boaters visiting reservoir l in time period t for the base case scenario. $Q_{l,t}$ is equal to the number of boats visiting reservoir l in time period t, $B^0_{l,t}$, multiplied by the average number of persons per boat, k. The indirect costs to boaters on reservoir l during time period t are given in equation (24):

$$X_{l,t} = W * \rho Q_{l,t} + \frac{L}{D} * W * (1 - \rho) Q_{l,t} \qquad (24)$$

where L is the average length of a boat inspection, and D is the average length of a boater day.

The value estimated for $X_{l,t}$ using equation (24) will be an overestimate, because the equation assumes that the consumer surplus for boaters who choose to stay home is $0 dollars, and thus ignores substitutions options. Boaters who are deterred by the boat inspection program may substitute to hand-launched boats, which do not require inspections, or may substitute to other recreational activities. Thus, the true reduction in consumer surplus is less than W, and is equal to the difference between W and the consumer surplus derived from the substitute activity. This overestimate is accounted for in the model results by bounding surplus estimates between $0 dollars and the high estimates provided by equation (24).

Parameter Values for the Indirect Costs Equation

The choice of parameter values for ρ are detailed in Section 2.2.2(a), with low, base, and high values of ρ set to 0, 0.01, and 0.03. Values for $Q_{l,t}$ are equal to the values of $B^0_{l,t}$ listed in Table 4 multiplied by the average number of people per boat, k. The remainder of this section describes the choice of parameter values for W, L, k and D.

Consumer Surplus per Boater per Day

The parameter value for W, average consumer surplus per boater per boating day, is estimated using the method of benefit transfer. Benefit transfer is an accepted method for evaluating management and policy impacts when primary research is not possible due to budget constraints or time limitations (Rosenberger & Loomis, 2000; Kaval & Loomis, 2003). Several conditions are necessary for performing effective benefits transfers. The first necessary condition is that the impacts of the policy being evaluated must be clearly defined. For the case of the CDOW boat inspection program, the impact being evaluated is the increase in boater costs incurred due to wait times for boat inspections. Specifically, this analysis is concerned with increased costs to recreationists using trailered boats on one of the seven boatable reservoirs of the Colorado-Big Thompson system. Another necessary condition is that the markets for and conditions of the study site and the policy site are similar.

In 2003, Kaval and Loomis (2003) compiled a comprehensive database of all studies that estimate outdoor recreation use values published between 1967 and 2003. Their database contains fifteen studies that estimate consumer surplus per person per day for motor boating. Within these studies, a total of 32 boater consumer surplus measures were estimated. Consumer surplus per boater per day estimates ranged between \$4.31 and \$232.01, with a mean of \$52.72 and a standard error of $8.46 (all values are converted to 2009 dollars using the Bureau of Labor Statistics inflation calculator). Kaval and Loomis separate studies by region, to provide region specific consumer surplus estimates. Seven of the fifteen motorboat studies were within the Intermountain Region. Consumer surplus per boater per day values for the Intermountain Region studies range between $6.03 and $232.01, with a mean of $61.16, a standard error of $21.61, and a standard deviation of $57.17. The base value for W is set at the average value for the Intermountain Region. Low and high values of W are set at two standard errors below and above the average.

Average Length of a Boater Day

In a recreational boater survey conducted by the US Coast Guard in 2002, the average length of a boater day, including all boat types, is reported as 5.4 hours per day (US Coast Guard , 2002). This average includes hand-launched boats such as canoes, kayaks, and inflatable boats, which are not affected by the CDOW boat inspection program. Trailered boats are the focus of this study, as these are the only type of boats affected by the mandatory boat inspection program. The average day length for trailered boats, excluding houseboats, is 5.5 hours per day. This data was collected from a national sample of boaters and includes recreation environments, such as ocean boating, that are very different from recreational boating opportunities in Colorado. Data from inspections at Grand Lake in 2009 provides local information on the length of a boater day. Inspectors at Grand Lake recorded the time of launch, and the time of the post-launch clean, drain, and dry check. This data provides some evidence as to the distribution of boater day lengths. Figure 7 shows the distribution of boater day lengths on Grand Lake in 2009. The average day length is 4.6 hours with a median day length of 3.2 hours. Based on the US Coast Guard recreation survey and data from Grand Lake, parameter values for D are set to range from a low of 2 hours per day to a high of 5.5 hours per day, with a base value of 3.2 hours per day.

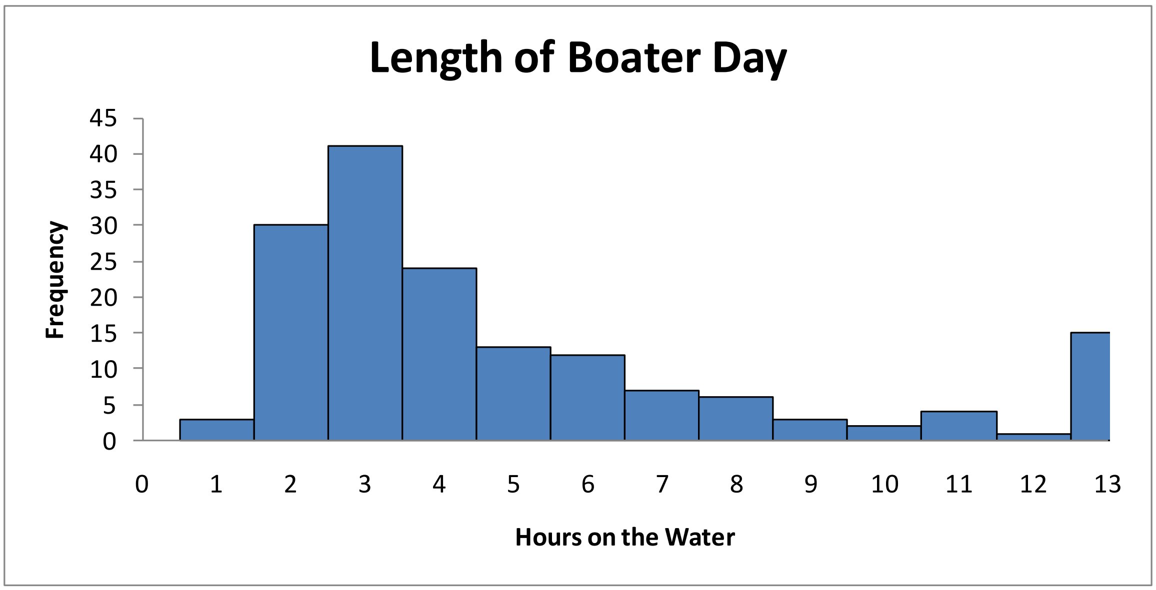

Figure 7: Distribution of boater day lengths for Grand Lake

Average Number of Persons per Boat

The US Coast Guard survey also reports average persons per boat (US Coast Guard , 2002). The base value for k is set at 3.63, the average number of people per trip for people using sailboats, open motorboats, cabin motorboats, and personal watercraft (excludes pontoons and houseboats). The low value is set at 2.94, the average for non-motorized sailboats, and the high value is set at 4.5, the overall average for all trailered boats (including pontoon boats and houseboats).

Average Length of a Boat Inspection

CDOW reports the average length of a standard inspection to be 3 minutes, and the average length of a high-risk inspection to be 20 minutes. In 2009, a total of 399,104 inspections were conducted in the state. Of these, 296,611 were standard inspections, 5647 were high-risk inspections, and 3364 were decontaminations; the remaining inspections were clean, drain, and dry checks. CDOW reports that, on average, standard inspections take 3 minutes and high-risk inspections and decontaminations take 20 minutes (CDOW, 2009). Assuming that clean, drain, and dry checks take the same amount of time as standard inspections, the weighted average overall inspection time for all inspections is 3.4 minutes, or .06 hours. In addition to the time it takes to actually be inspected, boaters may have to wait in a line to get their inspection or travel out of their way to go to an inspection station. Based on wait/travel times of 0 minutes, 10 minutes, and 20 minutes, respectively, the inspection time parameter, L, is assigned a low value of .06 hours, a base value of .22 hours, and a high value of .39 hours.

CHAPTER 3: RESULTS

This chapter highlights results of the bioeconomic simulation of the costs and benefits of preventative management in the Colorado-Big Thompson system. The focus is on how the preventative management program affects establishment patterns and associated control costs in the system. Special attention is paid to the spatial and intertemporal distribution of mussel establishment and associated control costs.

Based on trends in establishment patterns and control costs, the reservoirs in the system naturally break into three groups: the Grand County reservoirs (Willow Creek Reservoir, Lake Grandby, Shadow Mountain Reservoir, and Grand Lake), the central reservoirs (East Portal Reservoir, Mary's Lake, Lake Estes and Pinewood Reservoir), and the Front Range reservoirs (Horsetooth Reservoir, Flatiron Reservoir, Carter Lake, and Boulder Reservoir); see Figure 3, which is reproduced on page 108. Windy Gap Reservoir is omitted from the discussion, because it remains unestablished in all model runs.

Model results are generated by running the simulation with each of the model parameters set at their base values. A description of each of the variables used in the model is included in Appendix A, and a table of base parameter values is included in Appendix C. To test the sensitivity of results to parameter values, each variable is tested by holding all variables at their base values and varying one variable at a time. In some cases, combinations of non-base parameter values are tested to see how different levels of variables interact to affect the results. To account for uncertainty in the initial state of the system, the model is run both with the assumption that the Grand County reservoirs are established in 2009 and with the assumption that the Grand County reservoirs are unestablished in 2009. To account for uncertainty in the magnitude of control costs, the model is run using the low estimates of control costs to water treatment facilities developed from the Connelly et al. (2007) study, and with the high estimates developed from the City of Westminster (2010) study.

Section 3.1 describes program costs, establishment patterns and associated control costs using the base parameter values, and highlights differences in results based on the initial state of the Grand County reservoirs and on the level of water treatment control costs used. The section is broken into two subsections: the first describes establishment patterns in the system and highlights differences between the three groups of reservoirs, and the second provides results of the cost-benefit analysis. Section 3.2 describes the results of the sensitivity analysis. To test result sensitivity to parameter levels, the model variables are broken into five subsections, each describing a different aspect of the simulation. The parameter groups tested include environmental parameters, boat pressure parameters, flow parameters, program parameters, and economic parameters. To account for the fact that the Colorado-Big Thompson system has an overall low probability of invasibility, Section 3.3 considers how results would change for a similar system with very high probabilities of invasibility. In Section 3.4, conditions and parameter values that result in benefit-cost ratios greater than 1 are identified.

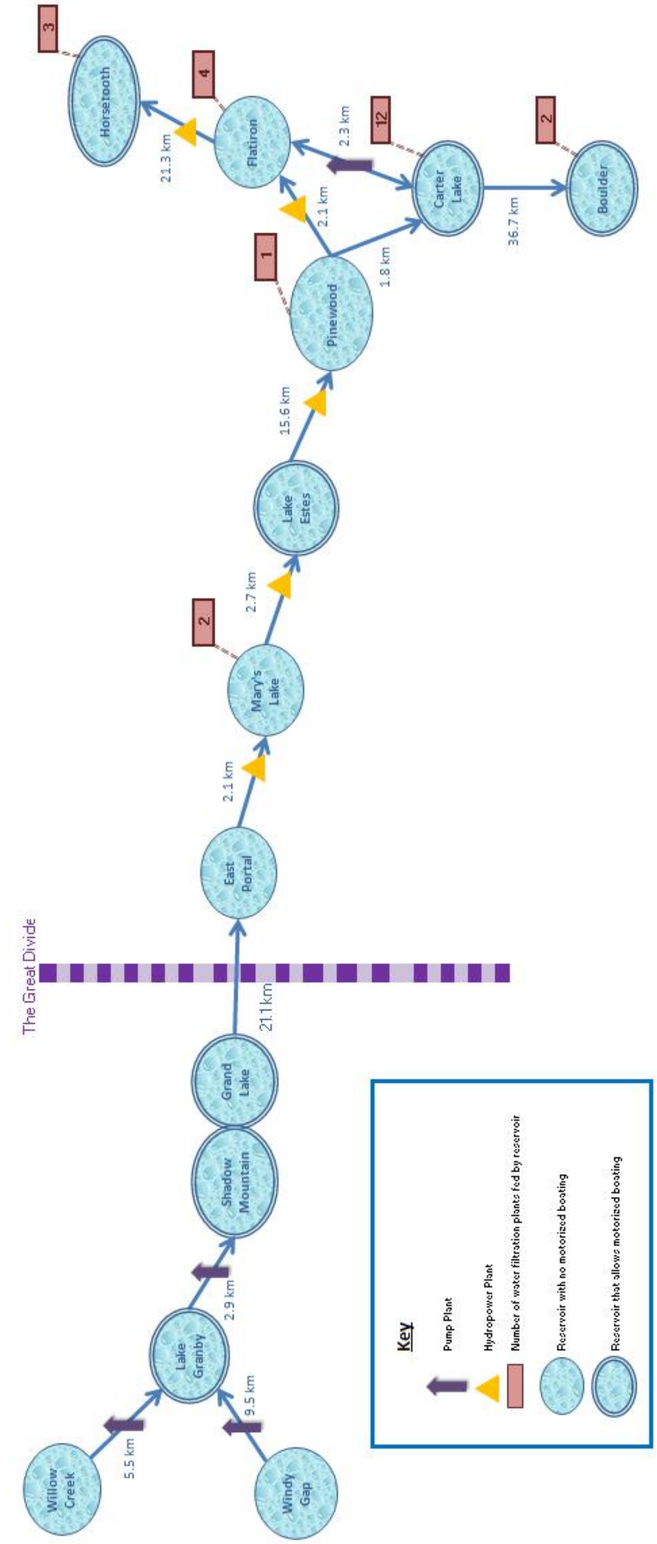

Figure 3: Schematic of the Colorado-Big Thompson system

3.1 Model Results using Base Parameter Values

This section describes results of the bioeconomic simulation of the costs and benefits of preventative management in the Colorado-Big Thompson system using the set of base parameter values. Overall, the results suggest that the preventative management program is very effective at reducing the probability that reservoirs in the system become established; however, program benefits, measured as reduced control costs to dams, pump plants, hydroelectric facilities, and water treatment facilities, are substantially smaller than program costs. The spatial layout of the system, the environmental characteristics of the reservoirs, the level and location of recreational boating activity, and the type of infrastructure in the system play a key role in determining colonization frequency and timing and the associated benefits of the preventative management program.

Section 3.1.1 describes establishment patterns and timing of establishment in the system and details the factors affecting establishment patterns and control costs across the three groups of reservoirs. Section 3.1.2 provides results of the cost-benefit analysis and discusses the factors that drive the results.

3.1.1 Baseline Establishment Patterns

Figures 8 through 11 show the simulated establishment patterns and timings of establishment in the system over a 50-year horizon. Figures 8 and 9 show results when the Grand County reservoirs are assumed established in 2009, and Figures 10 and 11 show results when the Grand County reservoirs are assumed unestablished in 2009. For most of the reservoirs in the system, the preventative management scenario results in no establishment over the 50-year horizon. Horsetooth Reservoir is the only reservoir that has a chance of establishment in the preventative management scenario, and the chance is very small. For the base-case scenario, the simulation results show strong spatial patterns in establishment across the system. The spatial layout of the system and the potential vectors of spread to each group make establishment patterns in the Grand County reservoirs, the central reservoirs, and the Front Range reservoirs independent from each other. Referring to Figures 8 and 10, establishment patterns in the central and Front Range reservoirs are independent of the initial state of the Grand County reservoirs.

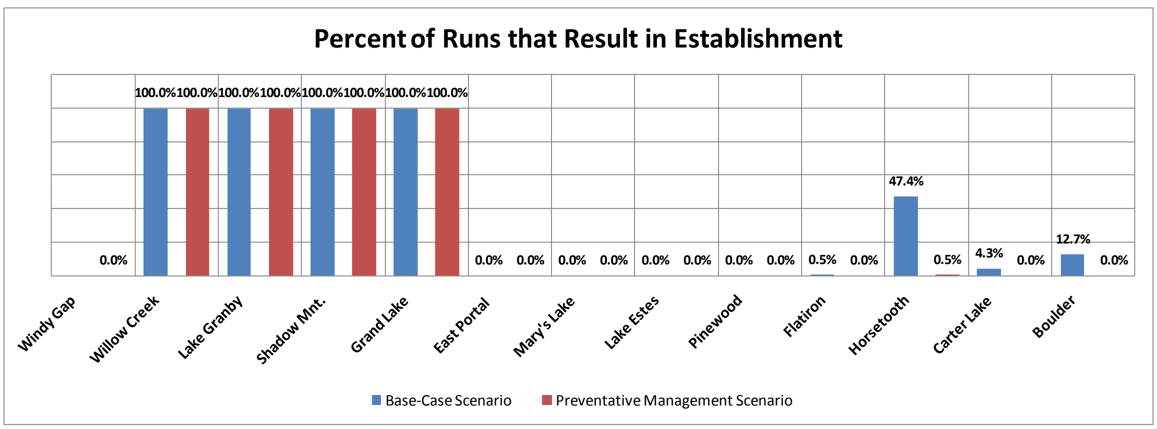

Figure 8: Simulated establishment patterns; generated using model base parameter values and assuming Grand County reservoirs are established in 2009.

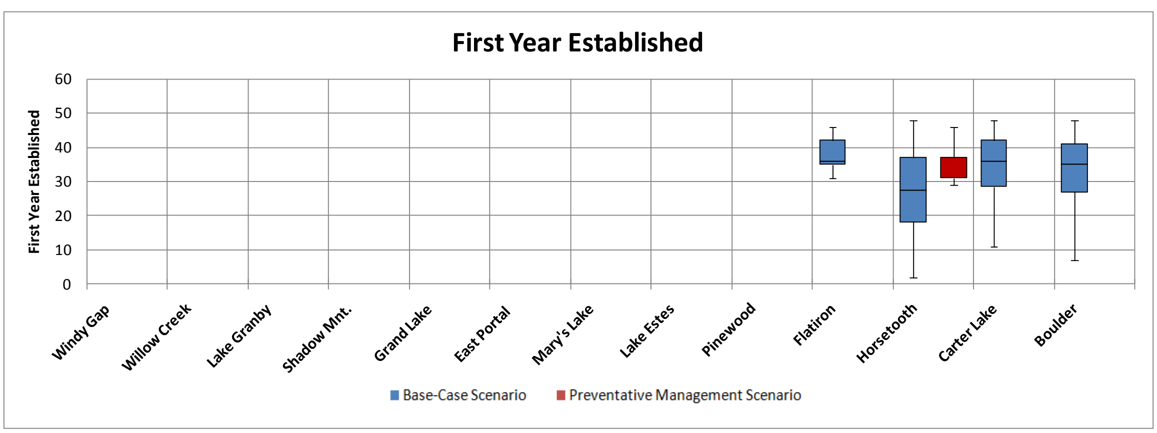

Figure 9: Simulated timings of establishment; generated using model base parameter values and assuming Grand County reservoirs are established in 2009.

