Final Report

Quagga/Zebra Mussel Risk Assessment and Treatment Study

City of Westminster

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List of Acronyms

FRICO – Farmers Reservoir and Irrigation Company
SLOC – Standley Lake Operating Committee
KDPL – Kinnear Ditch Pipeline
WTF – Water Treatment Facility

0.0 Executive Summary

The City of Westminster has undertaken this planning effort to prepare for the eventuality that Standley Lake may become infested with the invasive quagga or zebra mussels (*Dreissena bugensis, Dreissena polymorpha*). Both quagga and zebra mussels have invaded water bodies in the eastern U.S. and have recently been detected in Colorado. Once established in a water body, these mussels multiply rapidly and can quickly colonize submerged water system infrastructure causing significant impacts on the operations of Westminster and its partners at Standley Lake (Cities of Thornton and Northglenn and FRICO). Westminster has initiated a proactive lake protection program by monitoring and controlling access by motorized boats to the lake. This program reduces the risk of mussels being imported into Standley Lake, but does not entirely eliminate the possibility of infestation.

As part of this planning effort, a vulnerability assessment was conducted on both the upstream watershed that supplies Standley Lake and on Standley Lake itself. The assessment concluded that while portions of the upstream watershed are susceptible to the importation of mussels, conditions are not suitable for their translocation or growth. Therefore, the risk of mussels entering Standley Lake from upstream sources is low. The most likely pathway for entry into the lake is from recreational boats. For this reason, continued inspection and cleaning of boats and their accompanying trailers is essential for protecting Standley Lake from the translocation of mussels. The Colorado Division of Wildlife reported that in 2009 fifteen boats infested with mussels were intercepted at watercraft inspection stations across the state, indicating infested boats are present in Colorado. The consequences of mussels being introduced in Standley Lake will be serious. This is because once mussels are introduced into Standley Lake, the population is likely to thrive since the water quality and nutrient levels in the lake are favorable for mussel colonization.

The focal points of concern at Standley Lake are the two-level intake and the related downstream infrastructure that supplies water to all the partners. During the summer, the risk of mussels colonizing the lower intake is reduced due to low oxygen levels (anoxia) in the water at the bottom of the lake. But at other times of year, oxygen levels are high enough that mussels will thrive at the depth of the lower intake. Hence, anoxia alone is not sufficient to protect the lower intake from colonization. The upper intake (which is not currently in use) does not experience anoxia at any time of the year. Thus, the expectation is that if mussels arrive in the lake, they will colonize intakes, screens and downstream pipelines unless preventative measures are taken.

A number of methods for controlling mussels are available, but many of them are in the developmental stage and have not yet been applied at full scale. A summary of these methods is presented in the report with pros and cons and their applicability to Westminster's situation. If Westminster were to detect mussels in Standley Lake in the near future, the most likely method of control is use of an oxidant at the intake pipelines or at the valve house downstream of the dam. The choice of location of treatment depends on agreements that may be developed between Westminster and the other Standley Lake water users regarding cost sharing and an understanding of water quality issues associated with the addition of an oxidant to the raw water.

This report recommends a series of steps be taken by Westminster as part of the proactive plan for mussel control.

- Continue to focus on preventing the introduction of mussels into Standley Lake by maintaining aggressive control of motorized watercraft allowed on the Lake.
- Develop intergovernmental agreements with Thornton, Northglenn and FRICO, regarding selection of the most appropriate control approach for mussels at Standley Lake. Through discussion with the SLOC partners, the group should come to an agreement regarding the preferred approach so that design can be initiated for the facilities included in that option.
- Monitor development of non-chemical treatment technologies for mussel control. Because using chemical oxidants is a less than ideal solution for an infestation at Standley Lake, other technologies may be better solutions when they are proven at full-scale. Westminster should be aware of the status of ongoing research and testing of new control methods.
- Adopt a phased strategy for implementation of control measures. The phases of implementation are tied to the timeframe in which mussels first appear in the lake and when they begin to colonize infrastructure. Specific actions for each phase are identified in the report.

Since Standley Lake is the sole source of drinking water for Westminster, the mussel control strategy must provide failsafe solutions that could be implemented in the event that the intake and pipelines to Westminster facilities are compromised by mussels. This may include provisions for eventual physical removal of mussels.

1.0 Introduction

The City of Westminster has recognized that invasive mussel species may be a threat to the water supply infrastructure that provides drinking water to the City. Invasive mussel species have been documented to have adverse effects on lake health and water transport infrastructure. A reduction in supply volume and water quality has been documented in mussel infested conduits and submerged infrastructure. Although stringent mussel prevention measures and monitoring activities are in place at Standley Lake, the possibility of a mussel infestation is not eliminated. In Colorado, seven lakes and reservoirs have reported the juvenile stage of mussels; however no adult mussels have been confirmed.

In a proactive framework, the City has initiated this project to establish a response program which can be executed if quagga or zebra mussels are discovered in Standley Lake. The objective of this project is to evaluate nationwide efforts to control mussels for application in Standley Lake and to develop a plan of action for implementing mussel control and/or treatment. This plan would be implemented in Standley Lake at any point in the future that mussels were found.

2.0 Background

2.1 Existing Water System

The Standley Lake Dam and Reservoir is owned and operated by the Standley Lake Operating Committee (SLOC), which includes FRICO (Farmers Reservoir and Irrigation Company) and the cities of Westminster, Thornton, and Northglenn. Standley Lake stores 43,000 acre-ft of water delivered via canals from Clear Creek, and to a lesser extent, South Boulder Creek, and Coal Creek. Standley Lake was originally constructed between 1908 and 1912, and the Standley Lake Dam was repaired in 1967. Standley Lake supplies the majority of Westminster and Northglenn's raw water and half of Thornton's supply. The storage rights in Standley Lake are currently allocated as follows:

• Westminster	51.4%
• Thornton	27.2%
• Northglenn	10.9%
• FRICO	10.4%

All SLOC water users draw water through a common intake in Standley Lake. The intake system includes an upper and lower intake, but the SLOC has never used the upper intake due to preferential water quality at the lower intake. FRICO's water is discharged just after it passes through the dam structure into Big Dry Creek. FRICO withdraws their water on a seasonal basis, and Big Dry Creek does not run year-round. The remaining water for the municipalities is routed through a valve house where two conduits transport water to Westminster and a common conduit transports water to Thornton and Northglenn.

The City of Westminster operates two drinking water treatment plants. The Semper Water Treatment Facility (WTF) is a conventional drinking water treatment facility and the Northwest WTF is a membrane micro-filtration facility. Two conduits that are 36" and 42" in diameter run in parallel and transport raw water approximately 2.3 miles to Semper WTF. A 36" conduit transports raw water 2 miles to the Northwest WTF, connecting to the conduits transporting water to Semper, just after the valve house. All conduits are mortar-lined and equipped with butterfly valves.

2.2 Characteristics of Zebra and Quagga Mussels

Native to Eastern Europe, including the Black, Azov, and Caspian seas, the zebra mussel (*Dreissena polymorpha*) spread through western Europe in the 19th century as canals and inland waterways were connected to facilitate trade. The species was believed to have been introduced to North America in 1985 or 1986 by the release of mussel larvae in ship ballast water. Zebra mussels were first documented in Lake St. Clair in 1988. The first quagga mussel (*Dreissena Bugensis)*, a cousin to the zebra mussel, was found in Lake Erie in 1989, however, it was not identified as a separate species until 1991.

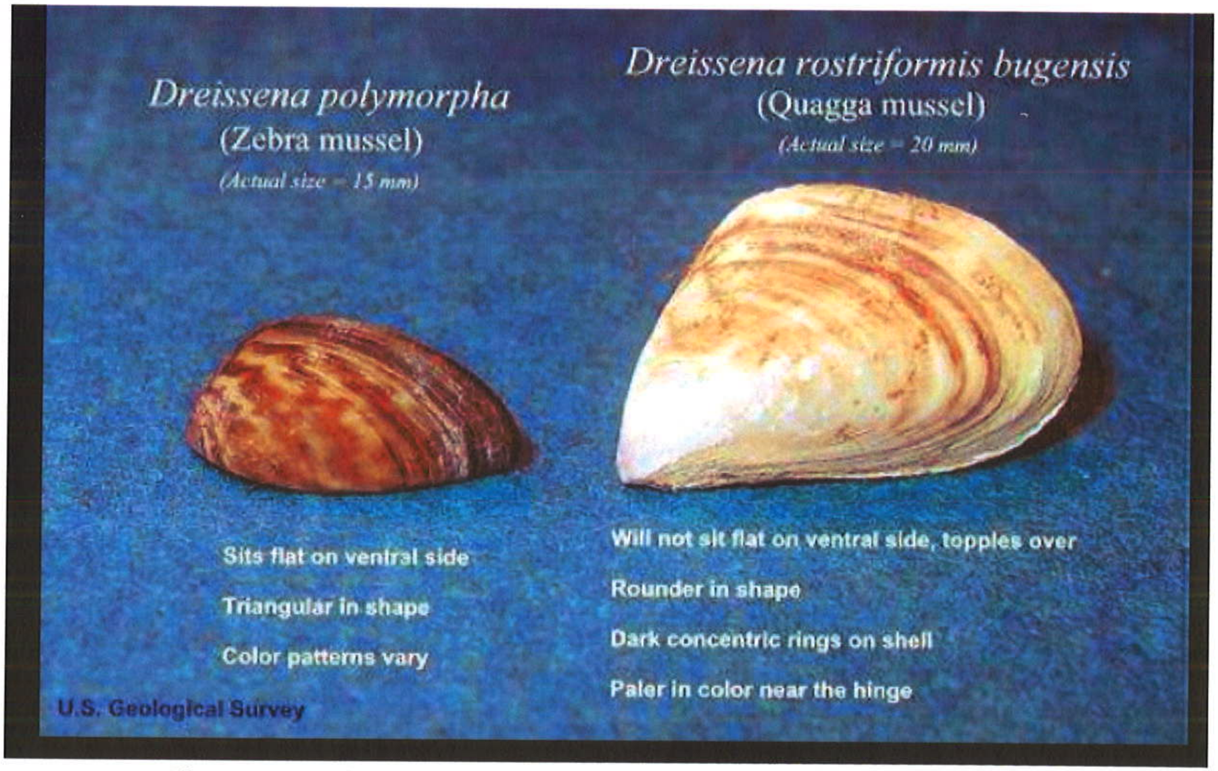

Figure 1. Zebra and Quagga Mussel Physical Characteristics

Mussels are mytiliform in shape and are striped or all black or white. The mussel life cycle has three main stages: larval, juvenile, and adult (Figure 2). As the planktonic larvae settle on a substrate during the end of the veliger stage, they develop into juveniles. The settling stages are the most sensitive, and mortality rates of 90 to 95 percent have been observed.

Quagga and zebra mussels are considered adults when they reach sexual maturity, which in North America is within the first year of life, and at a shell length of eight to ten millimeters. They have high fecundities, with females producing 30,000 to 1,610,000 eggs and males producing over one billion sperm. Eggs are fertilized within the water column. The growth rate of larvae and veligers is highly variable and depends mainly on temperature and chlorophyll-a concentration (e.g. phytoplankton). Within the Great Lakes, veliger growth and settlement rates were optimal between 15°C and 17°C. The life span of a zebra mussel is also highly variable, but typically between 1.5 and 2.0 years in North America.

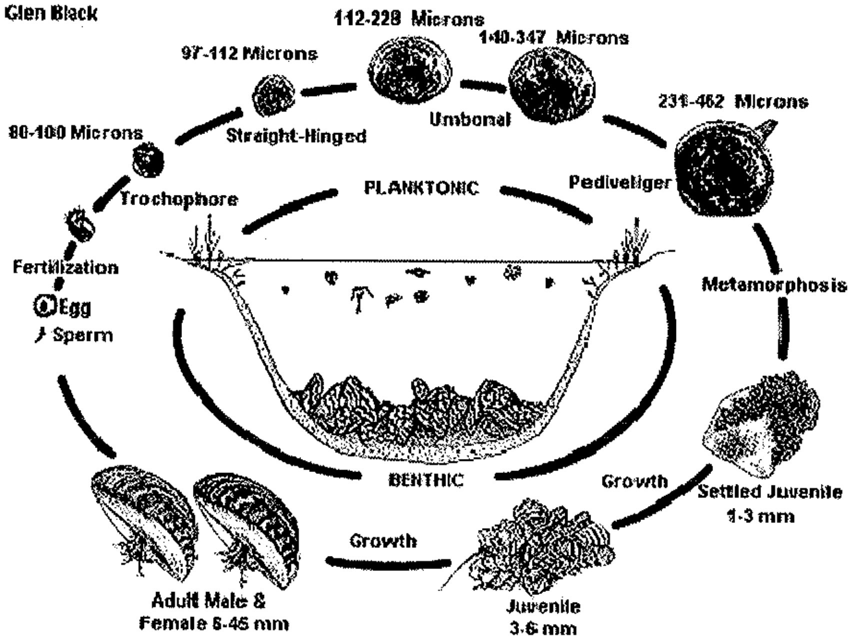

Figure 2. Zebra Mussel Life Cycle

Source: el.erdc.usace.army.mil/zebra/zmis/zmishelp4/life_cycle.htm

Mussels are filter feeders with multiple food sources, including micro-algae, micro-invertebrates, bacteria, detritus, and other organic materials. Food selection is performed by a variety of cilia, which generally select particles ranging from 15 to 40 µm for food, but can filter out particles as small as 0.7 to 1.0 µm in diameter. The filtration of mussels has been known to clarify the epilimnion and the littoral zones of lakes. As mussels ingest both organic and inorganic particles, the edible and non-edible portions are sorted. The rejected particles are bound in mucus globs, which are expelled as pseudofeces.

Zebra and quagga mussels are non-indigenous, invasive macrofoulers that can quickly colonize new areas and rapidly achieve high densities. The proliferation of the mussel in North America can be partially related to the species' external fertilization and planktonic larval stages. These life stages are not typically found in native North American freshwater mussel species, but are found in marine bivalves.

Unlike native mussels, which burrow in sand or gravel, zebra and quagga mussels spend their adult lives attached to hard substrates that can include rocks, logs, aquatic plants, and the shells of native mussels, as well as man-made structures of plastic, wood, concrete, fiberglass, and iron. The ability to attach to these various substrates, along with the species' high fecundity and passively dispersed planktonic veliger larval stage, have allowed zebra and quagga mussels to significantly change ecosystem trophic dynamics and spread rapidly throughout freshwater ecosystems. Invasive mussels have also demonstrated a high tolerance to many environmental and water quality factors (Table 1) that enhances the species survival in North American waters.