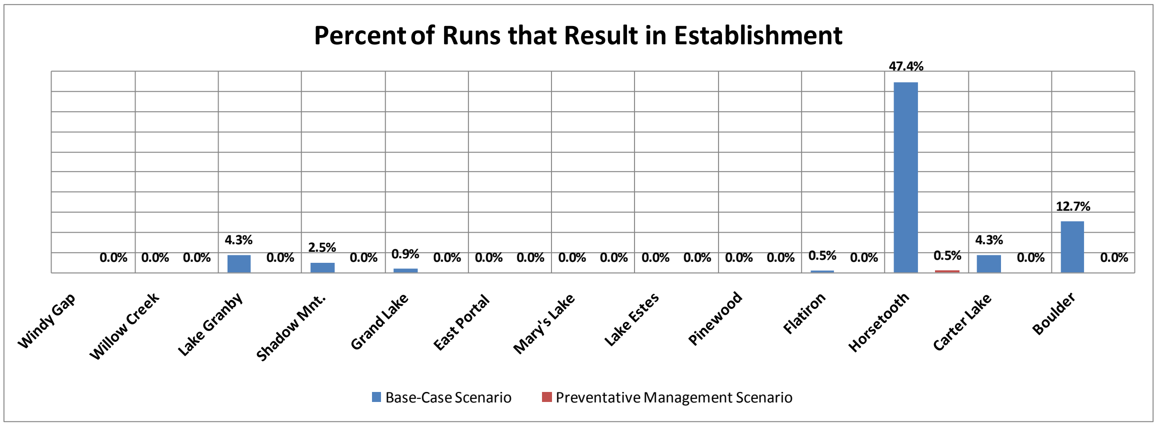

Figure 10: Simulated establishment patterns; generated using model base parameters and assuming Grand County reservoirs are unestablished in 2009.

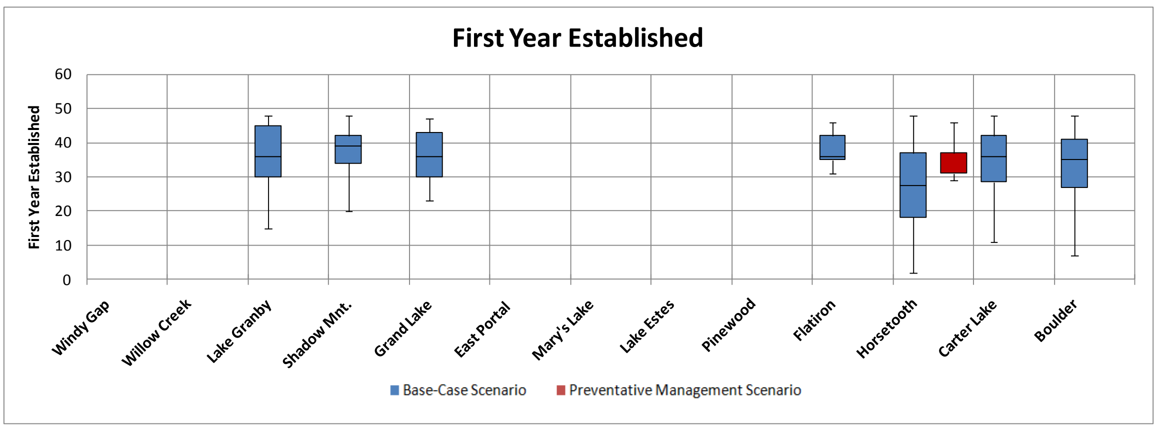

Figure 11: Simulated timings of establishment; generated using model base parameter values and assuming the Grand County reservoirs are unestablished in 2009.

Establishment is stochastically determined by the joint probability of colonization, which is a function of the environmental suitability of the reservoirs, propagule pressure from boats, and propagule pressure from flows. The importance of each of these factors differs between the reservoir groups. Figure 12 shows propagule pressure from boats, Figure 13 shows the joint probability of colonization from boats, and Figure 14 shows the joint probability of colonization from flows. For all reservoirs, the joint probabilities of colonization from boats remain below 0.02 for the entire horizon, and the joint probabilities of colonization from flows remain below 0.0007 for the entire horizon. The very low probabilities of establishment from flows result in flows making very little contribution to the establishment of reservoirs in the system. The relatively low probabilities of colonization from boats result in a low frequency of establishment throughout the entire system.

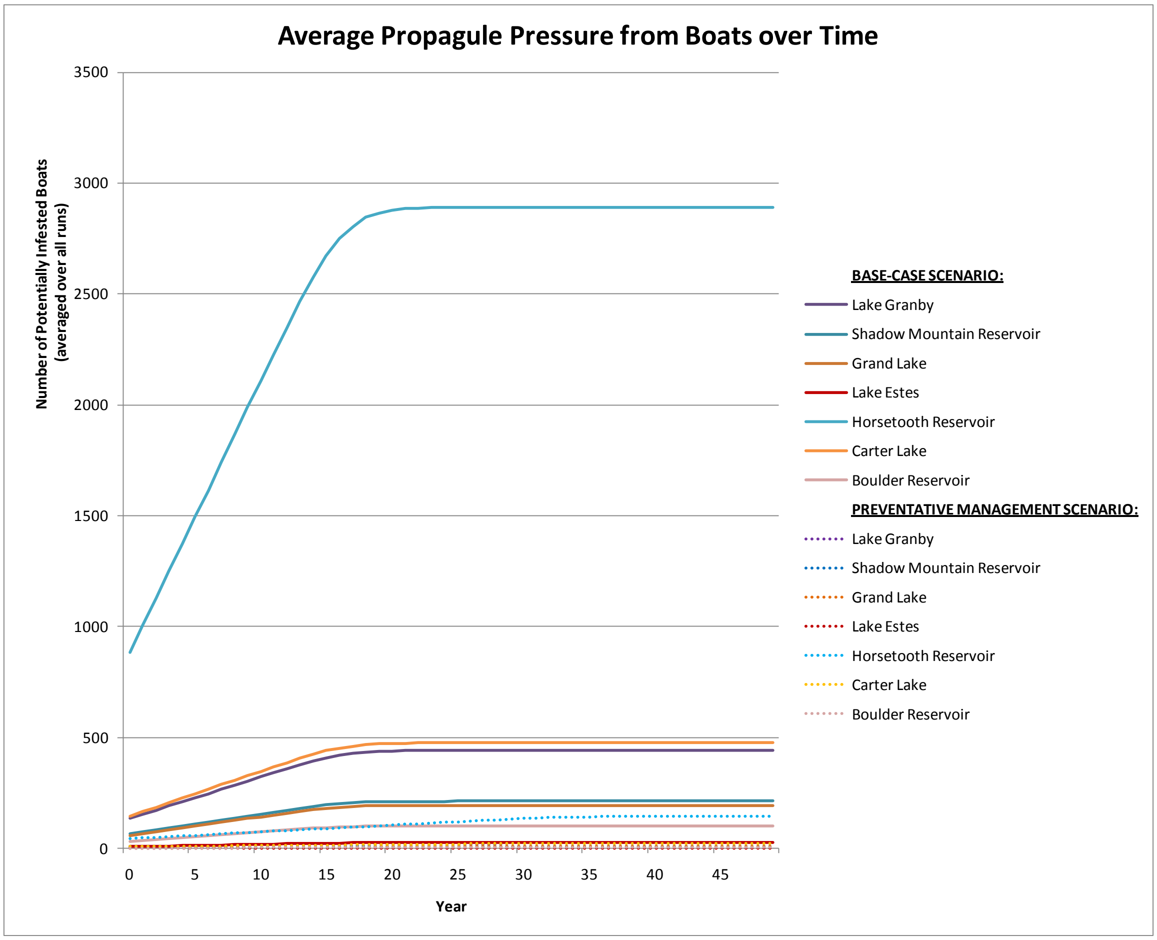

Figure 12: Simulated average propagule pressure from boats; generated using model base parameter values.

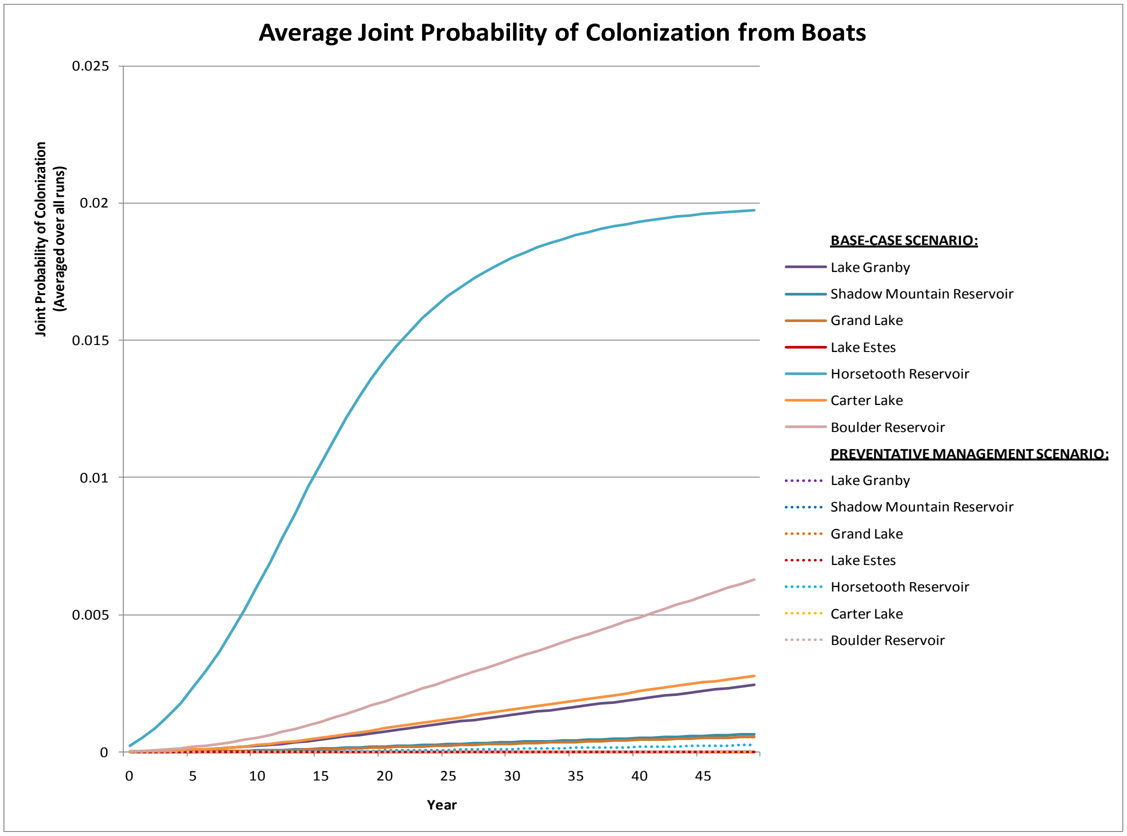

Figure 13: Simulated average joint probability of colonization from boats; generated using model base parameter values.

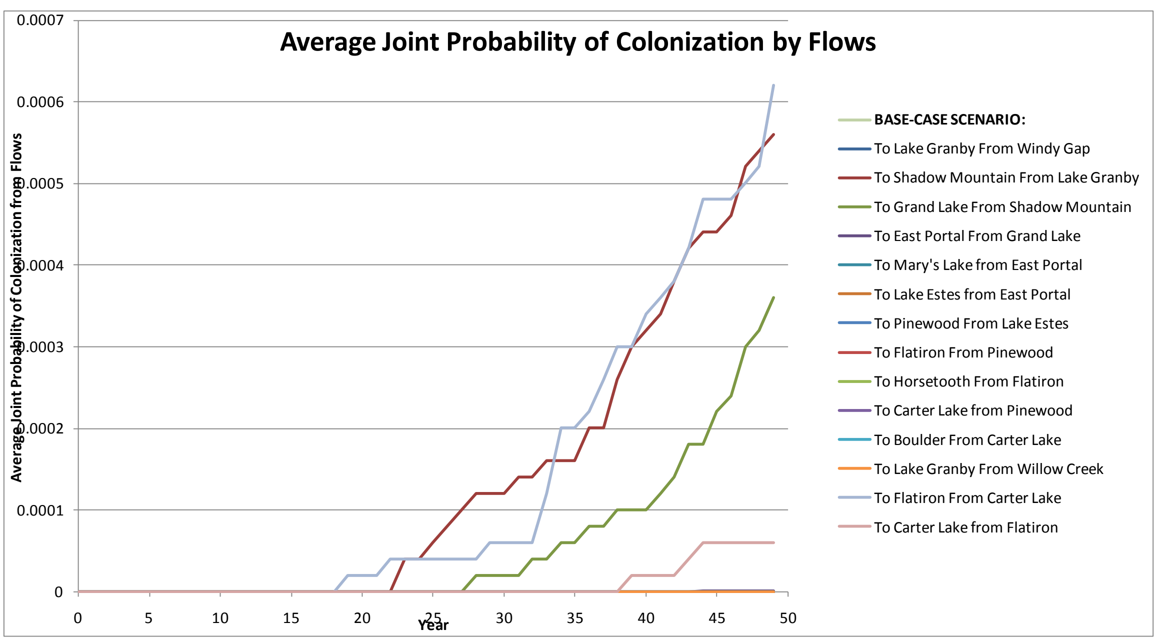

Figure 14: Simulated average joint probability of colonization from flows; generated using model base parameter values.

Establishment Patterns in the Grand County Reservoirs

The Grand County reservoirs have moderate boat pressure and are all very close to each other. They are therefore susceptible to establishment from boats or from flows. However, the reservoirs in this group all have very low probabilities of invasibility based on low calcium concentrations. The combination of very low probabilities of invasibility and moderate boat pressure result in overall low joint probabilities of colonization for the Grand County reservoirs (see figures 13 and 14)[6].

Establishment Patterns in the Central Reservoirs

Colonization of the central reservoirs is almost entirely dependent on propagule pressure from flows. Apart from a small number of trailered boat visits to Lake Estes, propagules traveling by flows from Grand Lake are the main source of vulnerability for the central reservoirs. East Portal Reservoir is at the head of the central reservoirs and is separated from Grand Lake by the 21.1 km Adams Tunnel. The probability of establishment from flows is a function of the distance between the source reservoir and the receiving reservoir, and the density of mussels in the source reservoir. Grand Lake has a very low calcium concentration and is therefore modeled as supporting a very low density of mussels. The low density of mussels in Grand Lake combined with the long distance between Grand Lake and East Portal Reservoir result in very low probabilities of establishment in the central reservoirs.

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[6] The fact that these reservoirs may already be established suggests that the joint probability of colonization for these reservoirs may be underestimated. This could indicate that the probability of invasibility in these reservoirs is underestimated or that the probability of establishment from boats is underestimated. Section 3.2.1 in the sensitivity analysis addresses the issue of invasibility, and Section 3.2.2 addresses the probability of establishment from boats.

These low probabilities of establishment combine with low probabilities of invasibility to make the joint probabilities of colonization from flows for the central reservoirs approximately zero (see Figure 14).

Establishment Patterns in the Front Range Reservoirs

The Front Range reservoirs have the greatest probability of establishment. Among these reservoirs, Horsetooth Reservoir and Boulder reservoir are the most vulnerable, but their vulnerability is driven by different factors. Horsetooth Reservoir has very high boat pressure, with nearly 50,000 boat visits each year (see Figure 12). The boat pressure in Horsetooth Reservoir is so large that the probability of establishment from boats approaches 1 near the end of the 50-year horizon. The joint probability of colonization for Horsetooth Reservoir is limited by the reservoir's very low probability of invasibility, and asymptotically reaches a maximum of .02 (see Figure 13). Even with this relatively low probability of colonization, Horsetooth Reservoir becomes established in nearly half of the simulation runs (see Figures 8 and 10).

Boulder Reservoir is the only reservoir in the system with a high probability of invasibility. Boats are the main source of propagules to Boulder Reservoir, and boat pressure in the reservoir is relatively low (see Figure 12). Despite low boat pressure, Boulder Reservoir's high probability of invasibility results in a steadily increasing joint probability of colonization over time (see Figure 13).

Timing of Establishment

On average, reservoirs become established between 30 and 40 years into the future (see Figure 11). Low joint probabilities of colonization in the system result in low rates of colonization in early years of the horizon. The joint probabilities of colonization are increasing over time. As the horizon approaches infinity, the joint probability of colonization approaches the probability of invasibility. Boat pressure is also increasing over time, which increases the rate at which the joint probability of colonization approaches its asymptote. The combination of a slow rate of increase in the percent of potentially infested boats and low probabilities of invasibility push possible invasions well into the future.

3.1.2 Cost-Benefit Results

This section details the simulated costs and benefits of the boat inspection program. Benefits are simulated using the base parameter values and with the assumptions of the Grand County reservoirs established in 2009 and unestablished in 2009, and with the low water treatment facility control costs based on Connelly et al. (2007) and the high water treatment facility control costs based on the City of Westminster (2010). Section 3.2.1 (a) provides a summary of program costs, and Section 3.2.1 (b) provides a summary of simulated control costs and associated benefits of the program. There is a gap between program costs and benefits. This gap is addressed in Section 3.2.1 (c). Table 18 at the end of this section provides a summary of program costs and benefits.

3.2.1 (a) Program Costs

Program costs are comprised of the direct costs of the inspection program and the indirect costs to boaters. Direct program costs are detailed in Section 2.5.1 and are assumed to be constant over the entire horizon. In total, it costs about $830 thousand dollars per year to implement the boat inspection program on the reservoirs in the Colorado-Big Thompson system. The net present value (NPV) of the cost of running the program for 50 years is about $23.5 million dollars. Indirect costs of the boat inspection program are measured as reduced welfare for boaters who have to spend time waiting for boat inspections. Section 2.5.2 provides details about the boater welfare calculation. In total, reductions in boater welfare are expected to amount to about $1.3 million dollars per year. Assuming welfare losses are constant over time, the NPV of welfare losses over the 50-year horizon is about $36 million dollars.

3.2.1 (b) Program Benefits

Program benefits are measured as the reduction in control costs to the dams, pump plants, hydropower plants, and water treatment plants in the system. The boat inspection program is very successful at reducing the probability that reservoirs in the system become established; however, this does not translate into large program benefits. There are several factors driving this result. The main factors are the relatively low establishment rates and the late timing of establishment in the system. For the base-case scenario, only Horsetooth Reservoir and Boulder Reservoir become established in a substantial number of runs, with

Horsetooth Reservoir becoming established in about 46% of runs and Boulder Reservoir becoming established in about 13% of runs. In the runs where these reservoirs become established, the timing of establishment is on average 30 to 40 years into the horizon. Furthermore, control costs to facilities below an established reservoir are scheduled to start eight years after the reservoir is established. So, for most of the facilities in the system, no control costs are incurred over the horizon, and for those that do experience control costs, they are not experienced until the last few years of the simulation.

Almost all of the control costs in the system are experienced by water treatment facilities below Horsetooth Reservoir, Boulder Reservoir, and Carter Lake. In the case where the Grand County Reservoirs are assumed established in 2009, the dams and pump plants associated with the Grand County reservoirs incur control costs starting in year 2009. These costs increase the NPV of control costs for both the base-case scenario and the preventative management scenario, so they are not included in program benefits. All of the hydropower facilities are located in the central reservoirs. The central reservoirs never become established, so no control costs are incurred by hydropower facilities.

The expected NPV of control costs to the system are sensitive to the assumed level of control costs to water treatment facilities. Using the Connelly et al. (2007) control cost values, the total NPV of control costs to the system are about $2.9 million dollars. Using the City of Westminster (2010) values, the NPV of control costs increase to about $12.5 million dollars. The two estimates produce very different benefit-cost ratios. For the Connelly case, the benefits to direct costs ratio is 0.02. This value increases to 0.43 when the Westminster control cost estimates are used. If the true control costs in the system are similar to the Connelly et al. (2007) estimates, then benefits of reduced control costs will never exceed the costs of the program. However, if the true control costs in the system are similar to the Westminster (2010) estimates, then parameter values that either increase the frequency of invasion or make the invasion happen earlier could easily push the benefits of reduced control costs greater than the costs of the program.

3.2.1 (c) Cost-Benefit Gap

Using the model base parameter values, the NPV of the costs of the inspection program exceed the simulated NPV of the program benefits of reduced control costs to dams, pump plants, hydropower plants, and water treatment facilities. The gap between direct program costs and program benefits is about $13 million dollars when the City of Westminster (2010) water treatment facility cost estimates are used, and about $23 million dollars when the Connelly et al. (2007) values are used. The simulated cost-benefit gap is driven by three factors: (1) the probability of establishment in the system is low, (2) once established, facility control costs in the system are relatively low compared to program costs, and (3) program costs are incurred in every year whereas program benefits are realized 30 to 40 years in the future. As measured in this analysis, benefits only include reduced control costs to infrastructure and facilities in the system. **Non-market benefits such as the prevention of ecosystem disruption, reductions in ecosystem**

services, and diminished recreational opportunities are not included in the benefit calculation. Also omitted from program benefits are reductions in control costs to irrigators and industries using raw Colorado-Big Thompson water. The boat inspection program is cost-effective if all of the omitted program benefits exceed the cost-benefit gap.

Table 18: Simulated costs and benefits of the preventative management program; generated using model base parameters and a discount rate of 0.0265.

Simulated Costs and Benefits of the Preventative Management Program				
Grand County Assumption:	Grand County Reservoirs Established in 2009	Grand County Reservoirs Unestablished in 2009	Grand County Reservoirs Established in 2009	Grand County Reservoirs Unestablished in 2009
Water Treatment Costs Based On:	Connelly et al. (2007)	Connelly et al. (2007)	City of Westminster (2010)	City of Westminster (2010)
NPV Direct Costs	$23,450,768	$23,450,768	$23,450,768	$23,450,768
NPV Indirect Costs	$36,040,097	$36,040,097	$36,040,097	$36,040,097
Total Program Costs	**$59,490,865**	**$59,490,865**	**$59,490,865**	**$59,490,865**
Average NPV Control Costs (Base-Case Scenario)	$2,893,030	$468,872	$12,534,265	$10,110,108
Average NPV Control Costs (Preventative Management Scenario)	$2,431,743	$1,683	$2,464,274	$34,215
Average Program Benefits	**$461,287**	**$467,189**	**$10,069,991**	**$10,075,893**
Average Net Benefits (direct costs only)	**-$22,989,481**	**-$22,983,579**	**-$13,380,777**	**-$13,374,875**
Average Net Benefits (direct and indirect costs)	**-$59,029,578**	**-$59,023,676**	**-$49,420,874**	**-$49,414,972**
Benefit-Cost Ratio (direct costs only)	**0.0197**	**0.0199**	**0.4294**	**0.4297**
Benefit-Cost Ratio (direct and indirect costs)	**0.0078**	**0.0079**	**0.1693**	**0.1694**

3.2 Sensitivity Analysis

This section describes the sensitivity of results to the choice of parameter values. Variables are broken into five groups, each describing a different aspect of the simulation. The parameter groups tested include environmental parameters, boat pressure parameters, flow parameters, program parameters, and economic parameters. Appendix A provides a description of each of the variables in the model and gives a low, base, and high parameter value for each variable. An online tool is available at http://dare.colostate.edu/tools/index.aspx, where users can test the effects of varying model parameter values and can enter user-defined parameter values.

3.2.1 Environmental Parameters

The probability of invasibility, ϕ_l, is an important and uncertain component in the model. Values for ϕ_l are chosen subjectively based on calcium concentrations. The low values of ϕ_l set the probability of invasibility for very low and low calcium reservoirs equal to zero. If probabilities of invasibility are this low in the system, only Boulder Reservoir is at risk of colonization. At base values of ϕ_l, the Grand County reservoirs, Carter Lake, and Horsetooth Reservoir become vulnerable to infestation, but the central reservoirs remain free of mussels. The same reservoirs are vulnerable at the high values of ϕ_l, but become established at higher frequencies and in earlier years. This is especially true for Horsetooth Reservoir, which on average becomes established 10 years earlier than with the base values of ϕ_l and becomes established in over 80% of runs.

The parameter values chosen for the probability of invasibility have a substantial effect on the average NPV of control costs and on program benefits. Using the Connelly et al. (2007) control values for water treatment facilities and assuming the Grand County reservoirs are unestablished in 2009, the NPV of control costs in the system increase from about $18 thousand dollars for the low values of ϕ_l, to about $890 thousand dollars for the high values of ϕ_l. This translates to about a $930 thousand dollar increase in program benefits, but has little effect on the benefit-cost ratio. Using the City of Westminster (2010) control values for water treatment facilities and assuming the Grand County reservoirs are unestablished in 2009, the NPV of control costs in the system increase from about $890 thousand dollars for the low values of ϕ_l, to about $19.8 million dollars for the high values of ϕ_l. This translates to an $18.9 million dollar increase in program benefits and increases the benefits to direct costs ratio from .038 to .845.

Probabilities of invasibility are assigned to reservoirs based on their calcium concentrations. Calcium concentrations in the central reservoirs are unknown and could range from very low to moderate. If the Grand County reservoirs are assumed unestablished in 2009, then the calcium levels in the central reservoirs make no difference in the probability of establishment for these reservoirs. If the Grand County reservoirs are assumed established in 2009, then the calcium levels in the central reservoirs have a slight effect on establishment patterns in the system. With very low calcium levels, the central reservoirs do not become established. With low and moderate calcium levels, there is a very small chance that East Portal Reservoir may become established by flows from Grand Lake. Overall, the calcium levels in the central reservoirs make very little difference on establishment patterns and the expected control costs in the system.

3.2.2 Boat Pressure Parameters

This section considers how parameters levels for the variables that affect boat pressure affect simulation results. The variables considered in this section include α_B, the shape parameter in the probability of establishment from boats function, R_{max} and p_{max}, the random walk variables that affect the rate at which the percent of potentially infested boats increases over time, and β, the percent by which the boat inspection program slows the rate of increase in the percent of potentially infested boats.

Average NPVs of control costs and program benefits are sensitive to the α_B shape parameter. The same reservoirs are susceptible to colonization for all levels of α_B, but the chance that these reservoirs become established increases as α_B increases. Reservoirs also become established earlier for larger values of α_B. Benefit-cost ratios remain low for all levels of $\alpha_B$when the water treatment cost values based on Connelly et al. (2007) are used; however, using the City of Westminster (2010) estimates and the high value for α_B, the benefits to direct costs ratio increases to 1.6. This suggests that results of the cost-benefit analysis are highly dependent on the probability of establishment from boats and estimates of control costs in the system.

Values of R_{max}, and p_{max} reflect how quickly the invasion is happening. In general, the faster the invasion, the greater the benefits of preventative management. If the invasion is not progressing (i.e. $R_{max} = 0$), then only Horsetooth Reservoir is at risk of colonization. This is due to the very large boat pressure at Horsetooth Reservoir. As the rate of invasion increases and a greater percent of boats become possible sources of propagules, the chance of invasion in Boulder Reservoir and Carter Lake increases, thus increasing control costs to the Front Range water treatment facilities. Overall, the rate of invasion has a very small effect on the expected NPV of control costs in the system and on program benefits.

The β parameter represents the percent by which the boat inspection program slows the rate of increase in the percent of potentially infested boats. The level of β has very little effect on establishment patterns in the preventative management scenario. This is largely due to the high efficacy of the boat inspection program. At its base parameter setting, the program catches and cleans 95% of the potentially infested boats that enter the system. At this level of efficacy, the rate at which the percent of potentially infested boats is growing makes no difference on establishment patterns in the preventative management scenario. At lower levels of program efficacy, β has a small effect on the probability of establishment in Horsetooth Reservoir.

3.2.3 Flow Parameters

Five variables affect the probability of establishment from flows: the density of the upstream water body ($D_{l^{up}}$), the lag time between when an upstream reservoir becomes established and when it becomes a source of propagules to downstream reservoirs (m), the rate at which veligers decay (b), and the alpha and c shape parameters in the probability of establishment by flows function (α_F and c_F). When the model is run with the base parameters and the Grand County reservoirs are assumed unestablished in 2009, none of these variables have a substantial effect on establishment patterns in the system.

To test how flows could affect establishment in the system under more favorable flow conditions, the model is run with the Grand County reservoirs assumed established in 2009, α_F set at its highest value, and c_F, b, and m set at their lowest values. At these parameter levels, the probability of establishment in the central reservoirs is greatly increased. Figures 15 and 16 show the establishment patterns and timings of invasion for this combination of parameter values. East Portal Reservoir becomes established in nearly half of the runs. Establishment in Mary's Lake is delayed and less likely, and establishment in Lake Estes is unlikely.

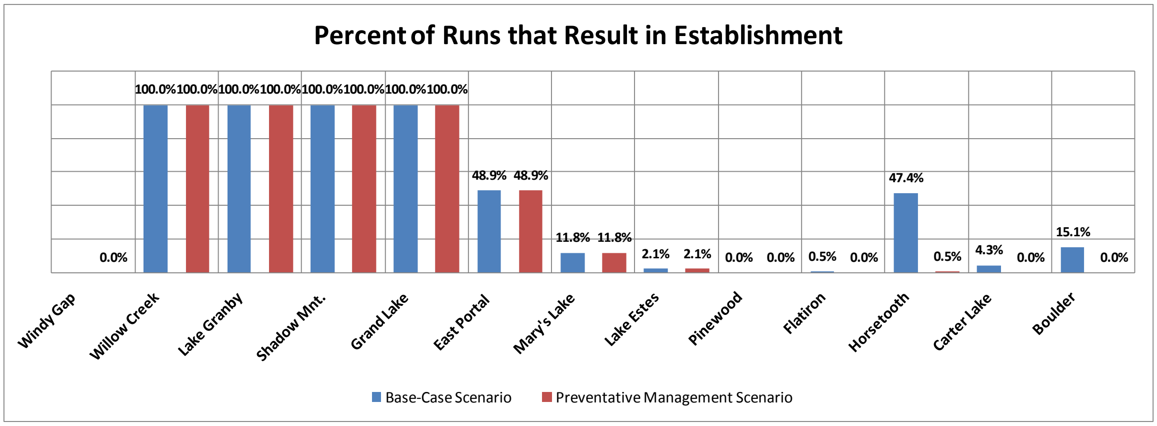

Figure 15: Simulated establishment patterns under favorable flow parameters and the assumption that the Grand County reservoirs are established in 2009 ($\alpha_F = 0.2$, $c_F = 0.5$, $b = -0.33$, and $m = 6$; all other parameters at base values).

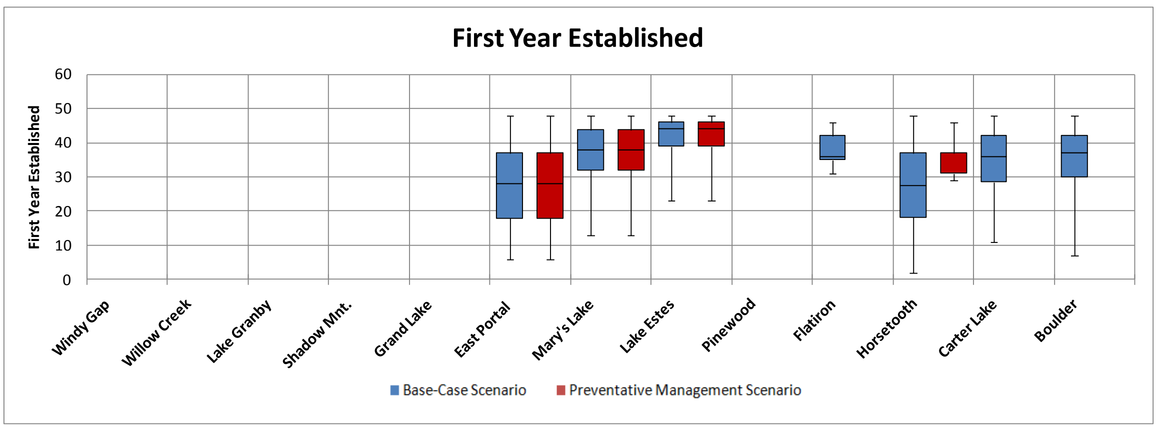

Figure 16: Simulated timing of establishment under favorable flow parameters and the assumption that the Grand County reservoirs are established in 2009 ($\alpha_F = 0.2$, $c_F = 0.5$, $b = -0.33$, and $m = 6$; all other parameters at base values).

If densities in the reservoirs are high and calcium concentration in the central reservoirs are assumed to be moderate, the rate of infestation in the system increases dramatically and infestation occurs earlier. Figures 17 and 18 show model results under high density conditions when the Grand County reservoirs are assumed established in 2009, α_F is set at its highest value, and c_F, b, and m are set at their lowest values. Under these conditions, establishment by flows becomes an important driver in the system.

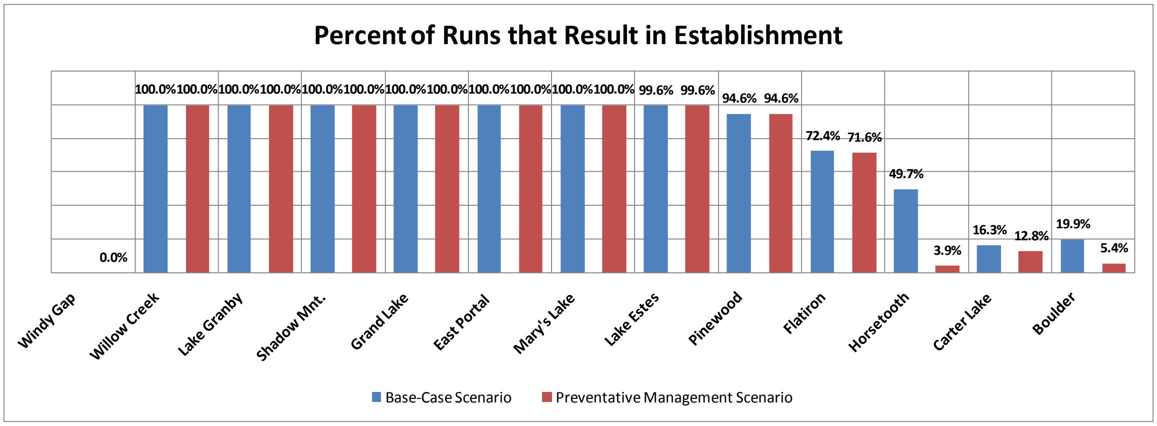

Figure 17: Simulated establishment patterns under favorable flow conditions, high densities, and the assumption that the Grand County reservoirs are established in 2009 ($D_l = 7500$ individuals per m² for all reservoirs in the system, calcium levels in the central reservoirs are assumed to be moderate, $\alpha_F = 0.2, c_F = 0.5, b = -0.33$, and $m = 6$; all other parameters at base values).

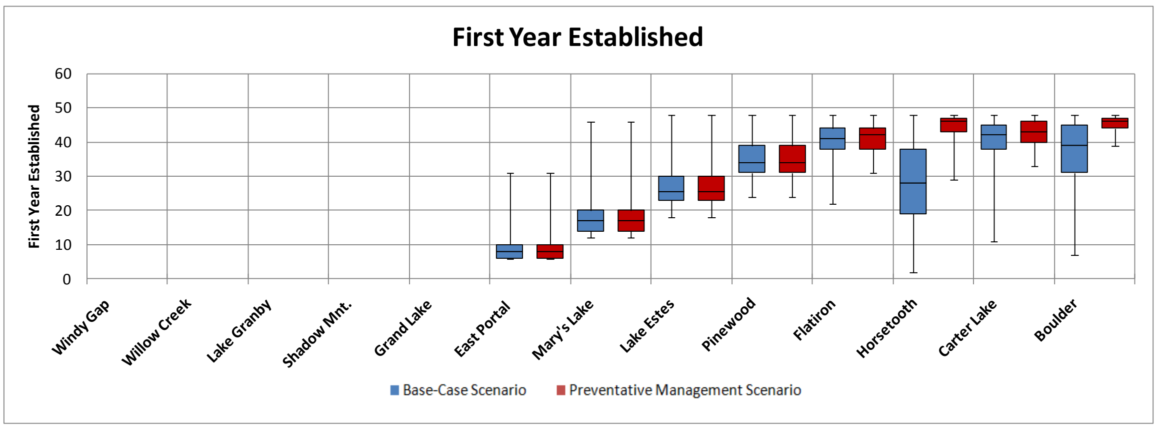

Figure 18: Simulated timing of establishment under favorable flow conditions, high densities, and the assumption that the Grand County reservoirs are established in 2009 ($D_l = 7500$ individuals per m² for all reservoirs in the system, calcium levels in the central reservoirs are assumed to be moderate, $\alpha_F = 0.2, c_F = 0.5, b = -0.33$, and $m = 6$; all other parameters at base values).