Table 1. Physio-Chemical Factors Effecting Invasive Mussel Colonization Potential

Key Parameters	***Colonization Potential***				***Standley Lake Characteristics***
Water Quality Variable	*High*	*Moderate*	*Low*	*Very Low*	*Range in Values*
Salinity (ppt)	*0.1*	*1-4*	*4-10*	*10-35*	
Calcium (mg/L)	*25->125*	*20-25*	*9-20*	*<9*	*56-80*
Total Hardness (mg $CaCO_3$/L)	*90-125*	*45-90*	*25-45*	*<25*	*96-120*
pH	*7.5-8.7*	*7.2-7.5* *8.7-9.0*	*6.5-7.2* *9.0*	*<6.5* *>9*	*7-9.1*
Water Temperature (°C)	*18-25*	*16-18* *25-28*	*9-15* *28-30*	*<8* *>30*	*5.5-20.1*
Turbidity (cm Secchi disk)	*40-200*	*20-40*	*10-20* *200-250*	*<10* *>250*	*175-650*
Dissolved Oxygen (ppm)	*8-10*	*6-8*	*4-6*	*<4*	*1.5-12*
Water Velocity (m/sec)	*0.1-1.0*	*0.09-0.1* *1.0-1.25*	*0.075-0.09* *1.25-1.5*	*<0.075* *>1.5*	
Conductivity (uS/cm)	*83->110*	*37-82*	*22-36*	*<22*	*167-633*

Reference: O' Neill, Zebra Mussel Impacts and Control, 1996.

Dispersal mechanisms of larval and adult zebra and quagga mussels have been divided into natural mechanisms (e.g. water currents, birds, insects, and other animals) and human-mediated or anthropogenic mechanisms (e.g. artificial waterways, ships and other vessels, fishing activities, amphibious planes, and recreational equipment). Generally, dispersal of mussels is believed to occur naturally primarily by river and lake currents that disperse plankton veligers. However, in the Western United States, transport has primarily been by attachment to boats that move between water bodies.

The "foot" is an extendible muscular organ located in the mid-ventral region of the mussel and is used primarily for locomotion. Located within the foot is the byssal gland, which produces secretions that are used to form byssal threads. These byssal threads are used by the mussel to attach to various surfaces. As environmental conditions change, the mussel has the ability to detach their byssal threads and move – either actively via the "foot" or passively via water currents.

Zebra and quagga mussel veligers have been consumed by crustacean zooplankton and larval fish, but the relative importance of this activity on overall mortality is unknown. In addition, the predation of juvenile and adult mussels has been observed by crayfish, fish, and waterfowl. In general, the predation of fish does not appear to limit the densities of invasive mussels, but diving waterfowl are important mussel predators in North America. Bay diving ducks have been known to consume as much as 57 percent of the autumnal biomass in Lake Erie and 90 percent of the winter zebra mussel mass in Lake Constance. However, these events had little impact on mussel biomass the following spring. The regulation of mussel biomass and abundance by waterfowl predation is limited to ice free periods.

2.3 Impacts of *Dreissena* Mussels on Drinking Water Facilities

The adverse financial and operational effects of zebra and quagga mussels on water supply facilities in the US have been well documented starting in the early 1990s. Mussels can infest many water supply system components including intake systems, transmission lines, treatment facilities, and any other components upstream of disinfectant chemical addition. Adverse effects of mussel attachment to water supply system components include:

- Loss of hydraulic capacity due to colonization inside pipes (up to 6" of macrofouling)
- Obstruction of valves and gates which limit operation
- Blockage of screens and trash racks which limits flow
- Increased corrosion of steel and cast iron pipes due to bacterial growth around byssal threads
- Accumulation of shells and detritus in water supply facilities
- Creation of taste and odor problems due to accumulation of decaying detritus

Many utilities have modified their plant intake systems and employed chemical addition to mitigate the adverse effects of mussel infestations. Costs associated with mitigating the effects of mussel infestations include:

- Retrofitting costs
- Physical removal / mechanical exclusion costs
- Chemical treatment costs

Costs are highly specific to the infrastructure that must be protected. When mussels were first detected in the Eastern United States, the State University of New York (SUNY) estimated that the average cost to drinking water facilities with an infested source was $214,000 (1995 dollars). Subsequent studies by Cornell University have estimated the cost of a mussel infestation for eastern drinking water utilities at $30,000 - $44,000 per year. A recent study, performed by HDR for the Minneapolis Water Works estimated the replacement of five trash racks with mussel resistant trash racks at $245,000.

The high costs of zebra and quagga mussel mitigation have motivated many utilities to implement rigorous monitoring programs to provide early detection of mussels. Employing a comprehensive mussel monitoring regimen, utilities can expect infestations to develop on infrastructure of concern approximately two years after the first veliger detection. At the first veliger detection, the population of adult mussels will be small and localized, but the rate of establishment of mussel infestations suggests that any mussel control plan should be implemented and operational within two years of detection.

2.4 Status of Mussel Infestation in Colorado

The first *Dreissena* veliger in Colorado was confirmed in Pueblo Reservoir in September of 2008. Since that time, six other reservoirs have confirmed the presence of veligers including Grand Lake, Lake Granby, Willow Creek, Shadow Mountain Reservoir, Jumbo Reservoir, and Tarryall Reservoir. Quagga mussel veligers have been found in all of the above Colorado reservoirs. In addition, Zebra mussels have been confirmed in Grand Lake and Pueblo Reservoir. Adult mussels, which indicate colonization of the water body, have not been found in Colorado. However, veliger density samples from Pueblo Reservoir indicate a spawning population is present in the Reservoir. Figure 3 is a graphical representation of zebra and quagga mussel sightings in the Western United States.

QUAGGA AND ZEBRA MUSSEL SIGHTINGS DISTRIBUTION IN THE WESTERN UNITED STATES
2007 - 2009

🟥 indicates presence of quagga mussels 🟩 indicates presence of zebra mussels

NEVADA
Lake Mead - January 2007
Lake Mohave - January 2007

CALIFORNIA
Parker Dam - January 2007
Colorado River Aqueduct - March 2007
Colorado RA at Hayfield - July 2007
Lake Matthews - August 2007
Lake Skinner - August 2007
Dixon Reservoir - August 2007
Lower Otay Reservoir - August 2007
San Vicente Reservoir - August 2007
Murray Reservoir - September 2007
Lake Miramar - December 2007
Sweetwater Reservoir - December 2007
San Justo Lake - January 2008
El Capitan Reservoir - January 2008
Lake Jennings - April 2008
Olivenhain Reservoir - March 2008
Irvine Lake - April 2008
Rattlesnake Reservoir - May 2008
Lake Ramona - March 2009
Walnut Canyon Reservoir - July 2009
Kraemer Basin - September 2009
Anaheim Lake - September 2009

ARIZONA
Lake Havasu - January 2007
Central Arizona Project Canal - August 2007
Lake Pleasant - December 2007
Imperial Dam - February 2008
Salt River - October 2008

COLORADO
Pueblo Reservoir - January 2008
Lake Granby - July 2008
Grand Lake - September 2008
Willow Creek Reservoir - September 2008
Shadow Mountain Reservoir - September 2008
Jumbo Lake - October 2008
Tarryall Reservoir - October 2008

UTAH
Electric Lake - November 2008
Red Fleet Reservoir - February 2009

TEXAS
Lake Texoma - April 2009

Data Sources: California Dept. of Fish and Game; Arizona Dept. of Game and Fish; Colorado Division of Wildlife; Utah Division of Wildlife Resources; City of San Diego; National Park Service; Imperial Irrigation District; Helix Water District; Irvine Ranch Water District, Texas Parks and Wildlife Dept., US Army Corps of Engineers, Kansas Dept. of Wildlife and Parks.

Map produced by the U.S. Geological Survey, October 6, 2009.

Figure 3. USGS 2009 Map of Mussel Distribution in the Western United States

2.5 Mussel Control Methods

There are various control methods that could potentially be used to limit the impact of invasive mussel species on the City of Westminster's water supply. This section gives an overview of a number of technological, biological, and physiological zebra mussel control methods that have been documented in scientific journals, government and state reports, and manufacturer literature. Many control methods are either lacking evidence of efficiency under full scale conditions or cannot be implemented in a full scale regime at this time due to technological constraints. Each of the identified control strategies has been categorized as follows:

- An emerging technology that will require further research, extensive testing, and regulatory approval before it can be implemented at public water system.
- A proven technology that is awaiting either regulatory or technological advances that will allow implementation on a full scale basis for drinking water facilities.
- An effective, implementable technology that has been successfully demonstrated at other water systems.

For the purpose of this report, technological methods have been divided into acoustic, chemical, electrical, or physical control methods. Biological methods have been separated into manipulation of water quality characteristics, exposure to bacteria, predation, or inhibition/reduction of spawning. Mussel control methods tend to focus on one or more of the following techniques:

- Prevention of settlement in critical locations
- Prevention of attachment to substrate
- Causation of mussel mortality

Note that some methods may not apply to all stages of zebra mussel life. For the purpose of this discussion, zebra mussel life stages will be divided into only three categories that are defined as follows:

1. Veliger – any zebra mussel in a planktonic stage that has no means of attachment
2. Juvenile – any zebra mussel that is seeking a location to attach or has recently attached
3. Adult – any zebra mussel that is attached to a substrate and above the age of one year

Table 2 summarizes each of the control methods discussed in this section. The criteria listed in the table apply only to a specific life stage of the zebra mussel. Although many of the technologies affect all life stages, they may be more effective at certain times. The relative capital costs are based on approximations of the probable costs associated with each alternative. Actual capital costs could vary after preliminary design or a more detailed implementation strategy is developed. Management options such as monitoring, research, education and outreach, and regulatory coordination have not been included in the relative capital costs of each technology. Detailed descriptions of each control technology can be found in Appendix A.

Table 2. Mussel Control Options for Drinking Water Facilities

Technology	Specific Method	Purpose	Target Age	Efficiency	Contact Time	Implementation Status	Comments/Disadvantages	Range of Capital Costs	Implementation Time
Biological	Bacterial Exposure	Mortality	All	> 95%	6 hrs	Proven – awaiting regulatory approval	Few treatments are required; Difficult to produce large quantities	Low	6 to 8 months
	Predation	Reduce biomass	All	Low	Not applicable	Implementable	Not effective in producing mortality	Low	4 to 6 months
	Spawning Inhibition	Limit Spread	Veligers	95-100%	2 to 4 hrs	Emerging – awaiting regulatory and technological advances	Only proven in laboratory setting	Low	8 to 12 months
Acoustic	Cavitation	Mortality	Veliger/Juvenile	NA	< 60 seconds	Emerging – awaiting technological advances	Effectiveness is reduced in high flows	High	12 to 18 months
	Sound Treatment	Limit Spread	Juveniles	90%	4 to 12 minutes	Emerging – awaiting technological advances	Does not produce mortality	High	12 to 18 months
	Vibration	Prevent Attachment Mortality	Veliger/Juvenile	100%	NA	Emerging – awaiting technological advances	Only applicable for locations with structures that can be subjected to vibration	Moderate	8 to 12 months
Chemical Oxidants	Chlorine	Mortality	Various	100%	2 hrs	Implementable for full scale	Not viable for open water system due to EPA regulations, can produce DBP's	Moderate	10 to 12 months
	Ozone	Mortality	All	100%	5 hrs	Implementable for full scale	Very difficult to maintain oxidant	Moderate	10 to 12 months
	Potassium Permanganate Sodium Permanganate	Prevent Attachment Mortality	All	90-100%	48 hrs	Implementable for full scale	Must have high continuous dosage for mussel mortality	Low	6 to 8 months
	Hydrogen Peroxide	Mortality	Veliger/Juvenile	100%	6 hrs	Implementable for full scale	High doses required	Low	6 to 8 months
Chemical Nonoxidants	Activated Starch	Mortality	Veligers	100%	0 to 72 hrs	Emerging – awaiting regulatory and technological advances	Not proven in open water system	Low	6 to 8 months
	Aluminum Sulfate	Prevent Attachment Mortality	All	50-100%	24 hrs	Implementable	High concentrations are needed; High solids loadings result	Low	6 to 8 months
	Chloride Salts	Mortality	Veliger/Juvenile	95-100%	6 hrs	Implementable	Very high doses required	Low	6 to 8 months
	Copper Ions	Prevent Attachment Mortality	Veligers	100%	24 hrs	Proven – requires regulatory approval	Causes skin irritation, regulatory restrictions	Low	6 to 8 months
	Potassium Salts	Mortality	Adults	95-100%	48 hrs	Implementable	Irritating to humans	Low	6 to 8 months
	Organic Molluscicides	Prevent Attachment Mortality	Various	95-100%	48 hrs	Few are implementable for water supply facilities	Difficult to handle (corrosive), regulatory restrictions for water supply facilities	Low	6 to 8 months
Electrical	Cathodic Protection System	Prevent Attachment	Adults	75%	Immediate	Implementable	Not effective in producing mortality	High	12 to 18 months
	Plasma Spark System	Prevent Attachment Mortality	Juvenile	90-100%	Several weeks	Proven – awaiting technological advances	Designed for pipes; Difficult to implement	Moderate	12 to 18 months
	Pulse Power Electric Field	Prevent Attachment Mortality	Juvenile	80-90%	seconds	Emerging – awaiting technological advances	High voltages required	High	12 to 18 months
Physical	Permeable Barrier	Limit Spread	All	Unproven	Immediate	Implementable for full scale	Navigational/migrational restrictions	Moderate	12 to 15 months
	Mechanical Cleaning	Prevent Attachment Mortality	Juvenile/Adult	95%	Immediate	Implementable	Must periodically repeat process	Low	Minimal
	Mechanical Filtration	Limit Spread Mortality	All	95%	Immediate	Proven – awaiting technological advances for full scale	Navigational/migrational restrictions; Designed for a confined area	High	12 to 18 months
	Light Sources	Limit Spread	Juvenile	0-50%	Several hours	Implementable	Effectiveness is very limited	High	12 to 18 months
	UV Radiation	Limit Spread Mortality	All	100%	4 min. to 4 hrs	Proven – awaiting technological advances for full scale	High intensities are required	High	12 to 18 months
	Infiltration Intake System	Limit Spread	All	100%	N/A	Implementable	Must replace current intake	High	36 months

3.0 Vulnerability Assessment of Westminster's Watersheds

Understanding the risk posed by mussels to the City's source water requires an evaluation of the vulnerability of Westminster's watersheds to a quagga or zebra mussel infestation, including an assessment of the potential impacts an upstream infestation might have on Standley Lake. Since Standley Lake is directly vulnerable to infestation from recreational activities in the lake, this infestation pathway must also be considered when assessing the overall watershed risk. This section of the report summarizes the findings of the watershed vulnerability assessment. Details of the vulnerability assessment are located in Appendix B.

3.1 Watershed Infestation Vulnerability

The primary source of the City's water in Standley Lake originates from snow melt and surface waters from the Clear Creek Basin in the mountains to the west. This raw water flows to Standley Lake through three main irrigation canals that divert water from the north bank of Clear Creek near Golden: the Farmers' High Line Canal (FHL), the Croke Canal and the Church Ditch. Over 85 percent of Westminster's water supply comes from Clear Creek through these irrigation canals. Standley Lake also receives water from the Moffat Tunnel area, the Coal Creek watershed, and other interbasin transfers. The Westminster water supply system is shown in Figure 4.