Even in very favorable flow conditions, the flow parameters have very little effect on program benefits. This is driven by the fact that reservoirs that are primarily established by flows become established at the same frequency and timing for both the base-case scenario and the preventative management scenario, resulting in zero program benefits. However, in environments where the probability of establishment from flows is high, preventative management in upstream boatable reservoirs can reduce the probability that upstream waters become sources of propagules from flows, which could result in substantial program benefits.

3.2.4 Program Parameters

This section considered two variables directly affected by the boat inspection program: the percent of potentially infested boats that are caught and cleaned by boat inspectors (γ), and the percent decline in the number of boats visiting the system (ρ).

Boat inspectors are expected to catch and decontaminate a large percent of the potentially infested boats that would have otherwise entered the system. However, the efficacy of boat inspections is uncertain, because there is no way to know how many potentially infested boats slip by. To test how sensitive results are to the efficacy of the program, values of γ between 50% and 100% are tested. For γ greater than 95%, the boat inspection program is 100% effective at preventing establishment within the system. In reservoirs with moderate to low boating pressure, establishment under the preventative management scenario remains low even at a γ level of 50%. Establishment in Horsetooth Reservoir, which has very high boat pressure, is more sensitive to γ. This suggests that the quality of boat inspections at reservoirs with high boat pressure is paramount to the overall effectiveness of the program.

The boat inspection program may induce some boaters to reduce the number of boating trips they take in a year. Overall, demand for boating is expected to be inelastic, and values of ρ between 0 and .03 are tested in the model. Over this range of values, boater behavior has very little effect on establishment patterns or control costs in the system. The level of ρ does have a substantial effect on the indirect costs of the boat inspection program. With no decline in boat visits (i.e. perfectly inelastic demand), the NPV of the indirect costs of the program are about $55 million. With a 3% decline in boat visits, the NPV of the indirect costs of the program increase to about $69 million.

3.2.5 Economic Parameters

This section addresses the effect of parameter levels for variables directly associated with the net present value calculations, control cost calculations, and program cost calculations.

Net Present Value Parameters

The discount rate (r) and the time horizon are the main variables driving the net present value calculations. With respect to the discount rate, the benefit-cost ratios decline as the discount rate increases. This is driven by the late onset of program benefits. With a higher discount rate, the benefits of the program are heavily discounted because they do not happen until well into the future. Overall, the discount rate has a minor effect on the benefit-cost ratios.

The choice of time horizon is important in the NPV calculations. The average time until establishment for the reservoirs in the system is about 30 to 35 years. In the short, 10-year time horizon, only Horsetooth Reservoir and Boulder Reservoir have a chance of becoming established, with establishment happening at low frequencies. Due to the lag time that must pass after establishment before control costs are incurred, no control costs are incurred below these reservoirs within a 10-year horizon. Overall, control costs in the system increase over time. This results in larger benefit-cost ratios with longer time horizons.

Control Cost Parameters

The interest rate (i) and the term length of the capital expenditure loan (ω) could affect control costs in the system. Sensitivity testing of these variables indicates that they make very little difference on the benefit-cost ratios.

Indirect Cost Parameters

The indirect costs of the system are dependent on the CS per boater per day value (W), the average length of a boater day (D), the average number of persons per boat (k), the length of boat inspections (L), and the percent decline in the number of boat visits (ρ). Sensitivity testing indicates that the calculation of the reduction in boater welfare is very sensitive to all of these variables. To give an idea of the possible range of values, lowest and highest scenarios are presented. Welfare losses are lowest when the average length of a boater day is set at its highest value, and the number of persons per boat, the length of a boat inspection, and the percent decline in the number of boat visits are all set at their lowest values. Holding W at its base value, the lowest estimate of the direct costs of the boat inspection program is $143 thousand dollars per year. To calculate the high estimate of direct costs, the length of a boater day is set at its lowest value, and the number of persons per boat, the length of a boat inspection, and the percent decline in the number of boat visits are all set at their highest values. This results in a high estimate of $4 million dollars per year. Thus, there is much uncertainty in the value of welfare losses to boaters, and this could be an important area for further research.

3.3 Results for a Highly Invasible System

The majority of the reservoirs in the Colorado-Big Thompson system have very low calcium levels, which results in low probabilities of invasibility. The CDOW boat inspection program is a statewide mandate, and could have different effects in other water bodies in the state that have higher probabilities of invasibility. Furthermore, the actual environmental probabilities of invasibility in the Colorado-Big Thompson waters are extraordinarily uncertain. The identification of mussels in the Grand County reservoirs is a sign that the system may be more susceptible to invasion than the base parameter values suggest. To consider the costs and benefits of preventative management in a highly invasible system, probabilities of invasibility are set to 0.8 and population densities are set to 7500 individuals/m^2 for all of the reservoirs in the system.

Figures 19 and 20 show establishment patterns in the reservoirs under these conditions. For the base-case scenario, the probability of establishment in the Grand County reservoirs, Horsetooth Reservoir, and Carter Lake are all very high due to moderate to high boat pressure in these reservoirs. Establishment in Boulder Reservoir is still relatively low due to low boat pressure and a low chance of probability from flows. Overall, flows play a much greater role in the system. The central reservoirs have a greatly increased chance of establishment in the base-case scenario. The boat inspection program is very effective at reducing the probability of establishment, with Horsetooth Reservoir being the only reservoir that has a substantial chance of establishment in the preventative management scenario.

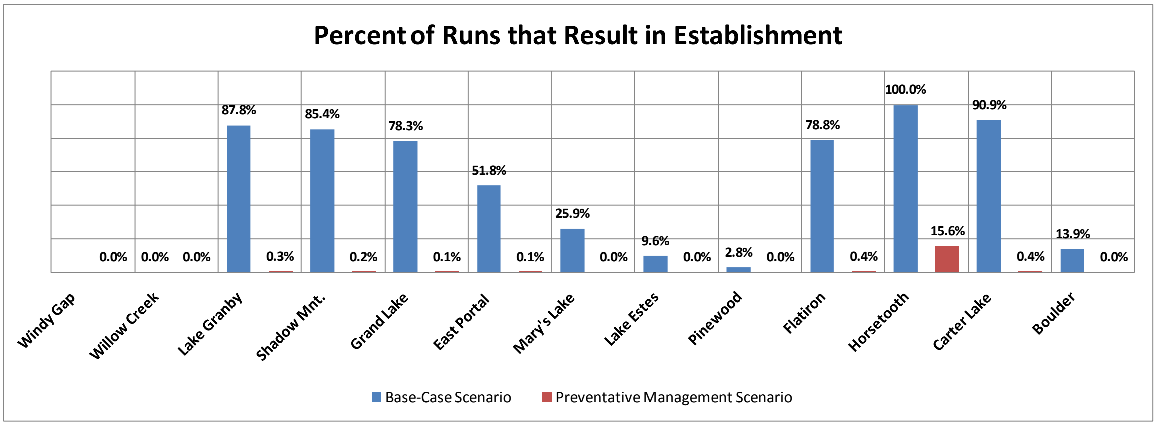

Figure 19: Simulated establishment patterns in a highly invasible system ($\phi_l = 0.8$ and $D_l = 7500$ individuals/m[2] for all reservoirs in the system; all other parameters at base values).

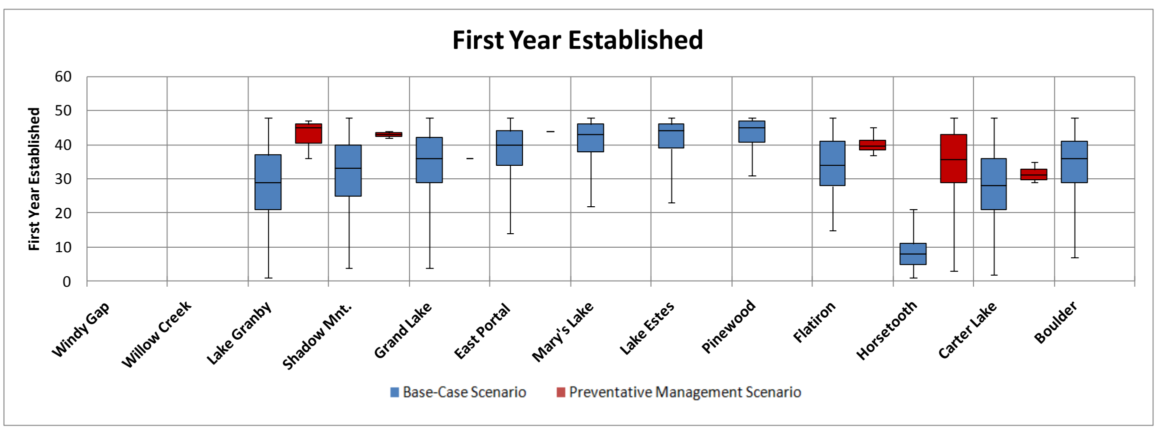

Figure 20: Simulated timing of establishment in a highly invasible system ($\phi_l = 0.8$ and $D_l = 7500$ individuals/m[2] for all reservoirs in the system; all other parameters at base values).

Table 19 shows the costs and benefits of the program for the highly invasible system. Benefit-cost ratios are still low for the case where the Connelly et al. (2007) water treatment control cost values are used. If control costs in the system are larger, such as with the City of Westminster (2010) control cost estimates, benefits of the program exceed the costs of the program. Considering only the direct costs of the program, program benefits are more than two and a half times program costs.

Table 19: Simulated costs and benefits of the preventative management program in a highly invasible system ($\phi_l = 0.8$ and $D_l = 7500$ individuals/m² for all reservoirs in the system; all other parameters at base values; discount rate=0.0265).

Simulated Costs and Benefits of the Preventative Management Program in a Highly Invasible System		
Water Treatment Costs Based On:	Connelly et al. (2007)	City of Westminster (2010)
NPV Direct Costs	$23,450,768	$23,450,768
NPV Indirect Costs	$36,040,097	$36,040,097
Program Costs	**$59,490,865**	**$59,490,865**
Average NPV Control Costs (Base-Case Scenario)	$3,974,432	$62,384,958
Average NPV Control Costs (Preventative Management Scenario)	$75,804	$1,515,144
Average Program Benefits	**$3,898,627**	**$60,869,815**
Average Net Benefits (direct costs only)	**-$19,552,141**	**$37,419,047**
Average Net Benefits (direct and indirect costs)	**-$55,592,237**	**$1,378,950**
Benefit-Cost Ratio (direct costs only)	**0.1662**	**2.5956**
Benefit-Cost Ratio (direct and indirect costs)	**0.0655**	**1.0232**

3.4 Benefit-Cost Ratios

Results suggest that benefit-cost ratios are sensitive to the probability of establishment from boats, the invasibility of the system, and the level of control costs facilities expect to incur if infested. If control costs for water treatment facilities are as low as the Connelly et al. (2007) study suggests, then benefits of reduced control costs will never exceed direct program costs. If control costs are higher, like those estimated in the City of Westminster (2010) study, then the gap between the benefits of reduced control and the direct cost of the boat inspection program is much smaller. At higher control costs, increasing the probability of invasibility in the system or increasing the probability of establishment from boats both result in benefit-cost ratios greater than 1. In the case of a highly invasible system, it would be reasonable to spend as much as $2.1 million dollars per year to reduce control costs in the system.

CHAPTER 4: SUMMARY AND CONCLUSIONS

Colorado is expected to spend about $2.3 million dollars per year to slow or prevent the spread of aquatic nuisance species in the state (Colorado Division of Wildlife and Colorado State Parks, 2010). Of those expenditures, about one-third is budgeted for boat inspections in the reservoirs of the Colorado-Big Thompson system. This study provides information about how the boat inspection program affects the potential spread of mussels in the Colorado-Big Thompson system, and subsequently, how the program affects control costs for facilities and infrastructure in the system. The objective of this analysis is to compare the costs of boat inspections on the reservoirs of the Colorado-Big Thompson system to the benefits of reduced control costs to the dams, pump plants, hydropower facilities, and municipal water treatment facilities associated with the system.

A bioeconomic simulation model is developed to intertemporally predict mussel spread in the reservoirs of the Colorado-Big Thompson system over a 50-year horizon. Joint probabilities of colonization are estimated for each reservoir in each year based on three factors: (1) the probability that the reservoir is invasible, (2) the probability that the reservoir becomes established by propagules introduced by boats, and (3) the probability that the reservoir becomes established by propagules introduced by flows from an infested upstream reservoir. In each year, reservoirs are subjected to a Bernoulli trail based on their joint probabilities of colonization and either become infested or remain uninfested.

The simulation model predicts spread in the system under a counterfactual base-case scenario of no preventative management, and under an alternative scenario in which the boat inspection program is in place. The key difference between the two scenarios is the probability that reservoirs become established by propagules introduced by boats. By slowing the rate of invasion and by catching and cleaning a large percent of boats that are potentially carrying mussels, the boat inspection program reduces the probability that a reservoir becomes established by propagules introduced by boats and thus reduces the joint probability of colonization.

Control cost schedules are developed for all of the dams, pump plants, hydropower facilities, and municipal water treatment facilities in the Colorado-Big Thompson system, and expected control costs in the system are assessed by intertemporally matching results of the simulated invasion to control cost schedules. Program benefits are measured as the difference in the net present value of expected control costs for the base-case scenario and for the preventative management scenario, and program costs are measured as the sum of the net present values of the direct costs of implementing the program and the indirect costs of reduced boater welfare. Net program benefits are equal to program benefits less program costs.

Results of the simulation suggest that the boat inspection program is very effective at reducing the probability that reservoirs in the system become established, and almost entirely eliminates the possibility of invasion in the system over the 50-year horizon. However, the benefits of reduced control costs to infrastructure are not likely to exceed the costs of the boat inspection program. The benefits measured in this analysis do not include benefits of reduced losses to biodiversity, recreation, and raw water users such as sprinkler irrigators and fossil-fuel fired electric generations plants. If these benefits exceed the cost-benefit gap identified in this analysis, then the program is cost-effective.

The main factor driving the simulated gap between costs and benefits is that the probability of invasion in the system is likely to be low even without the boat inspection program, thus leading to low expected control costs for the base-case scenario. The majority of the reservoirs in the Colorado-Big Thompson system have low or very low probabilities of invasibility based on low calcium concentrations. These low probabilities of invasibility result in low joint probabilities of colonization and overall low frequencies of invasion and late timings of invasion in the simulation. The spatial layout of the system also plays a role in the cost-benefit results. All of the hydropower facilities in the system are located between East Portal Reservoir and Flatiron Reservoir. With the exception of Lake Estes, which has a very small number of trailered boat visits each year, the reservoirs in this central stretch are closed to trailered boats. Thus, probabilities of colonization in the central reservoirs are almost entirely driven by flows. Simulation results suggest that the probability that these reservoirs become established by flows is close to zero, which results in zero control costs to hydropower facilities.

Within the system, Horsetooth Reservoir and Boulder Reservoir have the greatest risk of establishment. Horsetooth Reservoir has nearly 50,000 boat visits each year, making its probability of establishment by boats very high. The probability of invasibility in Horsetooth Reservoir is low and limits its joint probability of colonization; despite its low probability of invasibility, very large boat pressure leads to Horsetooth Reservoir becoming established in nearly half of all model runs. Boulder Reservoir has relatively low boat pressure, with about 1500 boat visits each year, but has a high probability of invasibility and becomes established in about 13% of model runs. The majority of the control costs incurred in the system are incurred by facilities below these reservoirs.

This study highlights several key differences between the eastern zebra mussel invasion and the invasion of the West. In the East, mussels were introduced, developed established colonies, and clogged infrastructure before people knew what they were dealing with. As witnesses of the eastern invasion, Colorado and other western states have the opportunity to try to stop an invasion before it happens. This proactive approach is a valuable option for dealing with an irreversible invasion that has the potential to cause severe ecological and economic damages; however, the costs of proactively slowing the invasion are large. This analysis suggests that the invasion and associated control costs are likely to be less severe in the West than they were in the East, which may make the benefits of slowing an invasion smaller than anticipated. This is driven by two major differences between the East and the West. The first difference is that water systems in the East are characterized by connected and navigable waterways, which greatly increases the probability that mussels spread. Water systems in the West are far less connected and thus have lower probabilities of colonization. The second major difference is the type and quantity of industries and facilities using raw water. Midwestern and eastern states are generally more industrial than western states, and have a large number industrial facilities located on the shores of large lakes and river systems. Many of these industries use raw lake water and are responsible for a large portion of the reported mussel related control expenditures. Lacking a large industrial presence, the West is expected to incur lower control costs than were experienced in the East.

CHAPTER 5: DISCUSSION AND LIMITATIONS

The results of this analysis bring into question the cost-effectiveness of preventative management for zebra and quagga mussels in the Colorado-Big Thompson system. This is contrary to other similar studies, which have all found that the benefits of preventative management far exceed the costs (Leung et al., 2002; Lee et al., 2007; Keller et al., 2009). This chapter addresses the major differences between this study and other similar studies, and explains the main drivers of the contrary results. **This analysis does <u>not</u> provide conclusive evidence that the costs of the boat inspection program exceed the benefits.** There are several important limitations to consider when interpreting the results of this analysis. Most importantly, this is not a complete cost-benefit analysis. There are many benefits that are omitted from the analysis, resulting in an underestimate of program benefits. Another limitation is the scope of the analysis, which is limited to the costs and benefits of preventative management within the Colorado-Big Thompson system. Inspecting boats on the reservoirs of the Colorado-Big Thompson system has external benefits that are not captured by this analysis. A further limitation is the uncertainty inherent in the bioeconomic model. This chapter details these limitations and gives suggestions for future research.