A total of 45 water bodies (lakes and reservoirs) were identified as being hydraulically connected to Standley Lake (see table 12 Appendix B). Each water body was evaluated for vulnerability using the following characteristics:

- Allow boating (particularly motorized boats)
- Easily accessible by vehicle
- Allow Fishing

Only one water body in the watershed, Gross Reservoir, has all three vulnerability characteristics and is considered at high risk for a mussel infestation. Fourteen other water bodies are accessible by vehicle and allow fishing, which has a lower likelihood of introducing mussels. Recreational boating with hand-powered craft, such as rafting and kayaking, occurs on some of the streams and rivers in the Standley Lake watershed. While these hand-powered craft have the possibility of introducing invasive mussels, the likelihood is considered to be low.

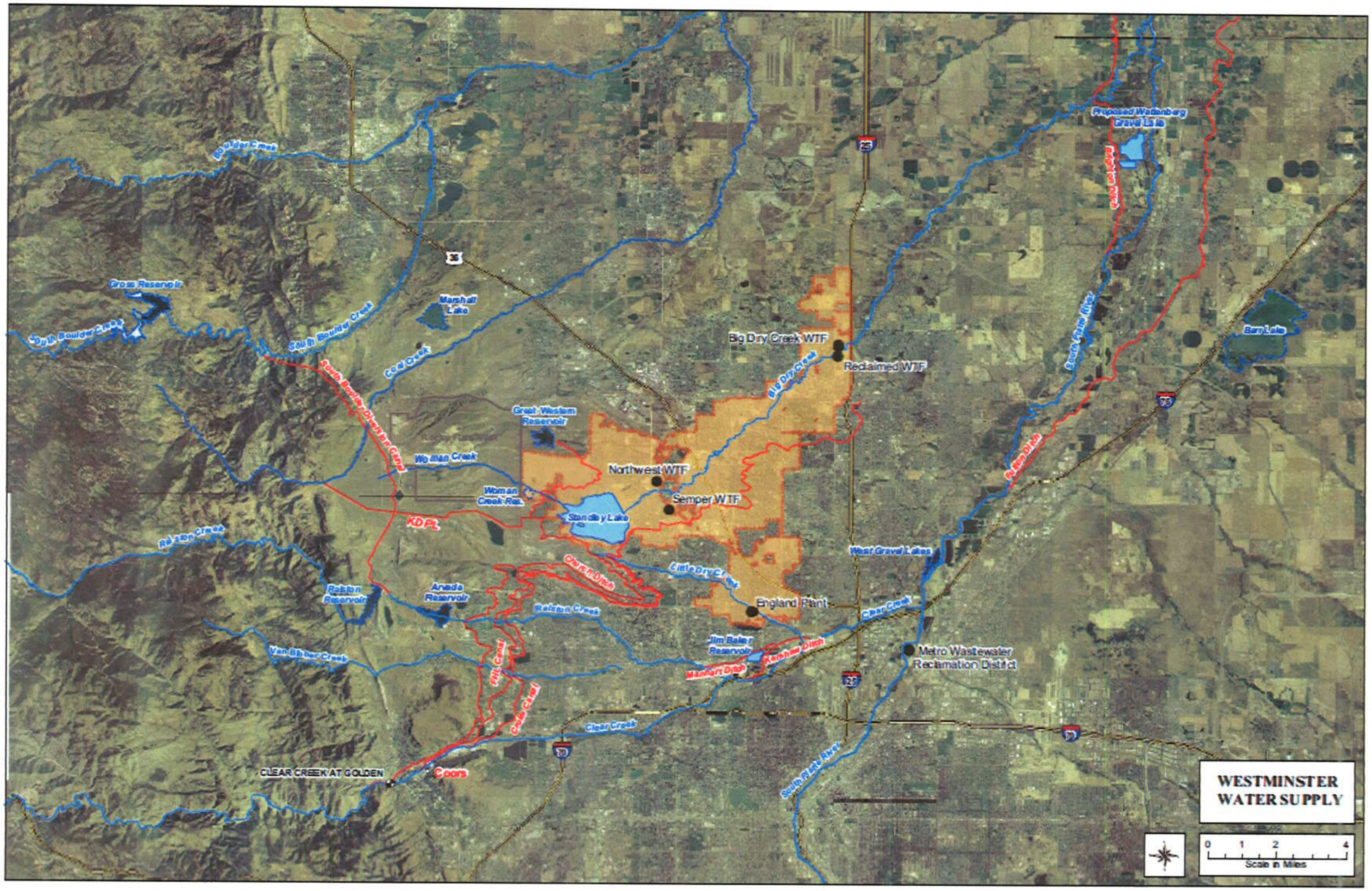

Figure 4. Westminster Water Supply System

3.2 Risk of an Infested Watershed to Standley Lake

The risk posed to Standley Lake of downstream transport of a mussel colony was investigated with regard to water quality and mussel transport mortality. Water quality parameters given the most importance were calcium concentration, temperature, and dissolved oxygen. The likelihood for mussel survival due to water quality in the Standley Lake watershed was characterized as marginal to poor, based on these water quality parameters. Additionally, the chances of mussel survival in the fast-flowing mountain streams which provide the travel pathway from the upper watershed to the canals was characterized as fair to poor. Possible transport was identified for the Church Ditch, Croke Canal, the KDPL, and on Clear Creek starting in Golden, if mussels existed upstream. An established kayak park is located on Clear Creek in Golden, so any mussel introduced at this location could be transported to Standley Lake.

3.3 Risk Assessment Conclusions

When assessing the risk of a mussel infestation in the City's watershed and the possible risk infestation poses to Standley Lake, some perspective must be kept in mind. The major pathway potential for overland dispersal and colonization of quagga or zebra mussels is by trailered motorized watercraft. Unlike simpler hand powered boats, these watercraft have features well suited for the translocation of mussels such as engines, cooling systems, bilges, live wells, bait buckets, trailers, and anchors, all of which increase the risk of carrying mussels to new locations. In addition, motorized craft are more difficult to desiccate and are more likely to be berthed in water than hand powered craft. The trailers needed to move motorized watercraft also provide an excellent pathway for translocation of mussels via aquatic plants.

The unique characteristics of the City's watershed amplify the risk posed by motorized watercraft. Standley Lake is the only water body in the City's watershed open to regular use of motorized watercraft. Standley Lake is also the only water body in Westminster's watershed whose water quality and habitat is favorable for developing a thriving zebra or quagga mussel population. Hence the highest risk pathway, trailered motorized boats, is coupled with the most vulnerable water body, Standley Lake.

Westminster has implemented a timely, aggressive and comprehensive inspection system for boats entering Standley Lake. However, no inspection system is perfect and other lakes with aggressive inspection programs have become infested. Although an assessment of the effectiveness of the inspection program is beyond the scope of this report, it is probable that continued motorized boating posses a greater risk of infestation to Standley Lake than any other potential risks in the City's watershed.

The risk of a quagga or zebra colonization the City's watershed and subsequent infestation of Standley Lake as a result of the upstream colonization is small. Of all the reservoirs hydraulically connected to Standley Lake, Gross Reservoir creates the greatest risk of infestation. However, there are two barriers to the transport of mussels from Gross Reservoir which are likely to protect Standley Lake. The two barriers are the turbulent nature of S. Boulder Creek, between Gross Reservoir and the S. Boulder Feeder Canal take-out and the wetlands the KDPL water passes through prior to entering Standley Lake (see Appendix B for details). The Golden Whitewater Park presents a small risk of translocation of mussels. When considering the entire water supply system, powered boating on Standley Lake remains the most likely infestation pathway.

3.4 Recommendations

While the conclusion of this assessment is that the City's watersheds are at a relatively low risk of infestation, there are specific actions that the City can take to reduce the risk of mussel infestations.

Promote protection of Clear Creek basin from the importation of mussels

When considering all the basins in Westminster's watershed, recreational activities in the Clear Creek Basin provides the most pathways for the importation of mussels. The City should support informational and outreach activities to better inform Clear Creek users of the risks mussels' pose and methods for preventing their spread. These efforts should be performed in concert with other interested parties in the basin. While Clear Creek Basin should be the priority, outreach to the other basins would be beneficial as well.

Perform in-depth assessment of risks posed by Golden Whitewater Park

Intense recreational activities at the Golden Whitewater Park provide a creditable pathway for the importation of mussels. The City should more closely evaluate the actual risk of importation of mussels at the Whitewater Park and their possible colonization in the FHL or Croke Canals.

Continue to assist in monitoring of Gross Reservoir

As Gross Reservoir was identified as the reservoir most at risk upstream of Standley Lake, the City should continue to assist in monitoring Gross Reservoir for the presence of quagga or zebra mussels.

Monitor and support research into understanding the adaptability of quagga mussels to mountain environments

Overall, water quality and environmental conditions that exist in the City's watersheds above Standley Lake are marginal for the successful colonization of zebra or quagga mussels. The City should monitor and possibly support research clarifying the minimal conditions necessary for the survival of quagga mussels in low calcium, low temperature, or high flow rate environments. The City should also monitor and possibly support research into Source – Sink relationships for mussel propagation in mountain streams and irrigation canals.

These recommendations should be considered in the appropriate context. The broader context is that recreational activities on Standley Lake, particularly motorized boating, by far represents the largest and most creditable pathway for the introduction and growth of a viable population of quagga or zebra mussels in to the City of Westminster's water system. The City should consider implementing the above recommendations for reducing infestation risk in its watersheds, but its primary focus should remain on the protection of Standley Lake from infestation risks posed by recreational activities.

4.0 Vulnerability Assessment and Mussel Control Strategies for Standley Lake

This section of the report will review the vulnerability of Standley Lake and the raw water infrastructure at Standley Lake to an infestation by mussels. It will also consider the degree of protection that periodic anoxia (low dissolved oxygen levels) in the lake provides to the raw water infrastructure. Lastly this section of the report will discuss strategies for controlling mussels at Standley Lake.

4.1 Vulnerability Assessment for Standley Lake and Raw Water Infrastructure

As presented in Table 1, water quality conditions in Standley Lake are suitable for the reproduction and growth of mussels. If mussels are introduced into Standley Lake, there is a high risk of a sustained and serious infestation in the lake. The lake is vulnerable to infestation by both quagga and zebra mussels, and will require mitigation measures be in place within two years of the first confirmed veliger detection.

Description of Raw Water Infrastructure

A new intake structure for the combined use of Westminster, Thornton, Northglenn, and FRICO was constructed in 2004. Two 72" intake laterals penetrate into the lake from a vertical shaft along the lake shore (Figure 5). Each intake inlet is covered with a removable trash rack with the 72" lateral pipe connected to a butterfly valve located in the valve shaft. Historically, only the lower intake (Lip El 5440) is used and the upper intake (Lip El 5449) is not used due to water quality concerns. However, to meet full design flow, both intakes must be used. The valves controlling the intakes have not been operated since the intake was installed. Currently the valve for the upper intake is closed and the lower intake valve is open. Included in the trash racks are covers for the intakes that can be lowered into place by divers. Both covers are currently open.

Downstream of the 72" butterfly valves, water from both intakes combines into a single 102" diameter conduit which feeds the stream release facility and the valve house. Two 60" diameter conduits split off from the 102" conduit and direct water to the stream release facility. Flow in the 60" diameter conduits is controlled by a combination of valves at the release point into Big Dry Creek.

The remaining flow continues to the valve house via a single 84" diameter pipe. At the valve house, flow is split between pipes supplying the City of Westminster and one 48" diameter conduit supplying the Cities of Northglenn and Thornton. Butterfly valves and meters are located in the valve house to control flow into the respective conduits. The City of Westminster is supplied by 42" and 36" diameter conduits running from the valve house to the Semper WTF and by a 36" diameter conduit running from just after the valve house to the Northwest WTF. All of these conduits are over 10,000 ft long. All the conduits also include an assortment of blow off valves, air and vacuum valves and butterfly valves typical of water conduits.

There is no redundancy for the either of the 102" and 84" diameter conduits running from the valve shaft to the valve house. These conduits cannot be taken out of service without interrupting flow to the stream release facility and the valve house.

The raw water infrastructure is sized for a peak flow of 321 cfs or 207 MGD. The demand allocation is contained in Table 3.

Table 3. Raw Water Demand

Organization	Peak Design Flow(CFS/MGD)	Average/Winter Design Flow(CFS/MGD)
FRICO	100/65	50/32
Northglenn	34/22	11/7
Thornton	62/40	53/34
Westminster	125/81	41/26
Total	321/207	155/100

Points of Vulnerability

Mussels will settle and attach directly on to interior pipe walls if water quality and hydraulic conditions are suitable. Additional mussels can settle and attach to the mussels already attached to the pipe wall, building up a layer of mussels which reduces the cross section of the pipe. This process is self limiting since eventually mussels that are directly attached to the pipe no longer receive enough nutrients for survival. These mussels die or detach from the pipe wall, destabilizing the layer of mussels. Experience has shown the maximum depth of mussel buildup in a pipe is about 6" thick on the pipe wall interior surface. This is independent of pipe diameter. In addition to reduced pipe diameter, mussel attachment on the pipe interiors increases friction loss through the pipe. Hazen-Williams C factors have been measured as low as 70 in conduits with mussel infestations.