<u>Comparison to Other Cost-Benefit Studies</u>

Several studies consider the costs and benefits of preventative management for aquatic nuisance species, and they all find that preventative management is cost effective (Leung et al., 2002; Lee et al., 2007; Keller et al., 2009). To place this study in the context of these studies, it is important to highlight several key differences.

The Lee et al. (2007) study and the Keller et al. (2009) study both consider non-market benefits in their analysis. Non-market benefits of the CDOW boat inspection program are not included in this analysis, but are likely to be large. The following section on omitted benefits provides a discussion of the potential magnitude of the non-market benefits of the Colorado boat inspection program.

Another difference between this study and the Keller et al. (2009) study is the magnitude of the costs of preventative management. In Keller et al. (2009), the cost per year of protecting a lake from invasion is $7000 dollars. Costs of the CDOW boat inspection program range from $100,000 per lake per year to $165,000 per lake per year.

Leung et al. (2002) conclude that it is optimal to spend up to $324,000 per year to prevent invasions in a single lake with a power plant. There are two major differences between this study and the Leung et al. (2002) study that drive the discrepancy in results. First, Leung et al. (2002) consider costs to a fossil fuel-fired power plant, which are known to have large control costs. The control cost estimates for the facilities considered in the Colorado-Big Thompson system are generally smaller, thus leading to lower benefits of preventative management. A further distinguishing factor is the likelihood that a water body becomes established. Leung et al. (2002) model their lake as having a 0.7% chance of becoming infested each month. This is significantly greater than the probabilities of colonization derived for the reservoirs in the Colorado-Big Thompson system. When the Colorado-Big Thompson system is modeled as a highly invasible system with higher control costs, model results are more in line with those found by Leung et al. (2002). With high probabilities of invasibility and high control costs, the benefits of preventative management are large and suggest that it would be reasonable to spend as much as $2.1 million dollars per year to reduce control costs in a highly invasible system similar to the Colorado-Big Thompson system.

Limitations

Omitted Benefits

This is not a complete cost-benefit analysis. The simulated benefits of the CDOW boat inspection program only include reduced control costs to hydropower plants, water treatment facilities, and water conveyance structures directly associated with the Colorado-Big Thompson system. Reduced control costs to irrigators and industries that use raw water from the Colorado-Big Thompson system are not included, nor are the vast ecological benefits of reduced establishment. Beyond ecological benefits, benefits to human recreation and natural resource dependent industries such as fishing and aquiculture are not included in this analysis. Thus, the accounting stance for this cost-benefit analysis is restricted to a comparison of money spent on boat inspections and money saved by stakeholders directly associated with the Colorado-Big Thompson system (see page 29 for a complete list of the benefits of the preventative management program).

Simulation results using model base parameter values suggest that the gap between the NPV of the direct costs of the program and the NPV of the benefits of reduced control costs is between $13 million and $23 million dollars. This suggests that total program benefits will exceed program costs if all of the omitted benefits of the program exceed these values. To put this in perspective, consider the value of sport fishing in the state. Dreissena mussels can profoundly change the food web in lake systems, which can affect the abundance and quality of sport fishing (Higgens & Vander Zanden, 2010). Based on a meta-analysis of valuation studies, the value of sport fishing in the intermountain states is on average $66.55 per angler day for cold water species, and $48.47 per angler day for warm water species (Loomis et al., 2008)[7]. In 2008, over 450 thousand anglers purchased Colorado fishing liscenses and averaged 23 angler days per permit, resulting in a total of nearly 11 million angler days (Holsman, 2010). Sixty percty of Colorado anglers target cold water species and 10 percent target warm water species (Holsman, 2010). Assuming that the remaining anglers target a combination of cold and warm water species, the total value of sport fishing in the state is about $650 million per year. Therefore, if mussels cause even small declines in angler welfare, the overall impact could be large. If the sum of the benefits to sport fishing and the other omitted benefits is greater than the cost-benefit gap indentified in this analysis, then the program is cost-effective.

[7] Values converted to 2009 dollars using the BLS inflation calculator.

External Benefits

This analysis only looks at one system within the state. The CDOW boat inspection program is statewide, and program benefits will be unique from system to system. Net benefits for other systems in the state are expected to differ based on the layout of the system, the type of infrastructure and level of control costs associated with the system, and the risk of invasion within the system. Thus, the net benefits of preventative management within other systems in the state are expected to differ from those found for the Colorado-Big Thompson system, which may result in a larger statewide benefit-cost ratio.

Positive externalities between systems are also expected to increase the statewide benefit-cost ratio. Boat inspections on the Colorado-Big Thompson reservoirs have positive external benefits to the rest of the state. If the Grand County reservoirs are already established, then expenditures on boat inspections in these reservoirs have low local benefits. However, by inspecting all boats that leave these infested reservoirs, the boat inspection program reduces the number of infested boats traveling to other reservoirs. Thus, the benefits of expenditures at the Grand County reservoirs are realized as reduced damage costs at other locations in the state. These positive externalities are not captured in this analysis; thus, statewide benefit-cost ratios are expected to be larger than those calculated for the Colorado-Big Thompson system.

Model Limitations

There is uncertainty inherent in the model developed for this analysis. The biological components of the model are simple, and the parameter estimates used in the simulations are subjective approximations based on values from the literature and best judgment. Most dispersal models are calibrated using invasion history; such data was not available for this study. The dreissena invasion of Colorado and the West is extremely young, and the Colorado-Big Thompson system represents a very different kind of water system than those previously studied. In the dispersal component of the model, the probability of invasibility and the parameters affecting downstream flows are the most uncertain parameters, and their values could have a major effect on establishment patterns and the associated benefits of the boat inspection program. There is also uncertainty about the magnitude of control costs in the system, which is an important driver in the cost-benefit results.

Areas for Future Research

The results of this study identify several areas for future research. To fully address the costs and benefits of preventative management for mussels in Colorado, valuation of the non-market benefits of the program is needed. The analysis of welfare loses to boaters conducted in this study is inconclusive, and it is suggested that a primary analysis be conducted to better estimate the indirect costs of the boat inspection program. Overall, the probability of invasibility and the magnitude of control costs in the system are important drivers in the cost-benefit analysis, and further research on these values is needed. The results suggest that targeted management may be a cost-effective alternative, and an optimal control study would be a logical extension of this work.

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APPENDIX A: VARIABLES AND PARAMETER VALUES

Cost-Benefit Model: Variables

Variable	Description	Equation
$NPV\ of\ Net\ Benefits$	The benefits of the boat inspection program less the direct and indirect costs of the program	(1)
φ^0	Net present value of expected damage costs from a mussel invasion for the base-case scenario	(2)
φ'	Net present value of expected damage costs from a mussel invasion for the preventative management scenario	(3)
θ_D	Net present value of the direct costs of implementing the program for the entire Colorado-Big Thompson system	(4)
θ_I	Net present value of the indirect costs of implementing the program for the entire Colorado-Big Thompson system	(5)
$C_{l,t}$	Control costs incurred by structures and facilities below reservoir l in time period t	
$E_{l,t}$	Binary state variable: $E_{l,t} = 1$ if reservoir l is established in time period t, and $E_{l,t} = 0$ if the reservoir is unestablished	
$P^0(E_{l,t} = 1)$	Base-case scenario probability that reservoir l is established in time period t	
$P'(E_{l,t} = 1)$	Preventative management scenario probability that reservoir l is established in time period t	
$Z_{l,t}$	Direct costs of implementing the boat inspection program on reservoir l in time period t	
$X_{l,t}$	Indirect costs to boaters on reservoir l during time period t	(24)
r	Discount rate	

Dispersal Model: Variables and Parameter Estimates

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
The Probability of Invasibility						
ϕ_l	Probability that reservoir l is invasible	Very Low Risk Reservoirs			This is an uncertain value. Parameter value ranges are assigned based on reservoir calcium level.	(6)
		0	.02	.05		
		Low Risk Reservoirs				
		.01	.05	.10		
		Moderate Risk Reservoirs				
		.10	.25	.50		
		High Risk Reservoirs				
		.50	.75	1		
Propagule Pressure from Boats						
ρ	Percent decline in number of boat visits attributable to the boat inspection program	0	.07	.275	2008 CDOW Boater Survey Data. Based on Q27 and Q12.	
$B'_{l,t}$	Number of boats visiting reservoir l in time period t in the preventative management scenario	See Table 4			Equal to the number of boat inspections in 2009, as reported by CDOW.	
$B^0_{l,t}$	Number of boats visiting reservoir l in time period t in the base-case scenario	See Table 4			Backed out from 2009 boat inspection data.	(7)
p_0	Percent of visiting boats that are traveling from infested waters in year 0 (2009)	.011	.018	.029	From CDOW 2009 boat inspection data. The base case is the percent of entrance inspections that were high-risk. The high case is the percent of entrance inspections that were high risk or resulted in decontamination. The low case is the percent of inspected boats that were required to be decontaminated.	

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
R_{max}	Increase in percent of infested boats over time, max value for the random walk	0.00	.005	.056	Kraft2000. The base value is set low to reflect a slow invasion, Johnson2006.	
p_{max}	Max percent infested boats	.002945	.0589	.589	Whittier2008. The high value is the percent of ecoregions that are at high risk of invasion based on calcium concentrations. The low value is 5% of this value. The base value is set at 10% of high-risk ecoregions.	
p_t^0	Base-case scenario percent of potentially infested boats in period *t*					(8)
β	Percent reduction in the maximum percent increase in infested boats per year, preventative management scenario	.25	.5	.75	This is an uncertain value.	
p_t'	Preventative management scenario percent of potentially infested boats entering the system in period t					(9)
γ	Percent of infested boats that are caught by inspection and get cleaned	.9	.95	1	This is an uncertain value.	
p_t''	Percent of potentially infested boats that are missed by boat inspections					(10)

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
$N_{l,t}^{B^0}$	Propagule pressure from boats in reservoir l in time period t for the base-case scenario					(12)
$N_{l,t}^{B'}$	Propagule pressure from boats in reservoir l in time period t for the preventative management scenario					(13)
Density of Veligers that Survive Downstream Transport						
A	Y-intercept for veliger transport exponential decay function		80.1		Horvath1999.	
b	Decay rate for veliger transport exponential decay function	-.67	-.45	-.33	Horvath1999. Based on density falling to 0.1% after 10, 15 and 20 km, respectively. From Bobeldke2005, lakes greater than 20km downstream had a lower chance of being invaded. Horvath1996 found isolated veligers 12km downstream. The smaller b is, the lower mortality is.	
x_l	Distance between reservoir l and the reservoir directly upstream	See Figure 3 on page 13 for distances between reservoirs			Distance data provided by Northern Water.	
$D_{l^{up}}$	Maximum population density in the reservoir directly upstream from reservoir l (individuals/m^2)	20	800	7500	Ramcharan1992. These are the min, mean, and max densities of mussels in European Lakes.	

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
Propagule Pressure From Flows						
m	Lag time (number of years after upstream establishment before downstream establishment is possible, i.e. number of years until mussels reach maximum density)	6	8	10	1-2 years less than those reported by Burlakova2006.	
$N_{l,t}^{F}$	Propagule pressure from flows in reservoir l in time period t					(13)
The Probability of Establishment from Boats						
α_B	α shape parameter for probability of establishment from propagule pressure from boats	.00005	.00010 3	.0005	The base value is from Leung2004.	
c_B	c shape parameter for probability of establishment from propagule pressure from boats		1.86		The base value is from Leung2004.	
$E\left(N_{l,t}^{B^0}\right)$	Base-case scenario probability of establishment from boats for reservoir l in time period t					(14)
$E\left(N_{l,t}^{B'}\right)$	Preventative management scenario probability of establishment from boats for reservoir l in time period t					(15)

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
			The Probability of Establishment From Flows			
α_F	α shape parameter for probability of establishment from propagule pressure downstream flows (percent living veligers)	.005	.05	.2	This is an uncertain value, as there is much uncertainty in how veligers survive and are transported through conveyance systems. The larger α_F is, the greater the probability of downstream establishment.	
c_F	c shape parameter for probability of establishment from propagule pressure from downstream flows (percent living veligers)	.5	1	1.86	The high value is from Leung2004; however, this value was used for boat pressure, not stream pressure. This parameter concerns the presence or absence of an Allee effect, and it is assumed that the value is the same for pressure from flows as it is for pressure from boats. The largerc_F is, the quicker the probability of establishment falls from 1 to 0.	
$E\left(N_{l,t}^F\right)$	Probability of establishment from flows for reservoir l in time period t					(16)
			The Joint Probability of Colonization			
$\vartheta_{l,s}$	Probability that reservoir l is colonized by period s, given reservoir l is invasible					(17)
$\psi_{l,s}$	Joint Probability that reservoir l is colonized by period s					(18)

Control Cost Model: Variables and Parameter Estimates

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
n	Lag time (number of years post establishment when damages are first incurred for downstream structures)	6	8 2	10	1-2 years less than those reported by Burlakova2006 (following initial colonization). Westminster2010 (following detection).	
i	Interest rate for capital expenditure loan	4	4.75	5	MSRB EMMA website. Based on a sample of 100 bond trades from 6/8/2010. Low, base, and high values are Q1, median, and Q3, respectively.	
ω	Tem length for capital expenditure loan	15	20	30		
P_0	Capital expenditure loan value	Varies by facility type See section 2.3.3				
P	Principal and interest payment on capital expenditure loan					(19)
τ	Index for control cost schedules ($\tau = 1$ represents costs incurred in the first year mussels settle in a facility)					
$t_{e^l}^0$	First year reservoir l is established for the base-case scenario	Simulated value				
t'_{e^l}	First year reservoir l is established for the preventative management scenario	Simulated value				
S_l	Number of structures under reservoir l	See Appendix B for a list of structures and upstream sources				

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
$C_{s,t+1-\tau}$	Incurred cost of control for structure s in year t	Varies by facility type and size See section 2.3.3				
$C_{l,t}^{0}$	Simulated control costs incurred by facilities under reservoir l in time period t in the base-case scenario					(20)
$C'_{l,t}$	Simulated control costs incurred by facilities under reservoir l in time period t in the preventative management scenario					(21)
r	Discount Rate	0	.0265	.053	Based on a discount factor of no greater than .95.	
$\emptyset^{0}$	Simulated NPV of incurred control costs under the base-case scenario					(22)
$\emptyset'$	Simulated NPV of incurred control cost under the preventative management scenario					(23)

Indirect Program Costs: Variables and Parameter Estimates

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
$X_{l,t}$	Indirect costs to boaters on reservoir l in time period t					(24)
$Q_{l,t}$	Number of boat trips taken to reservoir l in time period t	Equal to $B^0_{l,t} * k$ Values for $B^0_{l,t}$ are in Table 4				
k	Average number of persons per boat	2.94	3.63	4.5	From USCG 2002 National Recreation Survey. The base value is the average number of people per trip for people using sailboats, open motorboats, cabin motorboats, and personal watercraft (excludes pontoons and houseboats). The low value is the average for non-motorized sailboats, and the high value is the overall average for all trailered boats (including pontoon boats and houseboats).	
ρ	Percent decline in the number of boat visits attributable to the boat inspection program	0	.01	.03	2008 Boater Survey Data. Based on Q27 and Q12.	
L	Average length of a boat inspection	.06	.22	.39	Inspection time is the sum of the time it takes for the inspection and the wait/travel time to get the inspection.	

Variable	Description	Low Value	Mean Value	High Value	Source	Equation
D	Average length of a boater day	2	3.2	5.5	From Grand Lake Boater Survey Data: mean=4.6 hours, median=3.2 hours, min=1 hour, max=13 hours, n=161, distributions is positively skewed. From USCG National Recreation Survey, the average for sailboats, open motorboats, cabin motorboats and personal watercraft is 5.54.	
W	Average consumer surplus per boater per boating day for the base-case scenario	17.94	61.16	104.38	Kaval and Loomis 2003. Base is average WTP taken from 7 studies in the Intermountain Region. The low is 2 standard errors below the average and the high is 2 standard errors about the average.	