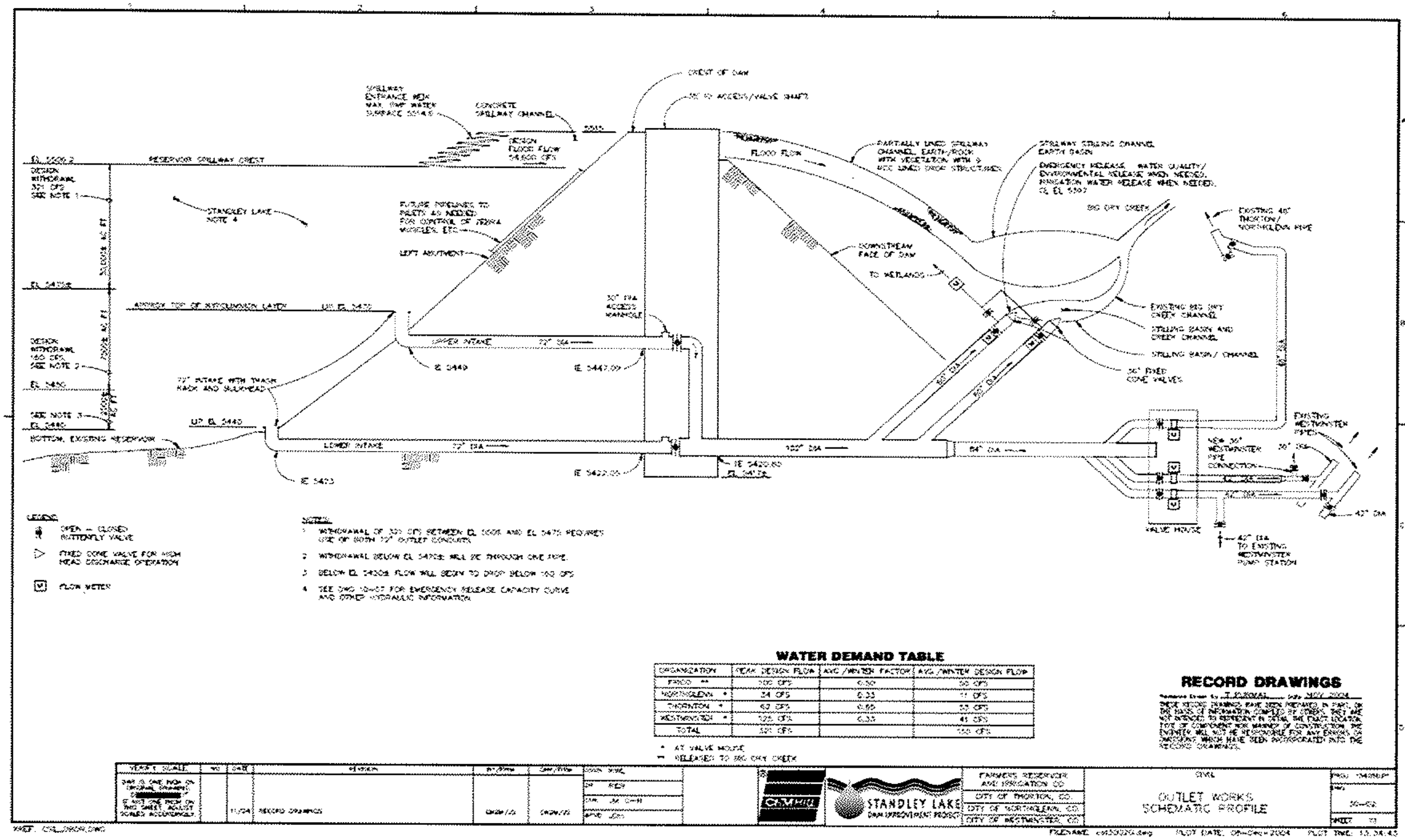

Figure 5. Schematic Profile of Raw Water Infrastructure at Standley Lake

Large diameter pipes can generally tolerate more mussel growth since the reduction in cross sectional area of the pipe caused by mussels attaching to the pipe wall is proportionally less in large pipes compared to small pipes. Table 4 presents the percentage reduction in cross sectional area assuming a 6" deep infestation attached to the interior pipe wall for various diameter pipes in the raw water system.

A consequence of a reduction in cross sectional area of the pipe and increased friction caused by mussel growth is that water in the pipe must move at a higher velocity to maintain the desired discharge. Higher water velocity in turn increases headloss, potentially to the point where there is insufficient head to maintain the desired discharge. Table 9 presents the theoretical decrease in discharge caused by the increase in friction and decrease in diameter caused by a mussel infestation.

Table 4. Potential reduction in raw water pipeline discharge due to mussels

Pipe Diameter (in)	Design Capacity (CFS) C=130	Loss in Capacity due to		Total loss due to infestation	Capacity after infestation (CFS) [2]
		Increase in Friction (C=70)	Decrease in Area [1]		
108	322	46%	27%	60%	127
84	221	46%	33%	64%	79
72	158	46%	38%	67%	53
60	50	46%	44%	70%	15
48	97	46%	53%	75%	24
42	63	46%	59%	78%	14
36	61	46%	66%	81%	11

1. Assuming mussel growth is 6" thick
2. Using Hazen-Williams Equation $Q= A*1.318*C*R^{0.63}*S^{0.54}$

C: Hazen - Williams Roughness Coefficient
A: Area (ft^2)
R: Hydraulic Radius (ft)
S: Slope (ft/ft)

S was fit to the Peak Design Flow specified in DWG 30-02 of the Standley Lake Dam Improvement Project, 2004

If a mussel population is allowed to grow in a pipe, provisions must be provided for collecting and removing from the pipe mussel shells and debris which slough off the pipe wall due to the natural mortality.

The operation of all valves and metering devices in the raw water system would be impacted by a mussel infestation. So would the trash racks and covers for the intakes. Valves and covers used for isolation purposes are of particular concern, as the mussel growth may prevent valve closure needed to isolate segments of the system. All of these features should be considered vulnerable to infestation and will require protection if an infestation occurs at Standley Lake.

Water Quality Impacts on Vulnerability of Intakes

Quagga mussels are much more tolerant of low temperatures than zebra mussels, and have been found at depths exceeding 200 ft in the Great Lakes. It is conceivable that a quagga mussel infestation could colonize any surface in the entire water column in Standley Lake, including both intakes. However, both quagga and zebra mussels are intolerant of anoxic conditions. Anoxic conditions (DO < 2 mg/L) have been found to be fatal to the veliger, juvenile and adult stages of the mussel life cycle. There is wide variability in the duration of anoxic conditions needed to cause 100% fatality of mussels. Variables such as the mussel's life stage, size, ambient temperature, period of acclimation to lower temperatures, available nutrients and many other factors impact the duration that mussels can tolerate anoxic conditions. Temperature seems to be the key variable, with less tolerance to anoxic conditions at higher temperatures than lower temperatures. None the less, the overall time period that can be tolerated ranges from hours to days. Hence, an extended period of anoxia will disrupt reproduction, inhibit settlement and greatly reduce the viability of established mussel populations.

Standley Lake stratifies every summer, creating anoxic conditions at the lower intake for an extended period of time. The stratification process may provide some degree of protection for the lower intake and downstream infrastructure from settlement and growth of mussels. By design, the upper intake is located near the top of the hypolimnion and will receive little protection from mussel settlement or growth due to anoxia.

In order to better understand the degree of protection that anoxia may provide for the lower intake and downstream infrastructure, historic water quality data collected by Westminster near the lower intake was analyzed. The data were analyzed to:

- Determine the temperature and dissolved oxygen concentration at the lower intake on a monthly basis
- Establish when and for how long the lake stratifies
- Determine the duration of anoxia at the lower intake
- Identify periods when the lower intake is at greatest risk of settlement and growth

Temperature and Dissolved Oxygen Levels at Lower Intake

Bimonthly temperature readings for the years 2006 – 2008 taken near the lower intake are plotted in Figure 6. Temperatures ranged from a low of approximately 3^0C in January to a maximum of approximately 16^0C in September. The temperature profile in Standley Lake was consistent for the three years considered. The water temperature at the lower intake never reaches levels favorable for supporting a mussel infestation, but is within the range of observed infestations for approximately six months of the year, May – October.

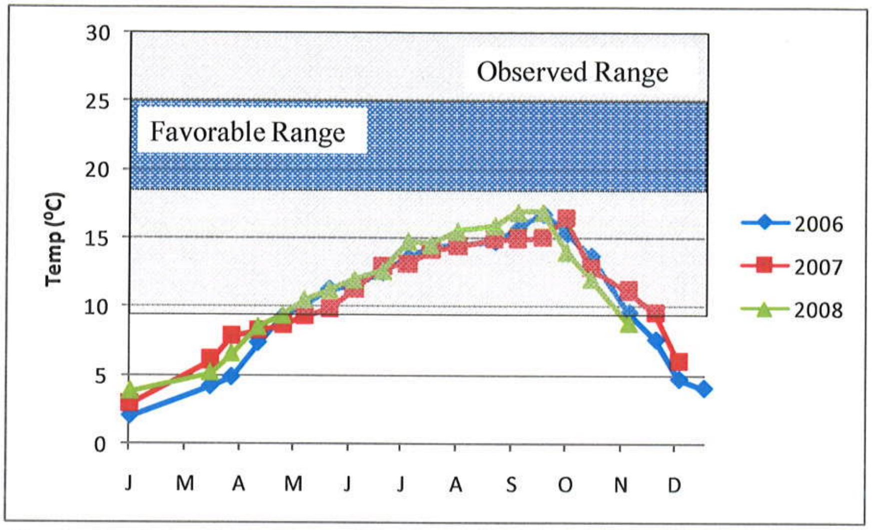

Figure 6. Annual Temperature Profile at Lower Intake 2006 - 2008.
Superimposed on the figure are the temperature range that mussels have been observed to survive and the narrower temperature range most favorable for growth.

Bimonthly DO values for the years 2006 – 2007 taken near the lower intake are plotted in Figure 7. Dissolved oxygen ranged from complete anoxia in August (DO ≈ 0 mg/L) to near saturation in December – March (DO ≈ 10 mg/L, degree of saturation controlled by temperature). Between June and mid-September, DO concentrations are below levels which have been observed to support infestations. For the two month period of July and August, anoxic conditions (DO < 2 mg/L) that can be fatal to mussels exist at the intake.

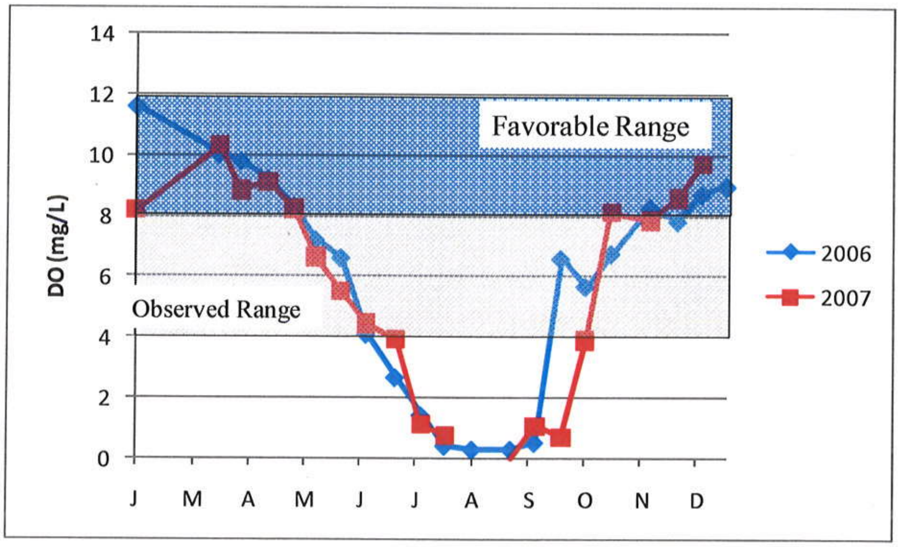

Figure 7. Annual DO Profile at Lower Intake 2006 - 2007.

Temperature in the Upper Layer of Standley Lake

Bimonthly temperature readings taken 9 feet below the surface for the year 2007 are plotted in Figure 8. The water temperature ranged from a low of approximately 3°C in February to a maximum of approximately 24°C in August. For almost four months, June – September, water temperature was favorable for mussel growth. For approximately 7 months, the water temperature is in the range observed to support infestations. Importantly, throughout this 7 month period, mussels are capable of spawning and providing a source of veligers for settlement.

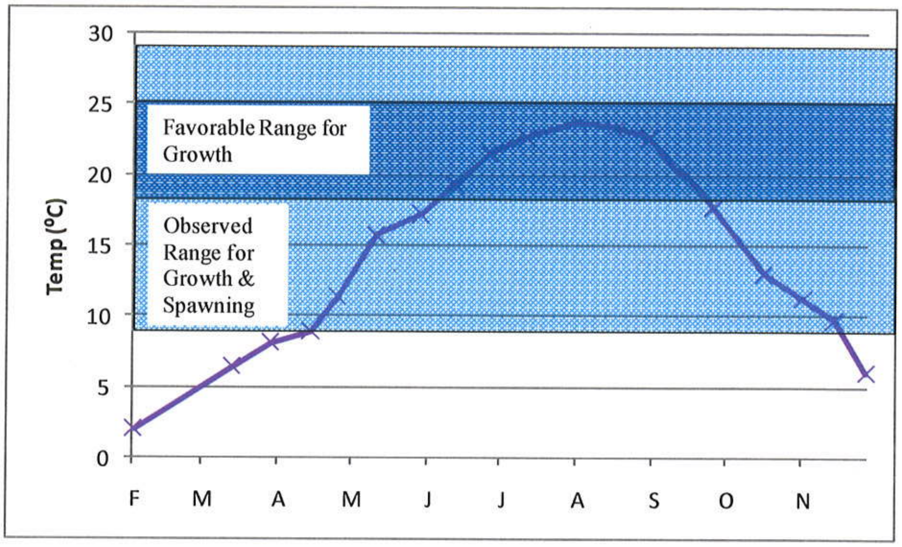

Figure 8. Annual Temperature Profile at Nine Feet below the Surface 2007.

Onset of Lake Stratification and Destratification

Temperature/depth profiles taken near the lower intake for 2007 were reviewed to determine when Standley Lake stratifies and destratifies. Figure 9 presents these profiles. The nearly uniform temperature profiles in April indicated that at this point in time Standley Lake was well mixed and not stratified. However, by early May the step like shape of the temperature profile indicates that stratification was beginning. Stratification remained in place through September, but by early October the uniform temperature profile indicated that the lake was again well mixed and that turn-over had occurred. Overall the data presented in Figure 9 indicates that Standley Lake stratifies for approximately 6 months of the year, between May and September.

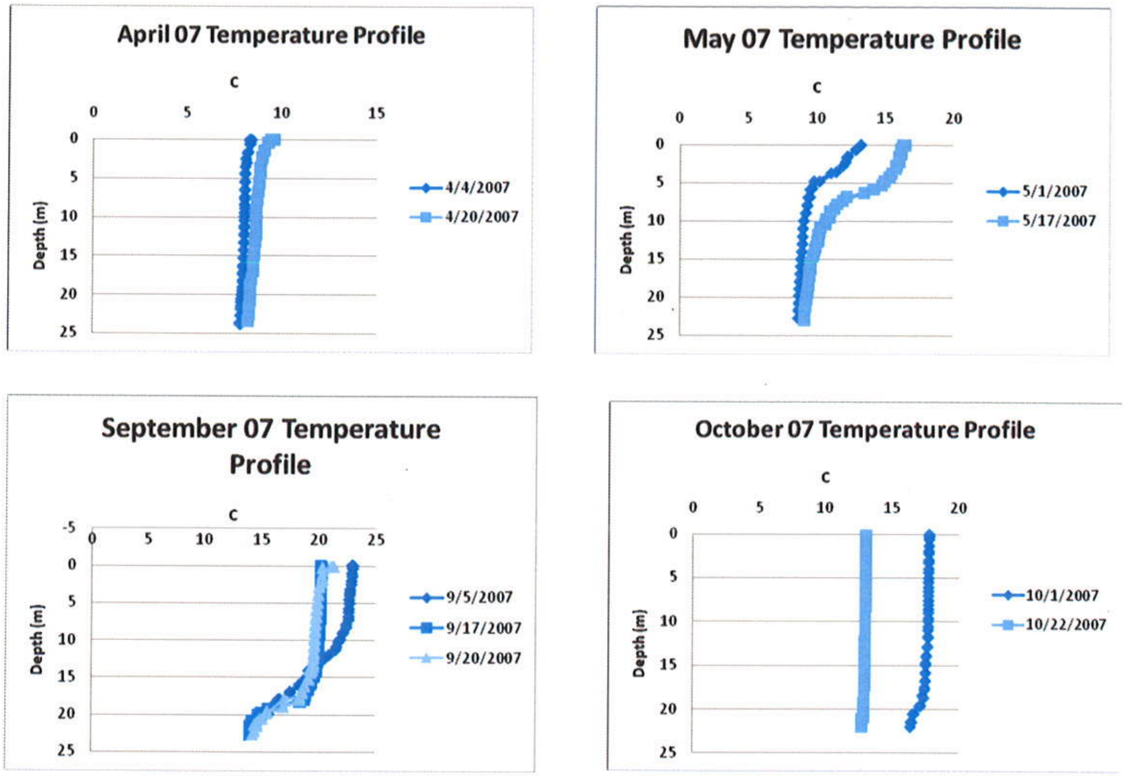

Figure 9. Temperature/Depth Profile near Lower Intake 2007.