APPENDIX B: MAJOR STRUCTURES AND FACILITIES IN THE COLORADO-BIG THOMPSON SYSTEM

Structure/Facility Name	Structure/Facility Classification	Upstream Water Body
Windy Gap Pump Plant	pump plant	Windy Gap Reservoir
Windy Gap Pipeline	Pipeline	Windy Gap Reservoir
Willow Creek Dam	Dam	Willow Creek Reservoir
Willow Creek Pump Canal	Canal	Willow Creek Reservoir
Willow Creek Pump Plant	pump plant	Willow Creek Reservoir
Granby Dam	Dam	Lake Granby
Farr Pumping Plant	pump plant	Lake Granby
Grandby Pump Canal	Canal	Lake Granby
Shadow Mountain Dam	Dam	Shadow Mountain Reservoir
Adams Tunnel	Tunnel	Grand Lake
East Portal Reservoir	Dam	East Portal Reservoir
Rams Horn Tunnel	Tunnel	East Portal Reservoir
Mary's Lake Hydropower Plant	Hydropower	East Portal Reservoir
Prospect Mountain Tunnel	Tunnel	Mary's Lake
Estes Hydropower Plant	Hydropower	Mary's Lake
Town of Estes	water filter plant	Mary's Lake
Mary's Lake (Town)	water filter plant	Mary's Lake
Olympus Dam	Dam	Lake Estes
Olympus Tunnel	Tunnel	Lake Estes
Pole Hill Tunnel	Tunnel	Lake Estes
Pole Hill Hydropower Plant	Hydropower	Lake Estes
Rattlesnake Tunnel	Tunnel	Lake Estes
Rattlesnake Dam	Dam	Pinewood Reservoir
Bald Mountain Tunnel	Tunnel	Pinewood Reservoir
Flatiron Hydropower Plant	Hydropower	Pinewood Reservoir
Newell Warnock	water filter plant	Pinewood Reservoir
Flatiron Reversible Pump	pump plant	Flatiron Reservoir
Flatiron Dam	Dam	Flatiron Reservoir
Carter Lake Pressure Tunnel	Tunnel	Flatiron Reservoir
Big Thompson Hydropower Plant	Hydropower	Flatiron Reservoir
Hansen Feeder Canal	Canal	Flatiron Reservoir
City of Loveland	water filter plant	Flatiron Reservoir
Emissaries of Divine Light	water filter plant	Flatiron Reservoir
Eden Valley	water filter plant	Flatiron Reservoir

Structure/Facility Name	Structure/Facility Classification	Upstream Water Body
Spring Canyon	water filter plant	Flatiron Reservoir
Horsetooth Dam	Dam	Horsetooth Reservoir
Soldier Dam	Dam	Horsetooth Reservoir
Dixon Dam	Dam	Horsetooth Reservoir
Spring Canyon Dam	Dam	Horsetooth Reservoir
Charles Hansen Supply Canal	Canal	Horsetooth Reservoir
Northern Poudre Supply Canal	Canal	Horsetooth Reservoir
Fort Collins	water filter plant	Horsetooth Reservoir
Soldier Canyon	water filter plant	Horsetooth Reservoir
Greeley	water filter plant	Horsetooth Reservoir
Carter Lake Dam 1	Dam	Carter Lake
Carter Lake Dam 2	Dam	Carter Lake
Carter Lake Dam 3	Dam	Carter Lake
Carter Lake Filter Plant 1	water filter plant	Carter Lake
Carter Lake Filter Plant 2	water filter plant	Carter Lake
St. Vrain Supply Canal	Canal	Carter Lake
Boulder Feeder Canal	Canal	Carter Lake
Southern Water Supply Project Pipeline	Pipeline	Carter Lake
West Longmont Pumping Plant	pump plant	Carter Lake
Louisville/Superior Pumping Plant	pump plant	Carter Lake
Town of Berthoud	water filter plant	Carter Lake
City of Longmont 1	water filter plant	Carter Lake
City of Longmont 2	water filter plant	Carter Lake
Louisville 1	water filter plant	Carter Lake
Louisville 2	water filter plant	Carter Lake
Superior	water filter plant	Carter Lake
Town of Erie	water filter plant	Carter Lake
Broomfield	water filter plant	Carter Lake
City of Fort Lupton	water filter plant	Carter Lake
City of Fort Morgan	water filter plant	Carter Lake
Boulder Creek Supply Canal	Canal	Boulder Reservoir
South Platte Supply Canal	Canal	Boulder Reservoir
City of Boulder	water filter plant	Boulder Reservoir
City of Laffeyette	water filter plant	Boulder Reservoir

APPENDIX C: BASE PARAMETER VALUES

Dispersal Model Base Parameter Values

Probability of Invasibility	
Probability that a very low calcium reservoir is invasible	0.02
Probability that a low calcium reservoir is invasible	0.05
Probability that a moderate calcium reservoir is invasible	0.25
Probability that a high calcium reservoir is invasible	0.75
Treatment of reservoirs with unknown calcium levels	Model as very low calcium

Propagule Pressure from Boats	
Percent of visiting boats that are infested	1.80%
Percent of infested boats that are caught by inspection and get cleaned	95.00%
alpha shape parameter	0.000103
c shape parameter	1.86
Percent decline in number of boat visits attributable to the boat inspection program	1.00%
Max percent infested boats	5.89%
Maximum percent increase in infested boats per year (rate of infestation in the West)	0.50%

Propagule Pressure from Flows	
y-intercept parameter	0.801
Decay rate	-0.45
Lag time (m)	8
alpha shape parameter	0.05
c shape parameter	1
Mussel density for a very low calcium reservoir	22
Mussel density for a low calcium reservoir	22
Mussel density for a moderate calcium reservoir	800
Mussel density for a high calcium reservoir	7500

Damage Cost Model Base Parameter Values

Time Horizon	50
Lag Time (n)	8
Discount Rate	0.0265
Interest Rate	0.0475
Loan term length for capital expenditures (years)	20

Program Cost Base Parameter Values

Yearly Direct Costs: Variable Costs ($/year)	$827206
Yearly Direct Costs: Principal on Capital Expenditures ($/year)	$4656
CS per boater per day ($/boater/day)	61.16
Length of an Average Boater Day (hours)	3.2
Average Number of Boaters per Boat (persons/boat)	3.63
Inspection Length (hours)	0.22
Are indirect costs of the program included in the analysis?	Yes

APPENDIX D: VISUAL BASIC CODE

```
Sub Mussels()

'Random number arrays (to be imported from MUSSELS_random.xlsm)
    Dim RandomWalkLow(999, 49, 1) As Double 'RandomWalkLow(run, year,scenario)
    Dim RandomWalkBase(999, 49, 1) As Double 'RandomWalkBase(run, year,scenario)
    Dim RandomWalkHigh(999, 49, 1) As Double 'RandomWalkHigh(run, year,scenario)
    Dim RandomWalkUser(999, 49, 1) As Double 'RandomWalkUser(run, year,scenario)
    Dim RandomBoats(12999, 49) As Double 'RandomBoats(mix of run and reservoir, year)
    Dim RandomUpstream1(12999, 49) As Double 'RandomUpstream1(mix of run and reservoir, year)
    Dim RandomUpstream2(12999, 49) As Double 'RandomUpstream2(mix of run and reservoir, year)

'Constant Inputs (to be imported from sheet "Model Input")
    Dim Invasibility(12) As Double   ' Invasibility(reservoirs)
    Dim per_infest_0 As Double
    Dim per_cleaned As Double
    Dim a_boat As Double
    Dim c_boat As Double
    Dim per_decline As Double
    Dim BoatVisits_0(12) As Long 'BoatVisits_0(reservoirs)
    Dim BoatVisits_1(12) As Long 'BoatVisits_1(reservoirs)
    Dim per_max As Double
    Dim R_max As Integer
    Dim B As Double
    Dim horizon As Integer
    Dim m As Integer
    Dim a_stream As Double
    Dim c_stream As Double
    Dim UpConnect1(12) As Integer   'UpConnect1(reservoir)
    Dim UpConnect2(12) As Integer   'UpConnect2(reservoir)
    Dim DensityAlive1(12) As Double    ' DensityAlive1(reservoir)
    Dim DensityAlive2(12) As Double    ' DensityAlive2(reservoir)
    Dim n As Integer
    Dim d_rate As Double
    Dim UpConnectStructure(67) As Integer   'UpConnectStructure(structure)
    Dim StructureType(67) As String 'StructureType(structure)
    Dim direct_costs_variable As Double
    Dim direct_costs_PI As Double
    Dim indirect_costs As Double
    Dim term_length As Integer


'Arrays to be populated
    Dim PerInfest(999, 49, 1) As Double ' PerInfest(run, year, scenario)
    Dim PerInfest_cleaned(999, 49) As Double 'PerInfest_cleaned(run, year)
    Dim RandomWalk(999, 49, 1) As Double 'RandomWalk(run,year,scenario)
    Dim NumInfest(999, 49, 12, 1) As Long 'NumInfest(run, year, reservoir, scenario)
    Dim AvgNumInfest(49, 12, 1) As Double 'AvgNumInfest(year, reservoir, scenario)
    Dim ProbEstab_Boats(999, 49, 12, 1) As Double ' ProbEstab_Boats(run, year, reservoir, scenario)
    Dim product_Boats(999, 49, 12, 1) As Double ' product_Boats(run, year, reservoir, scenario)
    Dim JointProb_Boats(999, 49, 12, 1) As Double ' JointProb_Boats(run, year, reservoir, scenario)
    Dim AvgJointProb_Boats(49, 12, 1) As Double 'AvgJointProb_Boats(year,reservoir,scenario)
    Dim ProbEstab_Up1(999, 49, 12, 1) As Double ' ProbEstab_Up1(run, year, reservoir, scenario)
    Dim ProbEstab_Up2(999, 49, 12, 1) As Double ' ProbEstab_Up2(run, year, reservoir, scenario)
    Dim JointProb_Up1(999, 49, 12, 1) As Double ' JointProb_Up1(run, year, reservoir, scenario)
    Dim JointProb_Up2(999, 49, 12, 1) As Double ' JointProb_Up2(run, year, reservoir, scenario)
    Dim Bernoulli_Boats(999, 49, 12, 1) As Boolean ' Bernoulli_Boats(run,year,reservoir,scenario)
```

```
    Dim Bernoulli_Up1(999, 49, 12, 1) As Boolean ' Bernoulli_Up1(run,year,reservoir,scenario)
    Dim Bernoulli_Up2(999, 49, 12, 1) As Boolean ' Bernoulli_Up2(run,year,reservoir,scenario)
    Dim invasionrecord(999, 49, 12, 1) As Boolean 'InvasionRecord(run,year,reservoir,scenario)
    Dim FirstYearEstab(999, 12, 1) As Integer 'FirstYearEstab(run, reservoir, scenario)
    Dim ControlCostSchedules(49, 67) As Double  'ControlCostSchedules(year,structure)
    Dim IncurredControlCosts(999, 49, 67, 1) As Double 'IncurredControlCosts(run,year,structure,scenario)
    Dim DiscControlCosts(999, 49, 67, 1) As Double  'DiscControlCosts(run,year,structure,scenario)
    Dim NPVControlCosts(999, 1) As Double   'NPVControlCosts(run, scenario)
    Dim Benefits(999) As Double 'Benefits(run)
    Dim DirectCosts(49) As Double   'DirectCosts(year)
    Dim DiscDirectCosts(49) As Double   'DiscDirectCosts(year)
    Dim NPVDirectCosts As Double
    Dim IndirectCosts(49) As Double 'IndirectCosts(Year)
    Dim DiscIndirectCosts(49) As Double 'DiscIndirectCosts(Year)
    Dim NPVIndirectCosts As Double
    Dim TotalCosts(49) As Double    'TotalCosts(Year)
    Dim DiscTotalCosts(49) As Double    'DiscTotalCosts(year)
    Dim NPVTotalCosts As Double
    Dim NetBenefits(999)    'NetBenefits(Run)
    Dim NPVResControlCosts(999, 12, 1) As Double 'ResControlCosts(run, reservoir, scenario)
    Dim StrucControlCosts(999, 6, 1) As Double 'StrucControlCosts(run, structure type, scenario)
    Dim Cause(999, 12, 1) As String 'Cause(run, reservoir, scenario)
    Dim AvgJointProb_Up1(49, 12, 1) As Double 'avgJointProb_Up1(year,reservoir,scenario)
    Dim AvgJointProb_Up2(49, 12, 1) As Double 'avgJointProb_Up2(year,reservoir,scenario)


'Functional Variables
    Dim startrow As Integer
    Dim startcol As Integer
    Dim Count As Integer
    Dim Years As Integer
    Dim Runs As Integer
    Dim i As Integer
    Dim j As Integer
    Dim k As Integer
    Dim s As Integer
    Dim z As Integer
    Dim Candidate1 As Integer
    Dim Candidate2 As Integer
    Dim indicator As Boolean
    Dim Source As Integer
    Dim Start As Integer
    Dim sum As Double
    Dim term As Double
    Dim BoolArray(49) As Boolean    'BoolArray(year)
    Dim StringArray(999) As String  'StringArray(year or run)
    Dim DoubArray(999) As Double 'DoubArray(year or run)
    Dim cumsum(999, 49, 12, 1) As Integer 'CumSum(run,year,reservoir, scenario)
    Dim cumsum1(999, 49, 12, 1) As Integer 'CumSum1(run,year,reservoir, scenario)
    Dim cumsum2(999, 49, 12, 1) As Integer 'CumSum2(run,year,reservoir, scenario)


Load Userform1
Userform1.Show
Userform1.Label1.Caption = "Running Simulation."
Userform1.Repaint

'Set number of iterations
    Runs = 1000

Userform1.Label1.Caption = "Running Simulation.."
Userform1.Repaint

'Import inputs from "Model Input" sheet
    Worksheets("Model Input").Activate

    ' Invasibility(reservoirs)
    startrow = Range("Invasibility").Row
    startcol = Range("Invasibility").Column
```

```
For k = 0 To 12
   Invasibility(k) = Cells(startrow + k, startcol).Value
Next k

per_infest_0 = Range("per_infest_0").Value

per_cleaned = Range("per_cleaned").Value

a_boat = Range("a_boat").Value

c_boat = Range("c_boat").Value

per_decline = Range("per_decline").Value

'BoatVisits_0(reservoirs)
startrow = Range("BoatVisits_0").Row
startcol = Range("BoatVisits_0").Column
For k = 0 To 12
  BoatVisits_0(k) = Cells(startrow + k, startcol).Value
Next k

'BoatVisits_1(reservoirs)
startrow = Range("BoatVisits_1").Row
startcol = Range("BoatVisits_1").Column
For k = 0 To 12
   BoatVisits_1(k) = Cells(startrow + k, startcol).Value
Next k

per_max = Range("per_max").Value

R_max = Range("R_max").Value

B = Range("B_").Value

horizon = Range("horizon").Value

m = Range("m_").Value

a_stream = Range("a_stream").Value

c_stream = Range("c_stream").Value

'UpConnect1(reservoir)
startrow = Range("UpConnect1").Row
startcol = Range("UpConnect1").Column
For k = 0 To 12
   UpConnect1(k) = Cells(startrow + k, startcol).Value
Next k

'UpConnect2(reservoir)
startrow = Range("UpConnect2").Row
startcol = Range("UpConnect2").Column
For k = 0 To 12
   UpConnect2(k) = Cells(startrow + k, startcol).Value
Next k

'DensityAlive1(reservoir)
startrow = Range("DensityAlive1").Row
startcol = Range("DensityAlive1").Column
For k = 0 To 12
   DensityAlive1(k) = Cells(startrow + k, startcol).Value
Next k

'DensityAlive2(reservoir)
startrow = Range("DensityAlive2").Row
startcol = Range("DensityAlive2").Column
For k = 0 To 12
   DensityAlive2(k) = Cells(startrow + k, startcol).Value
Next k
```

```
    n = Range("n_").Value

    d_rate = Range("d_rate").Value

    'UpConnectStructure(structure)
    startrow = Range("UpConnectStructure").Row
    startcol = Range("UpConnectStructure").Column
    For s = 0 To 67
      UpConnectStructure(s) = Cells(startrow + s, startcol).Value
    Next s

    'StructureType(structure)
    startrow = Range("StructureType").Row
    startcol = Range("StructureType").Column
    For s = 0 To 67
      StructureType(s) = Cells(startrow + s, startcol).Value
    Next s

    direct_costs_variable = Range("direct_costs_variable").Value

    direct_costs_PI = Range("direct_costs_PI").Value

    indirect_costs = Range("indirect_costs").Value

    'ControlCostSchedules(structure, Year)
    startrow = Range("ControlCostSchedules").Row
    startcol = Range("ControlCostSchedules").Column
    For j = 0 To horizon - 1
      For s = 0 To 67
        ControlCostSchedules(j, s) = Cells(startrow + s, startcol + j).Value
      Next s
    Next j

    term_length = Range("term_length").Value

  'Generate random number arrays
    Rnd (-1)
    Randomize (Range("Seed").Value)

    Years = 50
    Count = 1000
    Limit = Range("R_max_low").Value
    For j = 0 To Years - 1
      For i = 0 To Count - 1
        RandomWalkLow(i, j, 0) = Rng_Number(0, Limit) / 10000
        RandomWalkLow(i, j, 1) = Rng_Number(0, Limit - B * Limit) / 10000
      Next i
    Next j

    Limit = Range("R_max_base").Value
    For j = 0 To Years - 1
      For i = 0 To Count - 1
        RandomWalkBase(i, j, 0) = Rng_Number(0, Limit) / 10000
        RandomWalkBase(i, j, 1) = Rng_Number(0, Limit - B * Limit) / 10000
      Next i
    Next j

    Limit = Range("R_max_high").Value
    For j = 0 To Years - 1
      For i = 0 To Count - 1
        RandomWalkHigh(i, j, 0) = Rng_Number(0, Limit) / 10000
        RandomWalkHigh(i, j, 1) = Rng_Number(0, Limit - B * Limit) / 10000
      Next i
    Next j

    Years = 50
    Count = 1000
    Limit = Range("R_max_userdefined").Value
    For j = 0 To Years - 1
```

```
    For i = 0 To Count - 1
      RandomWalkUser(i, j, 0) = Rng_Number(0, Limit) / 10000
      RandomWalkUser(i, j, 1) = Rng_Number(0, Limit - B * Limit) / 10000
    Next i
  Next j

  Count = 13000
  For j = 0 To Years - 1
    For i = 0 To Count - 1
      RandomBoats(i, j) = Rnd
    Next i
  Next j

  For j = 0 To Years - 1
    For i = 0 To Count - 1
      RandomUpstream1(i, j) = Rnd
    Next i
  Next j

  For j = 0 To Years - 1
    For i = 0 To Count - 1
      RandomUpstream2(i, j) = Rnd
    Next i
  Next j

Userform1.Label1.Caption = "Running Simulation..."
Userform1.Repaint

'Simulate Number of infested boats

  'Assign RandomWalk(run, year,scenario) array based on R_max
  Select Case R_max
    Case 1
       For i = 0 To Runs - 1
         For j = 0 To horizon - 1
         RandomWalk(i, j, 0) = RandomWalkLow(i, j, 0)
         RandomWalk(i, j, 1) = RandomWalkLow(i, j, 1)
         Next j
       Next i
    Case 2
      For i = 0 To Runs - 1
        For j = 0 To horizon - 1
          RandomWalk(i, j, 0) = RandomWalkBase(i, j, 0)
          RandomWalk(i, j, 1) = RandomWalkBase(i, j, 1)
        Next j
      Next i
     Case 3
       For i = 0 To Runs - 1
        For j = 0 To horizon - 1
          RandomWalk(i, j, 0) = RandomWalkHigh(i, j, 0)
          RandomWalk(i, j, 1) = RandomWalkHigh(i, j, 1)
        Next j
      Next i
    Case 4
       For i = 0 To Runs - 1
        For j = 0 To horizon - 1
          RandomWalk(i, j, 0) = RandomWalkUser(i, j, 0)
          RandomWalk(i, j, 1) = RandomWalkUser(i, j, 1)
        Next j
      Next i
   End Select
  'Populate PerInfest(run, year, scenario) in year 0
  For i = 0 To Runs - 1
    PerInfest(i, 0, 0) = per_infest_0
    PerInfest(i, 0, 1) = per_infest_0
    PerInfest_cleaned(i, 0) = per_infest_0 * (1 - per_cleaned)
  Next i

  'Populate PerInfest(run, year, scenario) for all remaining years
```

```
  For i = 0 To Runs - 1
    For j = 1 To horizon - 1
      If PerInfest(i, j - 1, 0) + RandomWalk(i, j, 0) <= per_max Then
        PerInfest(i, j, 0) = PerInfest(i, j - 1, 0) + RandomWalk(i, j, 0)
      Else: PerInfest(i, j, 0) = per_max
      End If
      If PerInfest(i, j - 1, 1) + RandomWalk(i, j, 1) <= per_max Then
        PerInfest(i, j, 1) = (PerInfest(i, j - 1, 1) + RandomWalk(i, j, 1))
      Else: PerInfest(i, j, 1) = per_max
      End If
      PerInfest_cleaned(i, j) = PerInfest(i, j, 1) * (1 - per_cleaned)
    Next j
  Next i

'Propagule Pressure and Probabilities (Boats)

  'Populate NumInfest(run, year, reservoir, scenario)
  For i = 0 To Runs - 1
    For j = 0 To horizon - 1
      For k = 0 To 12
        NumInfest(i, j, k, 0) = BoatVisits_0(k) * PerInfest(i, j, 0)
        NumInfest(i, j, k, 1) = BoatVisits_1(k) * PerInfest_cleaned(i, j)
      Next k
    Next j
  Next i

  'Populate ProbEstab_Boats(run, year, reservoir, scenario)
  For i = 0 To Runs - 1
    For j = 0 To horizon - 1
      For k = 0 To 12
        ProbEstab_Boats(i, j, k, 0) = 1 - Exp(-1 * (a_boat * NumInfest(i, j, k, 0)) ^ c_boat)
        ProbEstab_Boats(i, j, k, 1) = 1 - Exp(-1 * (a_boat * NumInfest(i, j, k, 1)) ^ c_boat)
      Next k
    Next j
  Next i

  'Populate year 0 of product_Boats(run, year, reservoir, scenario)
    'Note:The product variable is a building block of the joint probability variable
  For i = 0 To Runs - 1
    For k = 0 To 12
      product_Boats(i, 0, k, 0) = 1 - ProbEstab_Boats(i, 0, k, 0)
      product_Boats(i, 0, k, 1) = 1 - ProbEstab_Boats(i, 0, k, 1)
    Next k
  Next i

  'Populate remaining years of product_Boats(run, year, reservoir, scenario)
  For i = 0 To Runs - 1
    For j = 1 To horizon - 1
      For k = 0 To 12
        product_Boats(i, j, k, 0) = product_Boats(i, j - 1, k, 0) * (1 - ProbEstab_Boats(i, j, k, 0))
        product_Boats(i, j, k, 1) = product_Boats(i, j - 1, k, 1) * (1 - ProbEstab_Boats(i, j, k, 1))
      Next k
    Next j
  Next i

  'Populate JointProb_Boats(run, year, reservoir, scenario)
  For i = 0 To Runs - 1
    For j = 0 To horizon - 1
      For k = 0 To 12
        JointProb_Boats(i, j, k, 0) = Invasibility(k) * (1 - product_Boats(i, j, k, 0))
        JointProb_Boats(i, j, k, 1) = Invasibility(k) * (1 - product_Boats(i, j, k, 1))
      Next k
    Next j
  Next i


'Bernoulli Trials

  'Populate Bernoulli_Boats(run,year,reservoir,scenario)for all years
```

```
  For i = 0 To Runs - 1
    For j = 1 To horizon - 1
      For k = 0 To 12
        If RandomBoats(i * 12 + k, j) <= JointProb_Boats(i, j, k, 0) Then
        Bernoulli_Boats(i, j, k, 0) = 1
        Else: Bernoulli_Boats(i, j, k, 0) = 0
        End If
        If RandomBoats(i * 12 + k, j) <= JointProb_Boats(i, j, k, 1) Then
        Bernoulli_Boats(i, j, k, 1) = 1
        Else: Bernoulli_Boats(i, j, k, 1) = 0
        End If
      Next k
    Next j
  Next i

Userform1.Label1.Caption = "Running Simulation...."
Userform1.Repaint

  'Populating Bernoulli_Up1 and Bernoulli_Up2 is a little trickier, because the trial in
  'year j is dependent on the invasion record of year j-m.  Therefore, InvasionRecord and
  'Bernoulli_Up1 and Bernoulli_Up2 will have to be populated iteratively.  The first m-1
  'years must be populated before the iterative process can start, because the code will ask
  'to look up the invasion record of upstream connections m years ago.
  'Note: All of the upstream trials in years 0 through m-1 will be false because the lag time
  'has not yet passed.  Year j=m is the first year that upstream infested water bodies become
  'candidates for downstream infestation.

  'Populate years 0 through m-1 of Bernoulli_Up1(run,year,reservoir,scenario)
  'and Bernoulli_Up2(run,year,reservoir,scenario) as false
  'Populate ProbEstab_Up1(run,year,reservoir,scenario),ProbEstab_Up2(run,year,reservoir,scenario)
  'and JointProb_Up1(run,year,reservoir,scenario), and JointProb_Up2(run,year,reservoir,scenario) as 0
  For i = 0 To Runs - 1
    For j = 0 To m - 1
      For k = 0 To 12
        Bernoulli_Up1(i, j, k, 0) = 0
        Bernoulli_Up2(i, j, k, 0) = 0
        Bernoulli_Up1(i, j, k, 1) = 0
        Bernoulli_Up2(i, j, k, 1) = 0
        ProbEstab_Up1(i, j, k, 0) = 0
        ProbEstab_Up2(i, j, k, 0) = 0
        JointProb_Up1(i, j, k, 0) = 0
        JointProb_Up2(i, j, k, 0) = 0
        ProbEstab_Up1(i, j, k, 1) = 0
        ProbEstab_Up2(i, j, k, 1) = 0
        JointProb_Up1(i, j, k, 1) = 0
        JointProb_Up2(i, j, k, 1) = 0
      Next k
    Next j
  Next i

 'Populated InvasionRecord(run,year,reservoir,scenario) for year 0; imported from input sheet
  startrow = Range("InvasionRecord_0").Row
  startcol = Range("InvasionRecord_0").Column
  For i = 0 To Runs - 1
    For k = 0 To 12
      invasionrecord(i, 0, k, 0) = Cells(startrow + k, startcol).Value
      invasionrecord(i, 0, k, 1) = Cells(startrow + k, startcol).Value
    Next k
  Next i

  'As of this point: Bernoulli_Boats is populated for all years;
  'Bernoulli_Up1 and Bernoulli_Up2 are populated through year m-1

  'Populate InvasionRecord(run,year,reservoir,scenario)
  'for all reservoirs for years 1 through m-2

  For i = 0 To Runs - 1
    For j = 1 To m - 2
      For k = 0 To 12
```

```
        If invasionrecord(i, j - 1, k, 0) = True Then
          invasionrecord(i, j, k, 0) = 1
        ElseIf Bernoulli_Boats(i, j, k, 0) = True Or Bernoulli_Up1(i, j, k, 0) = True Or Bernoulli_Up2(i, j, k, 0) = True Then
          invasionrecord(i, j, k, 0) = 1
        Else: invasionrecord(i, j, k, 0) = 0
        End If
        If invasionrecord(i, j - 1, k, 1) = True Then
          invasionrecord(i, j, k, 1) = 1
        ElseIf Bernoulli_Boats(i, j, k, 1) = True Or Bernoulli_Up1(i, j, k, 1) = True Or Bernoulli_Up2(i, j, k, 1) = True Then
          invasionrecord(i, j, k, 1) = 1
        Else: invasionrecord(i, j, k, 1) = 0
        End If
      Next k
    Next j
  Next i

'As of this point: Bernoulli_Boats is populated for all years;
'Bernoulli_Up1 and Bernoulli_Up2 are populated through year m-1;
'InvasionRecord is populated through year m-2

    'Populate first year of cumsum1 and cumsum2
    For i = 0 To Runs - 1
      For k = 0 To 12
        Candidate1 = UpConnect1(k)
        If Candidate1 = -999 Then
          cumsum1(i, 0, k, 0) = 0
          cumsum1(i, 0, k, 1) = 0
        Else
          cumsum1(i, 0, k, 0) = invasionrecord(i, 0, Candidate1, 0)
          cumsum1(i, 0, k, 1) = invasionrecord(i, 0, Candidate1, 1)
        End If
      Next k
    Next i
    For i = 0 To Runs - 1
      For k = 0 To 12
        Candidate2 = UpConnect2(k)
        If Candidate2 = -999 Then
          cumsum2(i, 0, k, 0) = 0
          cumsum2(i, 0, k, 1) = 0
        Else
          cumsum2(i, 0, k, 0) = invasionrecord(i, 0, Candidate2, 0)
          cumsum2(i, 0, k, 1) = invasionrecord(i, 0, Candidate2, 1)
        End If
      Next k
    Next i

    'Populate cumsum1 and cumsum2 through year m-2

    For i = 0 To Runs - 1
      For j = 1 To m - 2
        For k = 0 To 12
          Candidate1 = UpConnect1(k)
          If Candidate1 = -999 Then
            cumsum1(i, j, k, 0) = 0
            cumsum1(i, j, k, 1) = 0
          Else
            cumsum1(i, j, k, 0) = cumsum1(i, j - 1, k, 0) + invasionrecord(i, j, Candidate1, 0)
            cumsum1(i, j, k, 1) = cumsum1(i, j - 1, k, 1) + invasionrecord(i, j, Candidate1, 1)
          End If
        Next k
      Next j
    Next i

    For i = 0 To m - 2
      For j = 1 To horizon - 1
        For k = 0 To 12
          Candidate2 = UpConnect2(k)
          If Candidate2 = -999 Then
            cumsum2(i, j, k, 0) = 0
```

```
            cumsum2(i, j, k, 1) = 0
          Else
            cumsum2(i, j, k, 0) = cumsum2(i, j - 1, k, 0) + invasionrecord(i, j, Candidate2, 0)
            cumsum2(i, j, k, 1) = cumsum2(i, j - 1, k, 1) + invasionrecord(i, j, Candidate2, 1)
          End If
        Next k
      Next j
    Next i


'This next loop iteratively populates InvasionRecord in year j
'and then Bernoulli_Up1, Bernoulli_Up2, ProbEstab_Up1, ProbEstab_up2,
'JointProb_Up1, and JointProb_Up2 in year j+1 for years m-1 to horizon-2

For i = 0 To Runs - 1
  For j = m - 1 To horizon - 2
    'Populate InvasionRecord(run,year,reservoir,scenario) in year j for all reservoirs
    For k = 0 To 12
      If invasionrecord(i, j - 1, k, 0) = True Then
      invasionrecord(i, j, k, 0) = 1
      ElseIf Bernoulli_Boats(i, j, k, 0) = True Or Bernoulli_Up1(i, j, k, 0) = True Or Bernoulli_Up2(i, j, k, 0) = True Then
      invasionrecord(i, j, k, 0) = 1
      Else: invasionrecord(i, j, k, 0) = 0
      End If
      If invasionrecord(i, j - 1, k, 1) = True Then
      invasionrecord(i, j, k, 1) = 1
      ElseIf Bernoulli_Boats(i, j, k, 1) = True Or Bernoulli_Up1(i, j, k, 1) = True Or Bernoulli_Up2(i, j, k, 1) = True Then
      invasionrecord(i, j, k, 1) = 1
      Else: invasionrecord(i, j, k, 1) = 0
      End If

    Next k

    'Populate ProbEstab_Up1, ProbEstab_Up2, JointProbEstab_Up1 and JointProbEstab_Up2
    'in year j+1 for all reservoirs
    For k = 0 To 12
          Candidate1 = UpConnect1(k)
          If Candidate1 = -999 Then
            cumsum1(i, j, k, 0) = 0
            cumsum1(i, j, k, 1) = 0
          Else
            cumsum1(i, j, k, 0) = cumsum1(i, j - 1, k, 0) + invasionrecord(i, j, Candidate1, 0)
            cumsum1(i, j, k, 1) = cumsum1(i, j - 1, k, 1) + invasionrecord(i, j, Candidate1, 1)
          End If
          Candidate2 = UpConnect2(k)