Vulnerability of Lower Intake to Infestation

All of the above water quality data can be combined to develop an overall assessment of the vulnerability of the lower intake to mussel infestation. Summarizing the points from above:

- Conditions that are conducive to spawning, settlement and growth exist in the upper portions of the Standley Lake for approximately seven months of the year: mid-April through mid-November.
- Conditions that are conducive to spawning, settlement and growth exist for a much shorter period at the lower intake because of stratification.
- Standley Lake stratifies for approximately six months of the year, between May and September.
- The lower intake experiences anoxic conditions for approximately two months - July and August.

Because of annual variations in water temperature and anoxia caused by stratification, the risk of infestation at the lower intake is not the same throughout the year. In general the risk is greatest in spring and fall, when temperatures are warm enough to support spawning and settlement, and the lake is destratified and well mixed, creating vulnerable conditions at the lower intake. The risk at the lower intake is reduced during mid-summer, when anoxia at the intake inhibits settlement and growth. The lowest risk is during the winter and early spring, when temperatures throughout the lake are too cold to support spawning. Table 5 summarizes the relative vulnerability of the lower intake throughout the year.

Table 5. Infestation Risk at Lower Intake

Time Period	Stratification Status	Condition in Lake	Intake Risk Level
January – Mid April	Not Stratified	Water temperature too cold to support spawning or settlement throughout lake	Lowest
Mid April - May	Not Stratified	Warm enough for spawning to begin, lake is well mixed and DO at intake is high enough to support settlement	Highest
May –June	Stratified	Warm enough for spawning and successful settlement in upper lake, but conditions are becoming unsuitable for mussels at lower intake do to decreasing DO	Higher
July – Mid September	Stratified	Conditions in upper lake are very favorable for spawning, settlement and growth, but anoxic conditions exist at lower intake that are unsuitable for settlement or growth	Lower
Mid September - October	Not Stratified	Spawning continues, lake destratifies and DO rises at lower intake, lower intake at increased risk	Higher
November - December	Not Stratified	Spawning stops, water temperature too cold to support spawning or settlement throughout lake	Lowest

Hence stratification and anoxia will provide partial protection from the establishment of a mussel infestation in the infrastructure connecting the lower intake and the treatment plants. But anoxia does not protect this infrastructure during the entire period that mussels are capable of spawning and settling. It is unlikely that a self sustaining population will infest the infrastructure down stream of Standley Lake as long as the lower intake is exclusively used, However, periodic infestations caused by settlement or translocation of mature mussels during periods when dissolved oxygen and temperature are suitable (mid-April – June, mid September – October) may occur. The impact of these periodic infestations will include a loss of hydraulic capacity, and possible interference in the operations of valves or control structures. The die-off of mussels triggered by the anoxia occurring in mid to late summer will cause mussels to slough-off and be carried further down stream in the pipelines. The detritus will settle in low velocity locations and potentially clog valves or other equipment where it will require removal. If not removed, the detritus will decay over time, impairing water quality and imparting disagreeable taste to the water.

In summary, two points should be kept in mind when considering the assessment presented in Table 5. First, the assessment only applies to the lower intake. The upper intake is positioned too high in the water column to obtain protection from an infestation due to stratification and anoxia. Second, stratification and anoxia do not provide an absolute barrier to infestation for the lower intake and downstream infrastructure. Stratification and anoxia only provide a partial barrier to an infestation. As will be discussed later in the report, this partial barrier should be taken into consideration in the design of any system for the protection of the lower intake.

4.2 Mussel Control Strategies

The first and most basic mussel control strategy is to prevent the introduction of mussels into Standley Lake. The City of Westminster has already partially implemented this strategy through its boat inspection program. Despite this effort, mussels may be found in Standley Lake, at which point control will be essential. Four potential strategies for control of mussels and protecting the raw water infrastructure are discussed in this section.

Several considerations must be kept in mind when considering treatment strategies.

- Standley Lake and the intake are jointly owned and operated by Westminster, FRICO, Northglenn, and Thornton. Any changes to the operation or improvements to the joint facilities must be approved by all parties.
- The combined peak design flow for all uses of the raw water system, FRICO, Northglenn, Thornton and Westminster is 207 MGD. The City of Westminster's peak design flow is 81 MGD or 39% of the total peak design flow. Hence any system designed to prevent the entry of mussels at the intake will need to treat the combined total peak design flow for the users at Standley Lake. This is substantially more volume than Westminster's demand alone.
- Standley Lake is currently the City of Westminster's only raw water source. Until the Standley Lake by-pass is constructed, Westminster cannot take the

Standley Lake supply off-line for extended periods of time. Additionally, the by-pass will not provide water to the other users, and will not provide the other users with an alternate source of water if the intake is taken off line.

- The Standley Lake intake system has limited redundancy. While the two 72" diameter intake lines are redundant, there is no redundancy for the 102"/84" conduits supplying the stream release facility and the valve house. As the raw water supply system is currently designed, draining the 102"/84" conduits for cleaning requires taking Standley Lake off-line as a drinking water source.
- Any methods used for controlling mussels must not impair recreational opportunities in Standley Lake, must meet in-stream standards for water released to Big Dry Creek, must not render the Standley Lake water unsuitable as a drinking water source, and must not compromise the safety of the intake or dam.
- The joint partnership's long standing operational practice is to only treat water withdrawn from the lower intake. If mussels were found in Standley Lake, Westminster would prefer to continue exclusively treating water withdrawn by the lower intake. However, as the need for additional water supply increases, the upper intake will need to be used during the peak demand months.

4.2.1 Control in Standley Lake

The **Control at Standley Lake** strategy consists of eliminating the infestation of mussels in Standley Lake (Figure 10). The intakes and downstream infrastructure would be protected by creating conditions in Standley which do not support mussel reproduction or growth. The elimination of mussels in Standley Lake could be attempted through chemical additional, biological treatment, or changes in the management of the lake. Management changes for the lake could involve actions such as periodically draining the lake and desiccating or freezing the exposed population of mussels. Table 6 summarizes the other in-lake treatment approaches. None of these approaches are well suited for a lake of Standley's size. They are also inconsistent with the current usage of the lake for recreational activities and drinking water supply. None of these approaches are considered feasible for mussel control.

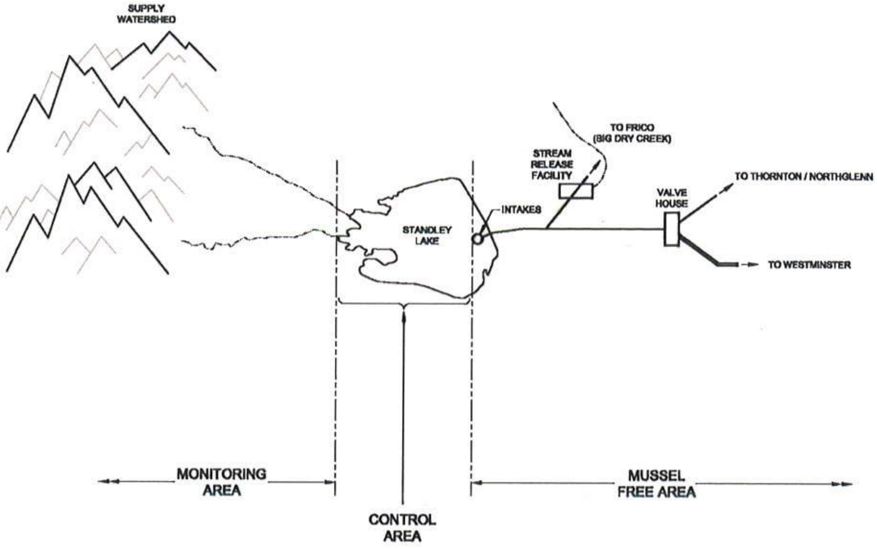

Figure 10. Strategy 1 - Control Mussels in Standley Lake.

Table 6. Strategy 1 - Approaches for Treating Mussels in Standley Lake.

Approach	Key Feature	Key Considerations
Manage reservoir to prevent infestation	Elimination of boating and other recreational activities at Standley	• Public acceptance improbable from boating and recreational community • Unable to interdict all possible pathways of infestation, including malicious actions (i.e. intentional introduction of mussels)
Biological treatment	Use of *Pseudomonas fluorescens* to control mussel population	• Unproven • Human health impacts in drinking water unknown • Dependence on a single supplier
Chemical treatment	Use of moluscicides to control mussel population	• Possible ecological and human health impacts • Unsuitable for drinking water • Difficult to obtain permits
Physical isolation of intakes	Seasonally install barrier curtain to protect intakes	• Unproven technology • Dependence on a single supplier

Manipulation of dissolved oxygen levels, desiccation or freezing	Manage Standley Lake water levels to control dissolved oxygen, periodically desiccate or freeze upper elevations of reservoir	• Adjusting level compromises water supply capacity • Unlikely to get 100% mussel kill, leaving downstream infrastructure vulnerable

4.2.2 Control at Intakes

The **Control at Intakes** strategy makes no additional attempt to control the mussel population in the lake. Instead it focuses on protecting the intakes and the down stream infrastructure by active treatment which creates conditions at the intake and in the conduits that prevent mussel settlement and growth (Figure 11). Table 7 summarizes treatment approaches for control at the intakes. Unlike the prior strategy, chemical treatment at the intake is technically feasible and likely to be effective. However, this strategy requires treating the combined flow for all users of the lake intakes. It also requires that discharges to Big Dry Creek meet in-stream standards, and that water quality is not degraded by the use of chemicals to control mussels (must meet NPDES discharge limits for the stream). This means dechlorinating the discharge to Big Dry Creek if chlorine or chloramines are used to oxidize at the intakes.

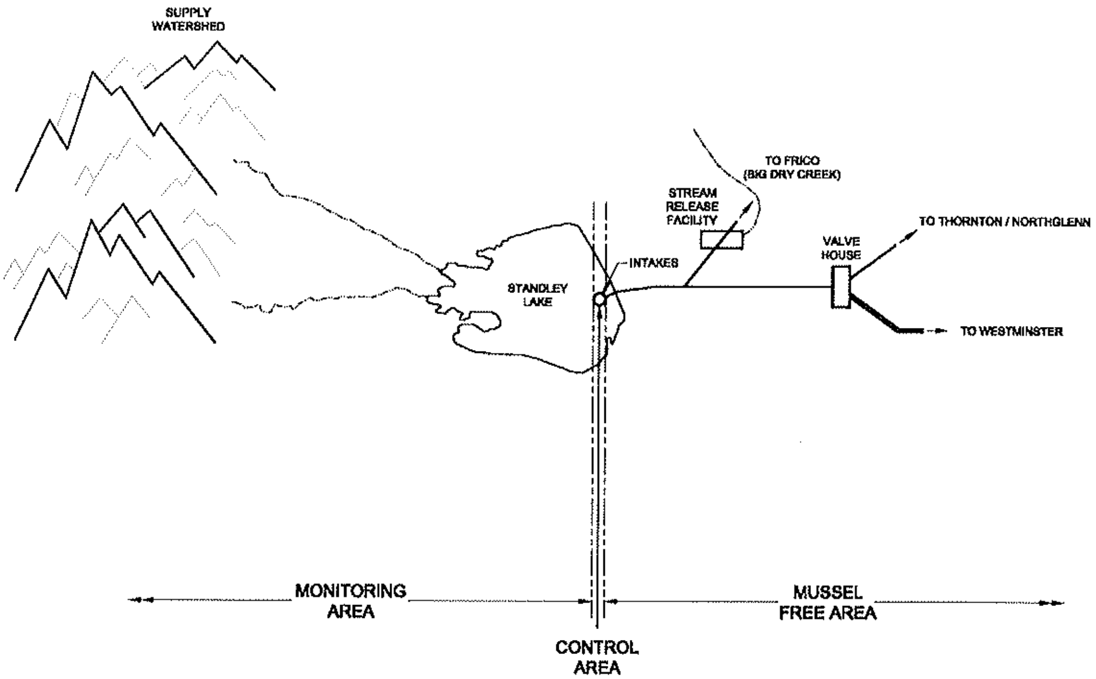

Figure 11. Strategy 2 - Control Mussels at the Intake.

Table 7. Strategy 2 - Approaches for treating mussels at the intake.

Approach	Key Feature	Key Considerations
Modify intake – use bank filtration	Modify reservoir for bank filtration of water from lower reservoir (hypolimnion)	• May not provide 100% barrier to veligers • Hydrogeology probably not suitable
Apply chemical oxidants at intake	Inject oxidant at intakes	• Several oxidants are effective • Creation of byproducts must be controlled • Possible premature oxidation of iron or manganese • Post treatment may be required to meet stream discharge standards
Ultraviolet irradiation at intake	Apply UV at intakes	• Questionable feasibility • High power consumption • Major UV suppliers not player in market
Biological treatment at intake	Inject *Pseudomonas fluorescens* at intakes	• Unproven • Human health impacts in drinking water unknown • Dependence on a single supplier
Plasma spark technology at intake	Create plasma pulse at intakes	• Unproven – pilot test in 30" pipe was effective • Impact on infrastructure integrity uncertain
Copper ion generation	Inject copper ion at intakes	• Unproven • Impact on water quality uncertain

4.2.3 Control at Valve House

The **Control at Valve House** strategy does not protect the raw water system between the intakes and stream release facility or valve house (Figure 12). Table 8 summarizes the treatment requirements for controlling mussels at the valve house. Any mussels that accumulate in the unprotected portion of the raw water system would be managed by mechanical cleaning on a periodic basis. The cleaning would most likely need to occur once a year, during the winter when the temperature of Standley Lake water is too cold to support spawning or settlement and raw water demand is low. Cleaning could take several weeks to complete. Active treatment, designed to protect the conduits supplying Westminster's treatment plants would be performed at the valve house.