          If Candidate2 = -999 Then
            cumsum2(i, j, k, 0) = 0
            cumsum2(i, j, k, 1) = 0
          Else
            cumsum2(i, j, k, 0) = cumsum2(i, j - 1, k, 0) + invasionrecord(i, j, Candidate2, 0)
            cumsum2(i, j, k, 1) = cumsum2(i, j - 1, k, 1) + invasionrecord(i, j, Candidate2, 1)
          End If
      'Note: When you sum boolean values, False=0 and True=-1 (i.e.True+True=-2)
      If Candidate1 = -999 Then
        ProbEstab_Up1(i, j + 1, k, 0) = 0
      ElseIf cumsum1(i, j, k, 0) < -1 * m + 1 Then
        ProbEstab_Up1(i, j + 1, k, 0) = 1 - Exp(-1 * (a_stream * DensityAlive1(k)) ^ c_stream)
      Else: ProbEstab_Up1(i, j + 1, k, 0) = 0
      End If
      JointProb_Up1(i, j + 1, k, 0) = Invasibility(k) * (1 - (1 - ProbEstab_Up1(i, j + 1, k, 0)) ^ (j + 2))

      If Candidate2 = -999 Then
        ProbEstab_Up2(i, j + 1, k, 0) = 0
      ElseIf cumsum2(i, j, k, 0) < -1 * m + 1 Then
        ProbEstab_Up2(i, j + 1, k, 0) = 1 - Exp(-1 * (a_stream * DensityAlive2(k)) ^ c_stream)
      Else: ProbEstab_Up2(i, j + 1, k, 0) = 0
      End If
      JointProb_Up2(i, j + 1, k, 0) = Invasibility(k) * (1 - (1 - ProbEstab_Up2(i, j + 1, k, 0)) ^ (j + 2))
```

```
            If Candidate1 = -999 Then
                ProbEstab_Up1(i, j + 1, k, 1) = 0
            ElseIf cumsum1(i, j, k, 1) < -1 * m + 1 Then
                ProbEstab_Up1(i, j + 1, k, 1) = 1 - Exp(-1 * (a_stream * DensityAlive1(k)) ^ c_stream)
            Else: ProbEstab_Up1(i, j + 1, k, 1) = 0
            End If
            JointProb_Up1(i, j + 1, k, 1) = Invasibility(k) * (1 - (1 - ProbEstab_Up1(i, j + 1, k, 1)) ^ (j + 2))

            If Candidate2 = -999 Then
                ProbEstab_Up2(i, j + 1, k, 1) = 0
            ElseIf cumsum2(i, j, k, 1) < -1 * m + 1 Then
                ProbEstab_Up2(i, j + 1, k, 1) = 1 - Exp(-1 * (a_stream * DensityAlive2(k)) ^ c_stream)
            Else: ProbEstab_Up2(i, j + 1, k, 1) = 0
            End If
            JointProb_Up2(i, j + 1, k, 1) = Invasibility(k) * (1 - (1 - ProbEstab_Up2(i, j + 1, k, 1)) ^ (j + 2))
        Next k

        'Populate Bernoulli_Up1(run,year,reservoir,scenario) and
        'Bernoulli_Up2(run,year,reservoir,scenario) in year j+1 for all reservoirs
        For k = 0 To 12
            Candidate1 = UpConnect1(k)
            Candidate2 = UpConnect2(k)
            If Candidate1 = -999 Then
                Bernoulli_Up1(i, j + 1, k, 0) = 0
            ElseIf invasionrecord(i, j + 1 - m, Candidate1, 0) = True And RandomUpstream1(i * 12 + k, j + 1) <= JointProb_Up1(i, j +
1, k, 0) Then
                Bernoulli_Up1(i, j + 1, k, 0) = 1
            Else: Bernoulli_Up1(i, j + 1, k, 0) = 0
            End If
            If Candidate2 = -999 Then
                Bernoulli_Up2(i, j + 1, k, 0) = 0
            ElseIf invasionrecord(i, j + 1 - m, Candidate2, 0) = True And RandomUpstream1(i * 12 + k, j + 1) <= JointProb_Up2(i, j +
1, k, 0) Then
                Bernoulli_Up2(i, j + 1, k, 0) = 1
            Else: Bernoulli_Up2(i, j + 1, k, 0) = 0
            End If
            If Candidate1 = -999 Then
                Bernoulli_Up1(i, j + 1, k, 1) = 0
            ElseIf invasionrecord(i, j + 1 - m, Candidate1, 1) = True And RandomUpstream1(i * 12 + k, j + 1) <= JointProb_Up1(i, j +
1, k, 1) Then
                Bernoulli_Up1(i, j + 1, k, 1) = 1
            Else: Bernoulli_Up1(i, j + 1, k, 1) = 0
            End If
            If Candidate2 = -999 Then
                Bernoulli_Up2(i, j + 1, k, 1) = 0
            ElseIf invasionrecord(i, j + 1 - m, Candidate2, 1) = True And RandomUpstream1(i * 12 + k, j + 1) <= JointProb_Up2(i, j +
1, k, 1) Then
                Bernoulli_Up2(i, j + 1, k, 1) = 1
            Else: Bernoulli_Up2(i, j + 1, k, 1) = 0
            End If
        Next k
    Next j
  Next i

  'Populate the last year of InvasionRecord(run,year,reservoir,scenario)

  For i = 0 To Runs - 1
    For k = 0 To 12
        If invasionrecord(i, horizon - 2, k, 0) = True Then
            invasionrecord(i, horizon - 1, k, 0) = 1
        ElseIf Bernoulli_Boats(i, horizon - 1, k, 0) = True Or Bernoulli_Up1(i, horizon - 1, k, 0) = True Or Bernoulli_Up2(i, horizon
- 1, k, 0) = True Then
            Bernoulli_Up2(i, horizon - 1, k, 0) = 1
        Else: invasionrecord(i, horizon - 1, k, 0) = 0
        End If
        If invasionrecord(i, horizon - 2, k, 1) = True Then
            invasionrecord(i, horizon - 1, k, 1) = 1
        ElseIf Bernoulli_Boats(i, horizon - 1, k, 1) = True Or Bernoulli_Up1(i, horizon - 1, k, 1) = True Or Bernoulli_Up2(i, horizon
- 1, k, 1) = True Then
```

```
        Bernoulli_Up2(i, horizon - 1, k, 1) = 1
      Else: invasionrecord(i, horizon - 1, k, 1) = 0
      End If
    Next k
  Next i

'Populate FirstYearEstab(run, reservoir, scenario)

  'Populate first year of CumSum(year)
    For i = 0 To Runs - 1
      For k = 0 To 12
        cumsum(i, 0, k, 0) = invasionrecord(i, 0, k, 0)
        cumsum(i, 0, k, 1) = invasionrecord(i, 0, k, 1)
      Next k
    Next i

  'Populate remaining years of CumSum(year)
    For i = 0 To Runs - 1
      For j = 1 To horizon - 1
        For k = 0 To 12
          cumsum(i, j, k, 0) = cumsum(i, j - 1, k, 0) + invasionrecord(i, j, k, 0)
          cumsum(i, j, k, 1) = cumsum(i, j - 1, k, 1) + invasionrecord(i, j, k, 1)
        Next k
      Next j
    Next i

Userform1.Label1.Caption = "Running Simulation....."
Userform1.Repaint

  'Determine the first year of establishment
   For i = 0 To Runs - 1
    For k = 0 To 12
      j = 0
      indicator = 0
      Do
        If cumsum(i, j, k, 0) <> 0 Then indicator = 1
        j = j + 1
      Loop Until indicator = True Or j = horizon
      If j = horizon Then
        FirstYearEstab(i, k, 0) = -999
      Else: FirstYearEstab(i, k, 0) = j - 1
      End If
      j = 0
      indicator = 0
      Do
        If cumsum(i, j, k, 1) <> 0 Then indicator = 1
        j = j + 1
      Loop Until indicator = True Or j = horizon
      If j = horizon Then
        FirstYearEstab(i, k, 1) = -999
      Else: FirstYearEstab(i, k, 1) = j - 1
      End If
    Next k
  Next i


'Populate IncurredControlCosts(run,year,structure,scenario)
  For i = 0 To Runs - 1
    For s = 0 To 67
      Source = UpConnectStructure(s)

      indicator = 0
      If FirstYearEstab(i, Source, 0) = -999 Then
        indicator = 1
      End If
      If indicator = 0 And FirstYearEstab(i, Source, 0) + n < horizon Then
        Start = FirstYearEstab(i, Source, 0) + n
        For j = 0 To Start - 1
          IncurredControlCosts(i, j, s, 0) = 0
```

```
            Next j
            For j = Start To horizon - 1
               IncurredControlCosts(i, j, s, 0) = ControlCostSchedules(j - Start, s)
            Next j
         Else: For j = 0 To horizon - 1
               IncurredControlCosts(i, j, s, 0) = 0
             Next j
         End If

         indicator = 0
         If FirstYearEstab(i, Source, 1) = -999 Then
            indicator = 1
         End If
         If indicator = 0 And FirstYearEstab(i, Source, 1) + n < horizon Then
            Start = FirstYearEstab(i, Source, 1) + n
            For j = 0 To Start - 1
               IncurredControlCosts(i, j, s, 1) = 0
            Next j
            For j = Start To horizon - 1
               IncurredControlCosts(i, j, s, 1) = ControlCostSchedules(j - Start, s)
            Next j
         Else: For j = 0 To horizon - 1
               IncurredControlCosts(i, j, s, 1) = 0
             Next j
         End If
      Next s
   Next i

'Populate DiscControlCosts(run,year,structure,scenario)
   For i = 0 To Runs - 1
      For j = 0 To horizon - 1
         For s = 0 To 67
            DiscControlCosts(i, j, s, 0) = (1 / (1 + d_rate)) ^ j * IncurredControlCosts(i, j, s, 0)
            DiscControlCosts(i, j, s, 1) = (1 / (1 + d_rate)) ^ j * IncurredControlCosts(i, j, s, 1)
         Next s
      Next j
   Next i

'Populate NPVControlCosts(run, scenario)
   For i = 0 To Runs - 1
      sum = 0
      For j = 0 To horizon - 1
         For s = 0 To 67
            term = (DiscControlCosts(i, j, s, 0))
            sum = sum + term
         Next s
      Next j
      NPVControlCosts(i, 0) = sum

      sum = 0
      For j = 0 To horizon - 1
         For s = 0 To 67
            term = (DiscControlCosts(i, j, s, 1))
            sum = sum + term
         Next s
      Next j
      NPVControlCosts(i, 1) = sum
   Next i

'Populate Benefits(run)
   For i = 0 To Runs - 1
      Benefits(i) = NPVControlCosts(i, 0) - NPVControlCosts(i, 1)
   Next i

'Populate DirectCosts(year)
   For j = 0 To term_length - 1
      DirectCosts(j) = direct_costs_variable + direct_costs_PI
   Next j
   For j = term_length To horizon - 1
```

```
      DirectCosts(j) = direct_costs_variable
   Next j

'Populate DiscDirectCosts(year)
   For j = 0 To horizon - 1
      DiscDirectCosts(j) = (1 / (1 + d_rate)) ^ j * DirectCosts(j)
   Next j

'Populate NPVDirectCosts
   NPVDirectCosts = WorksheetFunction.sum(DiscDirectCosts)

'Populate IndirectCosts(year)
   For j = 0 To horizon - 1
      IndirectCosts(j) = indirect_costs
   Next j

'Populate DiscIndirectCosts(year)
   For j = 0 To horizon - 1
      DiscIndirectCosts(j) = (1 / (1 + d_rate)) ^ j * IndirectCosts(j)
   Next j

'Populate NPVIndirectCosts
   NPVIndirectCosts = WorksheetFunction.sum(DiscIndirectCosts)

'Populate TotalCosts(year)
   For j = 0 To horizon - 1
      TotalCosts(j) = DirectCosts(j) + IndirectCosts(j)
   Next j

'Populate DiscTotalCosts(year)
   For j = 0 To horizon - 1
      DiscTotalCosts(j) = (1 / (1 + d_rate)) ^ j * TotalCosts(j)
   Next j

'Populate NPVTotalCosts
   NPVTotalCosts = WorksheetFunction.sum(DiscTotalCosts)

'Populate NetBenefits(run)
   For i = 0 To Runs - 1
      NetBenefits(i) = Benefits(i) - NPVTotalCosts
   Next i

'Populate NPVResControlCosts(run, reservoir, scenario)
   For i = 0 To Runs - 1
      For k = 0 To 12
         sum = 0
         For j = 0 To horizon - 1
            For s = 0 To 67
               If UpConnectStructure(s) = k Then
                  sum = sum + DiscControlCosts(i, j, s, 0)
               End If
            Next s
         Next j
         NPVResControlCosts(i, k, 0) = sum
      Next k
   Next i

   For i = 0 To Runs - 1
      For k = 0 To 12
         sum = 0
         For j = 0 To horizon - 1
            For s = 0 To 67
               If UpConnectStructure(s) = k Then
                  sum = sum + DiscControlCosts(i, j, s, 1)
               End If
            Next s
         Next j
         NPVResControlCosts(i, k, 1) = sum
      Next k
```

```
  Next i

'Populate Cause(run, reservoir, scenario)
  For i = 0 To Runs - 1
    For k = 0 To 12
      z = FirstYearEstab(i, k, 0)
      If z = -999 Then
      Cause(i, k, 0) = "not established"
      ElseIf Bernoulli_Boats(i, z, k, 0) = True And Bernoulli_Up1(i, z, k, 0) = True Then
      Cause(i, k, 0) = "both"
      ElseIf Bernoulli_Boats(i, z, k, 0) = True And Bernoulli_Up2(i, z, k, 0) = True Then
      Cause(i, k, 0) = "both"
      ElseIf Bernoulli_Boats(i, z, k, 0) = True Then
      Cause(i, k, 0) = "boats"
      ElseIf Bernoulli_Up1(i, z, k, 0) = True Then
      Cause(i, k, 0) = "flows"
      ElseIf Bernoulli_Up2(i, z, k, 0) = True Then
      Cause(i, k, 0) = "flows"
      Else: Cause(i, k, 0) = "error"
      End If
    Next k
  Next i

  For i = 0 To Runs - 1
    For k = 0 To 12
      z = FirstYearEstab(i, k, 1)
      If z = -999 Then
      Cause(i, k, 1) = "not established"
      ElseIf Bernoulli_Boats(i, z, k, 1) = True And Bernoulli_Up1(i, z, k, 1) = True Then
      Cause(i, k, 1) = "both"
      ElseIf Bernoulli_Boats(i, z, k, 1) = True And Bernoulli_Up2(i, z, k, 1) = True Then
      Cause(i, k, 1) = "both"
      ElseIf Bernoulli_Boats(i, z, k, 1) = True Then
      Cause(i, k, 1) = "boats"
      ElseIf Bernoulli_Up1(i, z, k, 1) = True Then
      Cause(i, k, 1) = "flows"
      ElseIf Bernoulli_Up2(i, z, k, 1) = True Then
      Cause(i, k, 1) = "flows"
      Else: Cause(i, k, 1) = "error"
      End If
    Next k
  Next i

'Populate AvgNumInfest(year, reservoir, scenario)
  For j = 0 To horizon - 1
    For k = 0 To 12
      sum = 0
      For i = 0 To Runs - 1
        sum = sum + NumInfest(i, j, k, 0)
      Next i
      AvgNumInfest(j, k, 0) = sum / (Runs - 1)
    Next k
  Next j

  For j = 0 To horizon - 1
    For k = 0 To 12
      sum = 0
      For i = 0 To Runs - 1
        sum = sum + NumInfest(i, j, k, 1)
      Next i
      AvgNumInfest(j, k, 1) = sum / (Runs - 1)
    Next k
  Next j

'Populate AvgJointProb_Boats(year, reservoir, scenario)
  For j = 0 To horizon - 1
    For k = 0 To 12
      sum = 0
      For i = 0 To Runs - 1
```

```
            sum = sum + JointProb_Boats(i, j, k, 0)
         Next i
         AvgJointProb_Boats(j, k, 0) = sum / (Runs - 1)
      Next k
   Next j

   For j = 0 To horizon - 1
      For k = 0 To 12
         sum = 0
         For i = 0 To Runs - 1
            sum = sum + JointProb_Boats(i, j, k, 1)
         Next i
         AvgJointProb_Boats(j, k, 1) = sum / (Runs - 1)
      Next k
   Next j

'Populate AvgJointProb_Up1(year, reservoir, scenario)
   For j = 0 To horizon - 1
      For k = 0 To 12
         sum = 0
         For i = 0 To Runs - 1
            sum = sum + JointProb_Up1(i, j, k, 0)
         Next i
         AvgJointProb_Up1(j, k, 0) = sum / (Runs - 1)
      Next k
   Next j

   For j = 0 To horizon - 1
      For k = 0 To 12
         sum = 0
         For i = 0 To Runs - 1
            sum = sum + JointProb_Up1(i, j, k, 1)
         Next i
         AvgJointProb_Up1(j, k, 1) = sum / (Runs - 1)
      Next k
   Next j
'Populate AvgJointProb_Up2(year, reservoir, scenario)
   For j = 0 To horizon - 1
      For k = 0 To 12
         sum = 0
         For i = 0 To Runs - 1
            sum = sum + JointProb_Up2(i, j, k, 0)
         Next i
         AvgJointProb_Up2(j, k, 0) = sum / (Runs - 1)
      Next k
   Next j

   For j = 0 To horizon - 1
      For k = 0 To 12
         sum = 0
         For i = 0 To Runs - 1
            sum = sum + JointProb_Up2(i, j, k, 1)
         Next i
         AvgJointProb_Up2(j, k, 1) = sum / (Runs - 1)
      Next k
   Next j

Userform1.Label1.Caption = "Running Simulation......"
Userform1.Repaint

'Print Output to "Output" sheet
   Worksheets("Output").Activate

   'Print NPVControlCosts(run, scenario)
      startrow = Range("output_npvcontrol_0").Row
      startcol = Range("output_npvcontrol_0").Column
      For i = 0 To Runs - 1
         DoubArray(i) = NPVControlCosts(i, 0)
      Next i
```

```
      ActiveSheet.Range(Cells(startrow, startcol), Cells(startrow, startcol + Runs - 1)).Value = (DoubArray)

      startrow = Range("output_npvcontrol_1").Row
      startcol = Range("output_npvcontrol_1").Column
      For i = 0 To Runs - 1
         DoubArray(i) = NPVControlCosts(i, 1)
      Next i
      ActiveSheet.Range(Cells(startrow, startcol), Cells(startrow, startcol + Runs - 1)).Value = (DoubArray)

   'Print Benefits(run)
      startrow = Range("output_benefits").Row
      startcol = Range("output_benefits").Column
      ActiveSheet.Range(Cells(startrow, startcol), Cells(startrow, startcol + Runs - 1)).Value = (Benefits)

   'Print NPVDirectCosts
      ActiveSheet.Range("output_npvdirect") = NPVDirectCosts

   'Print NPVIndirectCosts
      ActiveSheet.Range("output_npvindirect") = NPVIndirectCosts

   'Print NPVTotalCosts
      ActiveSheet.Range("output_npvtotal") = NPVTotalCosts

   'Print NetBenefits(run)
      startrow = Range("output_netben").Row
      startcol = Range("output_netben").Column
      ActiveSheet.Range(Cells(startrow, startcol), Cells(startrow, startcol + Runs - 1)).Value = (NetBenefits)

Userform1.Label1.Caption = "Running Simulation......."
Userform1.Repaint

   'Print FirstYearEstab(run, reservoir, scenario)
      'Print for scenario=0
         startrow = Range("output_estab_0").Row
         startcol = Range("output_estab_0").Column

         For k = 0 To 12
            For i = 0 To Runs - 1
               DoubArray(i) = FirstYearEstab(i, k, 0)
            Next i
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
         Next k
      'Print for scenario=1
         startrow = Range("output_estab_1").Row
         startcol = Range("output_estab_1").Column

         For k = 0 To 12
            For i = 0 To Runs - 1
               DoubArray(i) = FirstYearEstab(i, k, 1)
            Next i
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
         Next k

   'Print NPVResControlCosts(run, reservoir, scenario)
      'Print for scenario=0
         startrow = Range("output_ResControl_0").Row
         startcol = Range("output_ResControl_0").Column

         For k = 0 To 12
            For i = 0 To Runs - 1
               DoubArray(i) = NPVResControlCosts(i, k, 0)
            Next i
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
         Next k
      'Print for scenario=1
         startrow = Range("output_ResControl_1").Row
         startcol = Range("output_ResControl_1").Column

         For k = 0 To 12
```

```
        For i = 0 To Runs - 1
          DoubArray(i) = NPVResControlCosts(i, k, 1)
        Next i
        ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
      Next k

'Print Cause(run, reservoir, scenario)
   'Print for scenario=0
      startrow = Range("output_cause_0").Row
      startcol = Range("output_cause_0").Column

      For k = 0 To 12
        For i = 0 To Runs - 1
          StringArray(i) = Cause(i, k, 0)
        Next i
        ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (StringArray)
      Next k
   'Print for scenario=1
      startrow = Range("output_cause_1").Row
      startcol = Range("output_cause_1").Column

      For k = 0 To 12
        For i = 0 To Runs - 1
          StringArray(i) = Cause(i, k, 1)
        Next i
        ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (StringArray)
      Next k

'Print AvgNumInfest
    'Print for scenario=0
      startrow = Range("output_avgnuminfest_0").Row
      startcol = Range("output_avgnuminfest_0").Column

      For k = 0 To 12
        For j = 0 To horizon - 1
          DoubArray(j) = AvgNumInfest(j, k, 0)
        Next j
        ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
      Next k
   'Print for scenario=1
      startrow = Range("output_avgnuminfest_1").Row
      startcol = Range("output_avgnuminfest_1").Column

      For k = 0 To 12
        For j = 0 To horizon - 1
          DoubArray(j) = AvgNumInfest(j, k, 1)
        Next j
        ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
      Next k

'Print AvgJointProb_Boats
    'Print for scenario=0
      startrow = Range("output_avgjointprobboat_0").Row
      startcol = Range("output_avgjointprobboat_0").Column

      For k = 0 To 12
        For j = 0 To horizon - 1
          DoubArray(j) = AvgJointProb_Boats(j, k, 0)
        Next j
        ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
      Next k
   'Print for scenario=1
      startrow = Range("output_avgjointprobboat_1").Row
      startcol = Range("output_avgjointprobboat_1").Column

      For k = 0 To 12
        For j = 0 To horizon - 1
          DoubArray(j) = AvgJointProb_Boats(j, k, 1)
        Next j
```

```
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
        Next k

    'Print AvgJointProb_Up1(year,reservoir,scenario)

        startrow = Range("output_jointprob_up1_0").Row
        startcol = Range("output_jointprob_up1_0").Column

        For k = 0 To 12
            For j = 0 To horizon - 1
                DoubArray(j) = AvgJointProb_Up1(j, k, 0)
            Next j
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
        Next k
        startrow = Range("output_jointprob_up1_1").Row
        startcol = Range("output_jointprob_up1_1").Column

        For k = 0 To 12
            For j = 0 To horizon - 1
                DoubArray(j) = AvgJointProb_Up1(j, k, 1)
            Next j
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
        Next k

    'Print AvgJointProb_Up2(year,reservoir,scenario)

        startrow = Range("output_jointprob_up2_0").Row
        startcol = Range("output_jointprob_up2_0").Column

        For k = 0 To 12
            For j = 0 To horizon - 1
                DoubArray(j) = AvgJointProb_Up2(j, k, 0)
            Next j
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
        Next k
        startrow = Range("output_jointprob_up2_1").Row
        startcol = Range("output_jointprob_up2_1").Column

        For k = 0 To 12
            For j = 0 To horizon - 1
                DoubArray(j) = AvgJointProb_Up2(j, k, 1)
            Next j
            ActiveSheet.Range(Cells(startrow + k, startcol), Cells(startrow + k, startcol + Runs - 1)).Value = (DoubArray)
        Next k

Userform1.Label1.Caption = "Running Simulation......."
Userform1.Repaint
Userform1.Hide
Unload Userform1

Worksheets("Simulation Results").Activate

End Sub


Public Function Rng_Number(ByVal Lower, ByVal Upper)
'This function is just like Randbetween.  It will return a random
'number between the passed in upper and lower bounds.
    Dim Random_Num As Integer
   ' Randomize
    Random_Num = Int((Upper - Lower + 1) * Rnd + Lower)
    Rng_Number = Random_Num

End Function
```