The primary advantage of this strategy is that only the City of Westminster's water supply is treated. However, because of the lack of redundancy for the existing intake 102"and 84" diameter conduits, this strategy means that Standley Lake would not be available as a source during the time the unprotected portions of the raw water system are drained and mechanically cleaned. In addition, if a significant infestation were to occur, unacceptable headloss created by mussels accumulated in the exposed portion of the system may occur prior to an annual cleaning. Measures to minimize mussel attachment to key elements of the intake (i.e. trash racks, isolation valves, etc.) must be undertaken using special coatings and possibly cathodic protection. Lastly, provisions to collect mussels which slough off of pipe walls upstream of the valve house would be required to protect downstream infrastructure. This strategy is only feasible if redundancy is added to the system or an alternative source (for example the Standley Lake by-pass) is developed. This strategy also requires modifications to the raw water infrastructure to improve its suitability for mechanical cleaning.

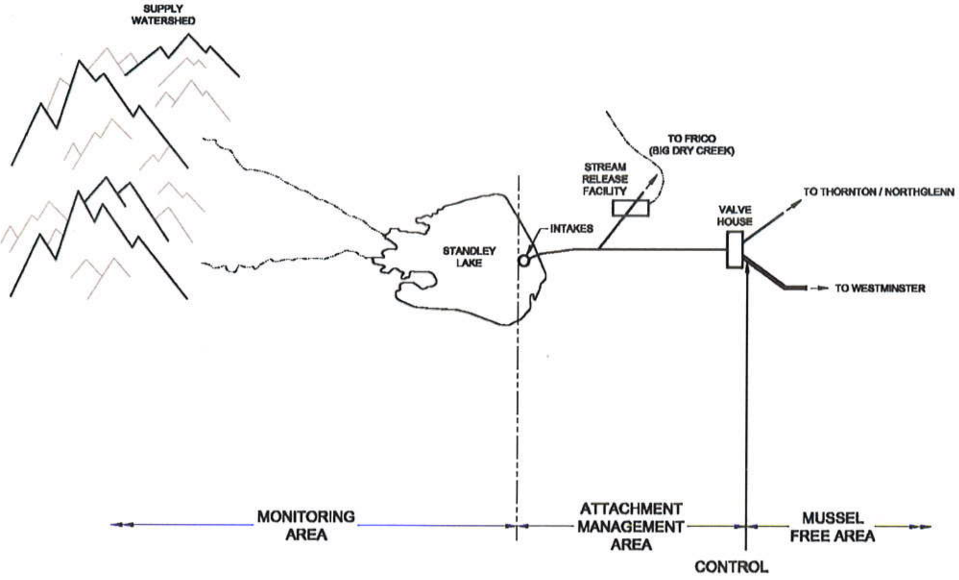

Figure 12. Strategy 3 - Control Mussels at the Valve House.

Table 8. Strategy 3 - Approaches for treating mussels at the valve house.

Approach	Key Feature	Key Considerations
Apply chemical oxidants to Westminster pipelines leaving	Inject oxidant into pipelines	• Several oxidants are effective • Creation of by-products must be controlled • Possible premature oxidation of

valve house		iron or manganese in conduits to treatments plants
Ultraviolet irradiation at Westminster pipelines leaving valve house	Apply UV at pipelines	• Questionable feasibility • High power consumption • Major UV suppliers not player in market
Discourage intake attachment with coatings	• Add coatings to trash rack and piping between intake and valve house • Add cathodic protection to valves	• Does not control veligers • Potential water quality impacts from coatings • Alternative source required during coating installation/maintenance
Periodic intake cleaning	• Isolation valve needed at added to intakes inlet • Piping between intake and valve house must be cleaned (drained, dried and flushed or mechanically cleaned) • Additional access provisions needed for cleaning	• Does not control veligers • Lengthy outage required • Cleaning will be difficult • Management of debris and water in pipe will be difficult • Alternative source required during cleaning

4.2.4 Control at the Treatment Plants

Like the previous option, the **Control at Treatment Plants** strategy also makes no additional attempt to control the mussel population in the lake. Nor is any attempt made to actively control mussel settlement and attachment anywhere in the raw water system upstream of Northwest WTF or Semper WTF. Existing oxidant feeds at these plants would be used to prevent settlement and growth of mussels in the treatment plants. Valves in the raw water system could be retrofitted with coatings or cathodic protection to discourage settlement of mussels. Any mussels that accumulate in the raw water system would be managed by pigging smaller diameter conduits and draining and mechanically cleaning the large diameter conduits on a periodic basis. Cleaning could take several weeks to complete.

The primary advantage of this strategy is that only the City of Westminster's water supply is treated. This option also avoids any water quality issues (DPB formation, premature oxidation of iron and manganese) that may arise from treatment at the valve house. But this option also has all the disadvantages of the previous approach plus the additional disadvantage of the increased risk of developing unacceptable headloss due to accumulation of mussels in the 36" and 42" conduits supplying the treatment plants between annual cleanings. Also, annual cleaning/pigging of the 36" and 42" conduits will be a difficult, if not impossible, process that will require taking the Northwest WTF and possibly the Semper WTF off-line for an extended period of time during the cleaning process. In addition, removal of 6" of mussel growth by pigging may not be successful. Control at the plant is not considered a realistic option.

4.2.5 Coordination with SLOC Members

Selection of a mussel control strategy is contingent on coordination among all users of Standley Lake water. Several of the possible approaches involve oxidation of the entire supply at the intake, so that the SLOC members would all have a stake in and an opinion about which is the best approach. For some, managing mussels at another location may be preferred, or they may not believe it necessary to manage mussels at all.

An effort should be made to work with the other SLOC members to develop a combined approach that is satisfactory to all parties. Issues such as DBP formation from the use of oxidants, dechlorination of creek discharges, and timing of potential shutdowns of the intake for cleaning must be on the discussion agenda.

A written agreement should be the end result of discussions among the SLOC members regarding the preferred approach to mussel management. If the preferred plan includes allowing the growth of mussels in the intake piping with eventual cleaning, the agreement should include language that addresses the relative decrease in flow for each user that may be a result of the overall reduction of flow volume through the pipelines due to mussel growth.

4.3 Mussel Control Options

Of the four control strategies discussed above, control at the intake or control at the valve house appear most practical. None of the controls in the lake are feasible and control at the treatment plants is not realistic due to the necessity of taking the plants off line to clean transmission lines. The remainder of the report will focus on the two practical strategies: mussel control at the intakes and mussel control at the valve house.

There are several options for implementing these strategies. The relevance of these options is related to their cost and the degree to which the other users of Standley Lake water are willing to participate in a mussel control program. The four options are:

1. Chemically treat the entire flow at the existing intakes. This approach is only realistic if all the users of Standley Lake water agree to chemical treatment of the water and some agreement can be reached to share the cost.
2. Chemically treat Westminster flow at the valve house and add redundant 102"/84" conduits. This option is suitable if the other users can tolerate an annual infestation of mussels which is cleaned once a year AND the other users must draw water from Standley Lake during the period that

cleaning occurs. This approach also requires agreement among the users of the intake.

3. Chemically treat Westminster flow at the valve house and build the Standley Lake by-pass. This option makes sense if the other users can tolerate an annual infestation of mussels which is cleaned once a year and they do not need to draw water from Standley Lake during the period that cleaning occurs.
4. Chemically treat Westminster flow at a Westminster dedicated intake. If the other Standley Lake users do not agree to participate in controlling mussels, then this approach makes sense for Westminster acting alone.

Table 9 presents an overview of the four treatment options. Each option is discussed in more detail following the table.

Table 9. Mussel Treatment Options

Option	Description	Required Infrastructure	Constraints
1	• Treat combined demand of all users at both existing intakes with chemical oxidant. • Treat Big Dry Creek release with reducing agent.	• Coat trash rack (2) • Chemical feed system for injecting oxidizing agent at intakes and at valve house • Chemical feed system for injecting reducing agent at stream discharge facility • Building for chemical feed systems	• Other Standley Lake users agree on chemical oxidation • DBP mitigation at 4 WTPs
2	• Treat only Westminster demand at valve house with chemical oxidants. • Modify existing infrastructure up-stream of valve house to allow for mechanical cleaning. • Provide redundancy for the 102" and 84" diameter conduit to supply the demands of all users during mechanical cleaning.	• Coat trash rack (2) • Cathodic protection of valves • Chemical feed system to supply oxidizing agent to valve house • Building for chemical feed system • Redundant conduits between valve shaft and valve house • Shell trap facility at valve house • Access provisions for draining and mechanical cleaning of conduits	• Other Standley Lake users agree on mechanical cleaning AND • Other Standley Lake users require withdrawal of water during mechanical cleaning
3	• Treat Westminster demand at valve house with chemical oxidants. • Modify existing infrastructure up-stream of valve house to allow for mechanical cleaning. • Develop alternative source of sufficient capacity to supply Westminster's demand during mechanical cleaning.	• Coat trash rack (2) • Cathodic protection of valves • Chemical feed system to supply oxidizing agent to valve house • Building for chemical feed system • Standley Lake by-pass system (including possible improvements in ditch infrastructure for operation during winter weather) • Shell trap facility at valve house • Access provisions for draining and mechanical cleaning of conduits	• Other Standley Lake users agree to mechanical cleaning AND • Other Standley Lake users do not require withdrawal of water during mechanical cleaning

4	• Build Westminster dedicated intake and conduit to valve house. • Treat Westminster demand at dedicated intake with chemical oxidant. • Consider maintaining connection to existing infrastructure as an emergency supply rather than building Standley Lake by-pass.	• Use copper alloy in new intake trash rack • Chemical feed system to supply oxidizing agent to valve house • Building for chemical feed system • Dedicated intake and conduit	• Other Standley Lake users do not agree to participate in mussel control program

Option 1 - Chemical Treatment at Intake

This option consists of adding chemical feeds at the upper and lower intakes, the stream release facility and the valve house. In addition, the existing trash racks would be coated with an anti-fouling or foul release coating to prevent mussel settlement and attachment to these facilities. Figure 13 illustrates option 1.

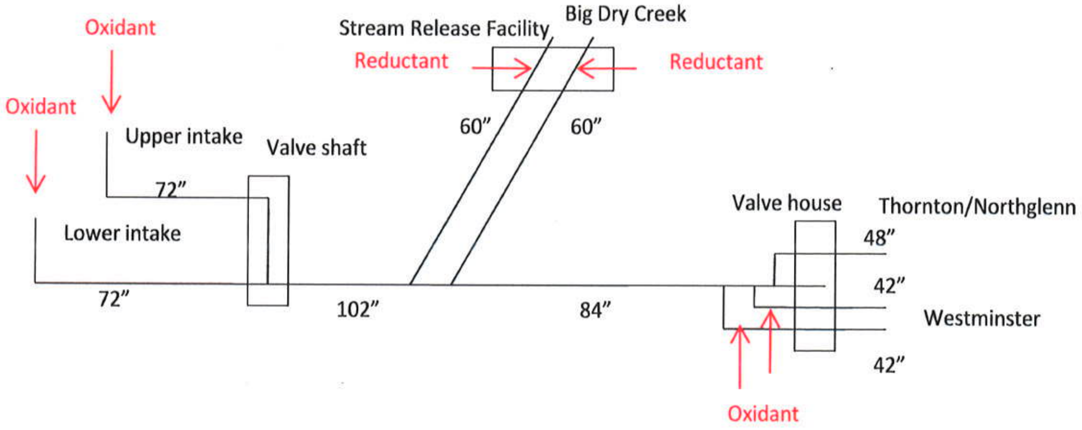

Figure 13. Option 1: Chemical Treatment at Intake

A chemical oxidant would be added at the intakes in order to prevent or discourage settlement and attachment of veligers in the raw water system. A second oxidant injection point would be added at the valve house as an optional booster station to provide additional protection for the smaller diameter transmission conduits to Westminster's treatment plants. A chemical reductant would be added to the water at the stream release facility in order to meet in-stream combined chlorine and sulfide standards for Big Dry Creek[1].

The oxidant would be used on a seasonal basis. Based on the conclusions of the vulnerability assessment discussed earlier in this report, the season would extend from approximately mid-April to November. The exact time to start and stop the chemical addition would be determined by monitoring water temperature. As long as only the lower intake is used, anoxia in Standley Lake will provide a degree of protection for this intake, and the amount of chemical added could be reduced during the period of anoxia (See Table 5). The addition of the reductant at the stream release facility would only be required when water is discharged to Big Dry Creek.

The advantages of Option 1 include:

- Minimal modifications to existing infrastructure
- Quickest approach to implement

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[1] Per Regulation #38 the pertinent the numeric standards for Big Dry Creek are: Cl_2(acute) = 0.019 mg/L, Cl_2(chronic) = 0.011 mg/L, H_2S = 0.002 mg/L

- Provides the greatest degree of protection to the entire raw water infrastructure
- Provides protection from mussels to all downstream users
- Multiple oxidant feed points improve protection for Westminster
- No/minimal physical cleaning of infrastructure required
- Minimal disruption to operation of raw water system

The disadvantages of Option 1 include:

- Large chemical demands
- Formation of regulated and unregulated disinfection products caused by oxidant addition
- Must meet discharge requirements for Big Dry Creek
- Premature oxidation of iron and manganese or other water quality changes possible from oxidant addition

Option 2 - Chemical Treatment at Valve House and add Redundant 102/84" Conduit

This option consists of adding a chemical oxidant feed at the valve house and adding an additional conduit between the valve shaft and the stream release facility/valve house. The option also requires building a shell trap facility at the valve house and adding any provisions required to drain, clean and remove shells from the existing conduits. Figure 14 illustrates option 2.

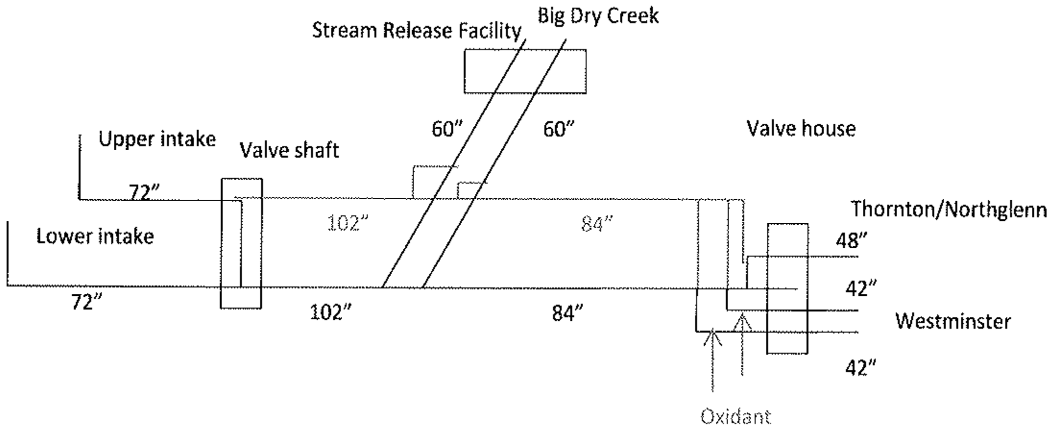

Figure 14. Option 2: Chemical treatment at valve house with redundant 102/84" diameter conduit

This option is predicated on allowing an infestation to occur in the raw water system between the intakes and the stream release facility/valve house. The infestation could be mechanically cleaned on a predetermined basis, probably annually between December and March. Alternatively, cleaning could be triggered when unacceptable hydraulic losses develop or when the operation of control features in the raw water system become impaired.

The chemical oxidant feed at the valve house would protect the smaller diameter transmission conduits supplying Westminster's treatment plants from settlement or attachment. The shell trap facility would capture shells which slough off the unprotected conduits, preventing them from entering Westminster's transmission conduits to the treatment plants.

The new conduit, added between the valve shaft and stream release facility/valve house, would provide redundancy for this portion of the raw water system. Adding the redundant conduit would permit uninterrupted withdrawals from Standley Lake by the all users during the time the conduits are being mechanically cleaned.

The advantages of Option 2 include:

- Reduced chemical demand since only Westminster water is treated
- No need to treat the water discharged to Big Dry Creek
- Improves reliability of existing infrastructure by adding redundancy (102"/84"conduits)
- Maintains flexibility in operation of raw water system - all users can with withdraw water during cleaning

The disadvantages of Option 2 include:

- Substantial and difficult infrastructure modification as modifications must not impact dam safety
- Mechanical cleaning of mussels in exposed portions of the system will be difficult and tedious
- Formation of regulated and unregulated disinfection byproducts caused by oxidant addition
- Premature oxidation of iron and manganese or other water quality changes are possible from oxidant addition

Option 3 - Chemical Treatment at Valve House with Standley Lake by-pass

Option 3 is similar to option 2 except it assumes that the other Standley Lake users can tolerate not withdrawing water during the cleaning period. In this case, the redundant conduit becomes unnecessary and Westminster could use the planned Standley Lake by-pass to maintain an uninterrupted source during cleaning. Figure 15 illustrates option 3.

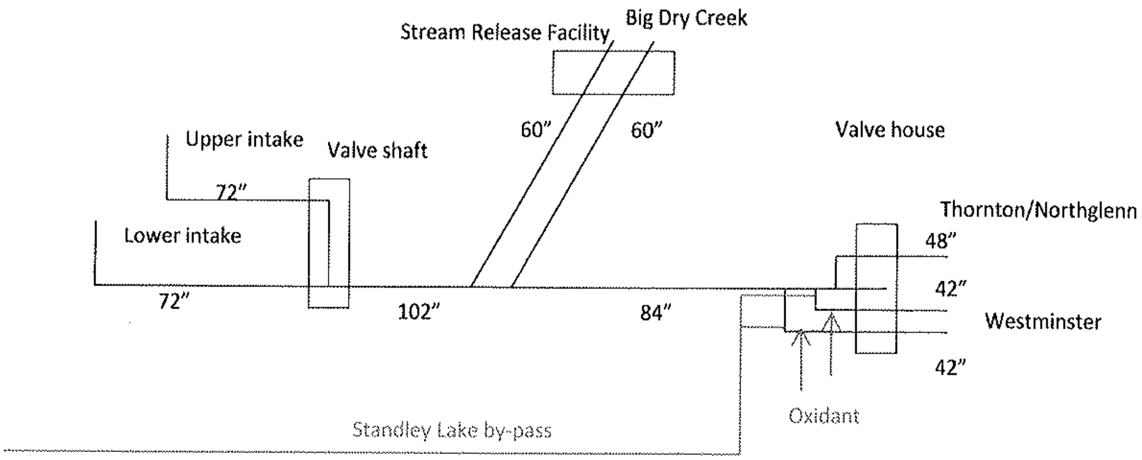

Figure 15 Option 3: Chemical treatment at valve house with Standley Lake by-pass

The other modifications discussed in option 2 would still be required. These include provisions for oxidant addition at the valve house, adding the shell trap facility prior to the valve house and adding any provisions required to drain, clean and remove shells from the existing conduits. This option also requires that the Standley Lake by-pass be designed to operate for extended periods during the winter months. It may also require that the ditch infrastructure supplying the by-pass be upgraded for reliable operation during extended periods of freezing weather.

The advantages of Option 3 include:

- Reduced chemical demand since only Westminster water is treated
- No need to treat water discharged to Big Dry Creek
- Improves Westminster's system reliability by providing alternative raw water source
- Takes advantage of existing plan to build the Standley Lake by-pass
- Modification to existing infrastructure are not as extensive as option 2
- Avoids major modifications at the dam

The disadvantages of Option 3 include:

- By-pass must be sized to supply Westminster for extended periods during winter
- Design/construction schedule for by-pass must be accelerated
- Mechanical cleaning of mussels in exposed portions of the system will be difficult and tedious
- Formation of regulated and unregulated disinfection products caused by oxidant addition
- Premature oxidation of iron and manganese or other water quality changes are possible from oxidant addition

Option 4 - Chemical Treatment at New Westminster Dedicated Intake

This option consists of building a new intake and conduit connecting the intake and the valve house. This system would be dedicated for Westminster's use. A chemical feed would be included in the intake and a booster feed would be at added at the valve house. A new screen for the new intake would be fabricated from mussel resistant alloys. The conduit would be designed for easy access for mechanical cleaning and removal of mussel shells. Connections to the existing raw water system would be maintained, and this system would serve as a backup system. Figure 16 illustrates option 4.

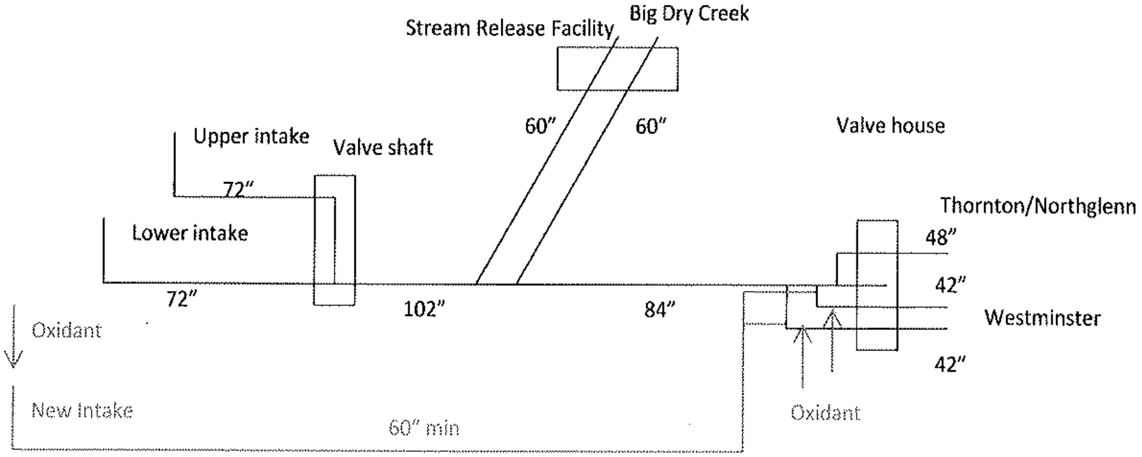

Figure 16. Option 4: Chemical treatment at new intake

This option should be considered if the other Standley Lake users do not agree to participate in a mussel control program at Standley Lake.

The advantages of Option 4 include:

- Reduced chemical demand since only Westminster water is treated
- No need to treat water discharged to Big Dry Creek
- Improves reliability by providing alternative intake
- New intake would be designed for mussels from the ground up
- No need for Westminster to be involved with mechanical cleaning

The disadvantages of Option 4 include:

- Formation of regulated and unregulated disinfection products caused by oxidant addition
- Premature oxidation of iron and manganese or other water quality changes are possible from oxidant addition
- Substantial infrastructure modification – modifications must not impact dam safety

5.0 Infrastructure Protection Plan Cost Estimates

Because each protection approach involves a group of control methods, the costs were developed for each infrastructure improvement, as shown in Table 10. The capital cost for constructing an oxidant feed system for the entire flow at the intake is significantly larger than the cost of a system to feed only Westminster's water at the valve house, particularly when the cost of feeding a reductant at the Big Dry Creek outlet is included. None of these costs include the annual chemical cost. Similarly, the costs for implementation of the pipe cleaning/pigging operations just cover the construction cost of the traps and pig launching facilities, but do not include the labor for doing this manual cleaning.

The ultimate cost to the City to implement mussel controls will depend on the approach taken for control, and that will depend on coming to agreement with the other Standley Lake users regarding mussel control. The costs identified for individual infrastructure improvements are grouped according to the location for placing the control in the system in Table 11. From a capital improvement cost perspective, the most economical approach is to plan to clean the piping between the intake and valve house periodically and oxidize only the flow belonging to Westminster at the valve house. However, in order for this to be a realistic option, the Standley Lake by-pass must be completed to supply Westminster demands and the other users must accept Standley Lake being taken off line as a source during cleaning. When the cost of the by-pass is included in the cost comparison, the comparative cost between the first three approaches will change. For either of the approaches which require cleaning of the intake pipelines, some additional investigation is warranted into how and who would clean the pipelines.

Table 10. Budget Level Cost Estimates for Individual Infrastructure Improvements

Mussel Control Improvements	Approximate Capital Costs in 2009 Dollars
Chemical Feed System to Supply Oxidizing Agent at Intake	
Dosing System Installation	$200,000
Feed System / Chemical Storage Structure	$ 3,000,000
Total	**$3,200,000**
Chemical Feed System to Supply Oxidizing Agent at Valve House	
Dosing System Installation	$ 100,000
Feed System / Chemical Storage Structure	$ 2,500,000
Total	**$2,600,000**
New Dedicated Westminster Intake with New Coated Trash Rack	
New Intake for Westminster Demand (Single Intake Pipe)	$4,000,000
New Coated or Copper/zinc Alloy Trash Rack	$250,000
Conduit to Existing Valve House	$1,500,000
Valve House Modifications	$300,000
Total	**$6,050,000**
Redundant Piping from Valve Shaft to Valve House	
Conduit	$1,500,000
Valve House Modifications	$400,000
Total	**$ 1,900,000**
Reductant Feed System at Discharge Facility to Big Dry Creek	
Dosing System Installation	$250,000
Feed System /Chemical Storage Structure	$ 2,000,000
Total	**$ 2,250,000**
Coat Existing Trash Racks (2)	
Coating Application	$ 50,000
Divers to Remove and Replace Trash Racks	$200,000
Total	**$250,000**
Manual cleaning between intake and valve house	
Access Provisions for Mechanical Cleaning	**$1,000,000**
Add Pigging Provisions Between Valve House and Treatment Plants	
Retrofit 42" and 36" Conduit with Pigging Stations (20 total)	**$5,000,000**
Mussel Shell Trap Facility	
Retrofit 102" or 84" conduit	**$1,500,000**
Cathodic Protection of Valves	
Cost of Adding Cathodic Protection to Intake Valves	**$ 200,000**

Table 11. Budget Level Costs for Improvements by Location of Control in 2009 Dollars

OPTION 1 Control at Intake		
Chemical Feed System to Supply Oxidizing Agent at Intake	$	3,200,000
Coat Existing Trash Racks (2)	$	250,000
Reductant 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	**$**	**8,260,000**
OPTION 2 Control at Valve House - Redundant Piping		
Chemical Feed System to Supply Oxidizing Agent at Valve House	$	2,600,000
Coat Existing Trash Racks (2)	$	250,000
Mussel Shell Trap Facility	$	1,500,000
Manual cleaning between intake and valve house	$	1,000,000
Cathodic Protection of Valves	$	200,000
Administration and engineering	$	2,220,000
Total	**$**	**7,770,000**
OPTION 3 Control at Valve House - Standley Lake By-pass		
Chemical Feed System to Supply Oxidizing Agent at Valve House	$	2,600,000
Coat Existing Trash Racks (2)	$	250,000
Mussel Shell Trap Facility	$	1,500,000
Cathodic Protection of Valves	$	200,000
Administration and engineering	$	1,820,000
Total (bypass not included)	**$**	**6,370,000**
OPTION 4 New Dedicated Westminster Intake		
New Dedicated Westminster Intake with Coated Trash Rack	$	6,050,000
Chemical Feed System to Supply Oxidizing Agent at Intake	$	3,200,000
Administration and engineering	$	3,700,000
Total	**$**	**12,950,000**

6.0 Recommendations and Implementation

The spread of mussels in western lake/reservoirs is a recent event, so there is little experience in dealing with infestations in western waters. Experience at Lakes Mead and Mohave in Arizona indicate rapid and severe infestations of quagga mussels can occur in western waters. Quagga mussels have shown a greater degree of adaptability than predicted from experience with zebra mussels in eastern waters. This makes prior preparation for an infestation all the more critical since the development of an infestation may not proceed along predictable pathways. Once an infestation begins in a vulnerable water body like Standley Lake, there is a one to two year period, before it becomes severe. Westminster should implement the following recommendations to prepare in advance for a potential infestation.

Focus on Preventing Introduction of Mussels into Standley Lake

If mussels are introduced into Standley Lake, there are no simple or inexpensive approaches for their control. Westminster should continue its aggressive measures to protect Standley Lake from the importation of mussels. Recreational activities in Standley Lake, particularly recreational boating, should continue to be closely regulated and monitored.

Develop Intergovernmental Agreements

The involvement of Thornton, Northglenn and FRICO, is essential for selecting the most appropriate control approach for mussels at Standley Lake. Through discussion with the SLOC partners, the group should come to an agreement regarding the preferred approach so that design can be initiated for the facilities included in that option. Westminster should develop the appropriate Intergovernmental Agreements with these entities defining the needs and responsibilities of each party.

Monitor Development of Non-chemical Treatment Technologies

Chemical treatment with oxidants is the most widely accepted and effective method for the prevention of settlement and attachment of mussels. However, it is a less than ideal solution for an infestation at Standley Lake. Westminster should continue to monitor advances in non-chemical treatment methods. Westminster should closely monitor on going research sponsored by the Bureau of Reclamation.

Adopt Phased Strategy for Implementation of Control Measures

A phased approach for dealing with mussels should be adopted. Implementation of the control strategy is dependent on the timeframe in which mussel mitigation is required. HDR recommends the following three stage control strategy.

Phase 1 is the period during which no indication of mussel colonization in Standley Lake is present. Recommended actions for Phase 1 include:

- Continue existing sampling program

- Monitor advances in technologies and investigate participation in emerging technology research
- Negotiate required Intergovernmental Agreements
- Perform oxidant chemical evaluation during mussel season
- Complete Standley Lake by-pass or redundant 102"/84" conduit engineering
- Design chemical feed system
- Design cathodic protection system for key valves
- Design trash rack improvements
- Design Improved intake access
- Close upper intake cover
- Develop capability/program to exercise valves
- Develop cleaning plan for raw water conveyance system

Phase 2 begins when the City confirms mussel colonization in Standley Lake. Recommended actions for Phase 2 are:

- Expedite Standley Lake by-pass or redundant 102"/84" conduit construction
- Build and operate chemical feed systems
- Install cathodic protection for valves (if needed)
- Coat trash racks
- Implement valve exercise program
- Establish monitoring/inspection program in raw water conveyance system
- Evaluate performance of mussel control measures
- Construct improvements to facilitate manual cleaning plan of raw water conveyance system (detritus traps, pigging provisions, valve replacement) not chemically protected.

Phase 3 begins when Westminster confirms that the raw water conveyance system has been colonized by mussels, in spite of any actions taken in Phase 2. The actions included in Phase 3 include:

- Seasonally operate Standley Lake by-pass or redundant 102"/84" conduit
- Conduct manual cleaning of intake facilities
- Conduct pigging of transmission conduits

7.0 Appendix A - Mussel Control Methods

Invasive mussel control options are discussed in detail below. Control options can be implemented in either a proactive or reactive regime. Control methods used to prevent mussel settlement or cause veliger mortality are proactive and designed to prevent any mussel attachment in the areas treated. Reactive methods remove a currently established mussel population, but do not prevent mussel re-colonization. Additionally, methods may be employed continuously or intermittently for adequate mussel control as determined by the infested utility. Control options have been divided into the following sections:

- Biologic Control
- Acoustic Control
- Chemical Oxidants
- Chemical Nonoxidants
- Electrical
- Physical

An overview of the mussel control methods can be found in Table 2.

7.1 Biological Control Methods

Dreissena mussels are sensitive to a number of environmental factors that can be manipulated to induce mortality at various life stages. Aerial exposure, calcium deficiency, acute or chronic heat exposures, freezing, oxygen depravation, parasitism, predation, and starvation are all natural control methods that could potentially reduce the size of zebra mussel populations. However, it is not feasible to adjust water quality parameters such as salinity, calcium concentration, dissolved oxygen concentration, pH, or temperature in natural systems or water supply facilities without serious repercussions. Biological control methods such as bacterial exposure and spawning inhibition are well documented in controlled settings, but have not been widely implemented at a full scale.

7.1.1 Bacterial Exposure

A natural bacterial toxin found in the CL0145A strain of *Pseudomonas fluorescens* is lethal to zebra mussels. The toxin works by destroying the mussel's digestive tract and is present in both live and dead bacterial cells, suggesting that the toxin is found in the cell walls. Unlike some biocides and other chemical treatment methods, the ingestion of CL0145A does not elicit an immediate adverse response (i.e. closing of siphons to adverse conditions). It is therefore likely that fewer and shorter duration treatments of CL0145A would be required to obtain mortality than traditional chemical control methods. Zebra mussels between 1 and 25 mm in shell length are equally susceptible to CL0145A. Mortality rates greater than 95 percent were accomplished using 100 mg/L of dry bacterial mass per unit volume for a duration of six hours. Quagga mussels, however, are less susceptible to the toxin and have shown only 70-85 % mortality when exposed to concentrations of 25 to 100 ppm for 24 hours. Unlike other treatment technologies, there are no known adverse effects of CL0145A to non-target species such as ciliates, daphnids, other bivalves, or fish.

This control strategy is close to being considered a proven technology, and Marrione Bio Innovations (MBI) is currently developing a bacteriological product, Zequanox, using the dead CL0145A strain of *Pseudomonas fluorescens* for commercial use. Zequanox is currently being tested on a full scale by the Bureau of Reclamation under a special release permit. MBI expects EPA Biopesticide registration in the summer of 2010, however, the likelihood of the product receiving approval for drinking water facilities is unknown.

7.1.2 Predation

Natural predation of zebra and quagga mussels by some duck and fish species is not an efficient method of inducing mortality in significant mussel populations. Predators are often negatively impacted by the high flow conditions surrounding intake pipes and are not found within closed systems such as water conduits and pipelines. Predators are also likely to affect populations of native mussels to the same extent as they impact zebra mussels.

7.1.3 Spawning Inhibition

Mussel spawning can be inhibited with various chemicals that target serotonin re-uptake.

Selective serotonin re-uptake inhibitors can be blocked by receptor antagonists such as cyproheptadine and mianserin. Low concentrations of these inhibitors can be used to block both spawning and parturition in males and females. Other antagonists such as tricyclic antidepressants have been studied in relation to zebra mussel spawning. Imipramine and desipramine can inhibit male spawning and clomipramine can inhibit both male and female spawning.

The use of spawning inhibition for mussel control is considered an emerging technology. Spawning prevention would be implemented in the open water system to prevent mussel population growth. The development of this method is dependent on determining the effects on non-target species (including humans) and the cost of dosing the chemicals to the source water. Many of the chemicals used for spawning inhibition are classified as emerging contaminants and would be inappropriate for use in drinking water applications.

7.2 Acoustic

Cavitation, sound treatment, and vibration are three acoustic treatments that can be used to control mussel populations. The impacts and effectiveness of these treatments are not fully proven, especially in large pipelines. These methods are fairly low maintenance technologies that have a low likelihood of harming non-targeted organisms. There is a possibility that resident fish may be affected by cavitation, but migratory fish should not be affected for short exposure times. Acoustic control methods are environmentally friendly and do not have associated safety issues. Although acoustic technology is still developing, there is evidence suggesting that sound energy could be an attractive alternative to chemical or electrical treatment. In order to implement acoustic treatment options, site adaptability considerations are required for constructability and periodic maintenance access. In addition, electrical service is required for signal generation and amplification. These technologies are not suitable to open water conditions; acoustic technologies can only be used within the conduits and structures transporting water.

7.2.1 Cavitation

Cavitation is a form of acoustical energy that initiates the formation and collapse of microbubbles in the water in the zone being protected. The bubble formation occurs in the region of decreased density and pressure in an intense ultrasonic wave or high velocity turbulent water flow. At frequencies between 1 and 380 kHz, this type of energy has demonstrated mortalities of veliger, juvenile, and adult zebra mussels. Exposure times are ranges of seconds for veligers, minutes for juveniles, and hours for adults.

The use of cavitation for mussel control would require further studies on the effects on pipes and the length of the system required for treatment. Pipe systems would need to be designed to withstand continuous turbulent flow conditions without loosing pipe integrity.

7.2.2 Sound Treatment

Low frequency sound energy has been demonstrated to prevent settlement by translocating zebra mussels and could be a valid option to reduce this form of infestation. Sound treatment uses waterborne acoustic energy in the form of sound waves (20 Hz to 20 kHz) or ultrasound waves (above 20 kHz) to disrupt the settlement of zebra mussels. This type of acoustic energy is effective against veligers at frequencies below 200 Hz by causing them to become stressed and immobilized, resulting in detachment and subsequent sinking in the water column. At frequencies between 39 and 41 kHz, ultrasound acoustic energy can fragment veligers within a few seconds and kill adults within 19 to 24 hours.

Sound treatment is an emerging technology that has not been proven to reliably control mussels in full scale pipes. Additionally, continuous sound treatment may cause brittleness in conduit materials, including metal and concrete.

7.2.3 Vibration

Vibration refers to the use of solid-borne acoustic energy in mechanical structures. This type of treatment requires that the zebra mussels are settled on a surface that can be subjected to vibration (e.g. pipes or water intakes). Vibrational energy is effective in killing mussel veligers and juveniles at just below 200 Hz.

As with acoustic control, vibration has not been demonstrated on full scale infrastructure. Additionally, long-term effects of vibration may include structural deterioration of conduits and structures.

7.3 Chemical Methods

Mussel control technologies can be generally categorized as either chemical or non-chemical due to the environmental or toxic impacts that occur with chemical additions, but not with other technologies. Chemical treatments are applicable to public facilities that can control the dispersion of chemical discharge, but they remain less practical for open water applications. If there is concern regarding environmental impacts or harm to aquatic life, non-chemical treatment is often used. However, chemical alternatives remain the most common treatment due to their proven effectiveness.

There are two main categories of chemical treatments: oxidants and non-oxidants. While oxidizing agents are very effective in controlling zebra mussel populations, many of them also target other aquatic species. Non-oxidizing agents are less harmful to aquatic species such as fish, but some of them are very toxic to native mussel species.

7.3.1 Chemical Oxidants

Chlorine, chlorine dioxide, chloramines, bromine, hydrogen peroxide, ozone, and potassium permanganate are oxidants that cause mortality in mussels when applied at the correct dose and for a sufficient amount of contact time. Although these oxidizing agents are efficient, they can affect organisms other than zebra and quagga mussels. Adult mussels are also capable of detecting the presence of oxidants and can close their valves for up to two weeks. As a result, longer and more frequent treatment times may be necessary to kill adult mussels. Dosages of chemicals discussed below are solely to impact mussels and do not take into account natural oxidant demand levels in the water, so the actual required dose will be higher.

All of these oxidants have been proven to be effective against mussels and are used by a variety of utilities to manage mussel infestations. Technology exists to implement chemical addition systems to a variety of water supply facilities.

7.3.2 Chlorine

Chlorination is the most common treatment method for mussel infestation in public facilities, but it is not commonly used to treat open waters. This is due to concerns regarding the formation of disinfection byproducts (e.g. trihalomethanes, haloacetic acids), which occur when waters containing natural organic matter are chlorinated. High toxicity towards other aquatic species is also an issue. Doses and application times, as well as the temperature and quality of the raw water, will impact the effectiveness of the treatment. For facilities that discharge back into a natural water system, dechlorination is required to neutralize any residual chlorine that may come into contact with aquatic life. Dechlorination is typically performed with sodium bisulfite .

Chlorination via hypochlorite, sodium chlorite, or chlorine gas targets adult zebra mussels at a water concentration of 2.0 mg/L and results in a 90 percent mortality after several weeks of exposure. Periodic or continuous treatment is usually needed to eliminate adult mussels, although less frequent treatment is effective against veligers. A chlorine concentration of only 0.5 mg/L is effective on veligers and results in 100 percent mortality after two hours.

7.3.3 Chlorine dioxide

Chlorine dioxide fed at a concentration of 0.5 mg/L targets veligers and produces 100 percent mortality after 24 hours. Periodic treatments of chlorine dioxide at 0.6 to 1.0 mg/L that last four days at a time can produce 70-100 percent mortality in adults. Chlorine dioxide offers advantages in terms of lower exposure time for adult mortality and the avoidance of halogenated disinfection byproduct formation. Chlorine dioxide forms chlorite as a byproduct of oxidation, so the regulated level of chlorite in drinking water limits the dosage level of chlorine dioxide. Safety concerns for operator handling must be addressed.

7.3.4 Chloramination

Chloramination produces 100 percent veliger mortality after 24 hours of exposure at 1.2 mg/L. The adult exposure times and lethal concentrations have not been reported. If there is a high nitrogen concentration in the water, administration of chlorine or hypochlorite will naturally produce chloramines. Under normal treatment circumstances, chlorine is dosed ahead of ammonia to form chloramines.

7.3.5 Bromine

Bromine produces effects similar to chlorine with respect to impacts on mussels, however the presence of bromine will lead to the production of brominated disinfection byproducts. Bromine concentrations between 0.1 and 0.5 mg/L for one to three weeks will produce 60 percent mortality in veligers. A 90-100 percent mortality of adult mussels can be achieved after approximately 30 days.

7.3.6 Hydrogen Peroxide

Hydrogen peroxide is not a common mussel control chemical, possibly due to the relatively high dose needed for treatment despite a relatively short exposure time and non-toxicity to many fish. After six hours at a concentration of 100 mg/L, 100 percent veliger mortality and 26 percent juvenile mortality was observed.

7.3.7 Ozone

Ozone is toxic to mussel veligers, juveniles, and adults at relatively low concentrations. A concentration of 0.5 mg/L has demonstrated 100 percent veliger mortality after five hours and 100 percent adult mortality after seven to twelve days. Ozone is typically used to control taste and odor issues in waters and must be generated on-site due to its volatility. Unless multiple injection points are installed, concentration-time values required to kill adult mussels throughout the downstream water systems cannot be maintained since it disperses rapidly.

7.3.8 Potassium Permanganate

Potassium permanganate is effective in reducing or eliminating zebra mussels when administered at high doses for extended periods. Mortality rates of 90-100 percent have been observed for adults when dosed at rates of 2.5 mg/L. Dosing rates of 1.0 mg/L may also be effective in preventing juvenile settlement, but direct toxicity has not been observed. Potassium permanganate is not recommended for open water systems since doses lethal to mussels are also lethal to fish.

7.3.9 Non-oxidant Chemicals

Activated starch, aluminum sulfate, chloride salts, potassium salts, copper ions, and organic molluscicides are examples of non-oxidizing agents that can be used to kill mussels. The major advantage of non-oxidizing agents over oxidizing agents is that adult mussels cannot detect them, preventing the mussels from closing their valves to block the chemical.

7.3.10 Activated Starch

An activated starch product developed by Barkley Distribution, LLC, may be very effective in mussel control. The reagent has demonstrated 100 percent mortality of veliger and adult zebra mussels at concentrations between 3.0 and 6.9 mg/L. Mortality may be achieved immediately, but may take up to 72 hours. The large variation in time suggests differences in acute concentrations at different mussel life stages. Barkley reports that the activated starch reagent has shown no known toxicity or adverse environmental impacts to date. The reagent is broken down by bacteria within hours of dosing. The product has been studied and proven in the laboratory and closed systems, but not significantly within open water systems. Barkley Distribution, LLC, has been very difficult to contact and it is unclear weather they are still in business. Their website is http://www.barkley-distribution.com, however the phone numbers and email addresses listed appear to no longer be active. Extensive testing and regulatory approval would be required to implement this technology on a full scale.

7.3.11 Aluminum Sulfate

Aluminum sulfate (alum) at concentrations of 20 to 50 mg/L is typically used by water treatment plants to remove suspended particles (turbidity) from the water. Veligers suffer 50 percent mortality rates at alum concentrations of 126 mg/L over 24 hours. Although the effects of aluminum sulfate on treatment processes are well documented and dosing technology is readily available, the high dosage of alum required to obtain mortality could produce large quantities of solids and that settle in the pipes and conduits, and negatively impact the treatability of the water.

7.3.12 Chloride Salts

Various chloride salts have been used to kill mussels and are safe for most fish species. These salts are advantageous because they have fewer operator safety concerns than chemical oxidants and need shorter exposure times (less than 24 hours) to induce mortality. The major disadvantage is the extremely high concentration needed to obtain mortality. Calcium chloride and sodium chloride produce 100 percent veliger and juvenile mortality after six hours at concentrations of 10,000 mg/L and 20,000 mg/L, respectively. These high concentrations make this approach impractical due to cost and drinking water quality concerns.

7.3.13 Potassium Salt

Potassium concentrations of approximately 50 mg/L can prevent the attachment of zebra mussels, but higher concentrations (between 88 and 288 mg/L) are necessary to produce mortality. At these high concentrations, 100 percent mortality can be achieved within 48 hours. However, native mussel species (but not fish) are also sensitive to potassium salts and eventual discharge of the water may be problematic. The high concentrations of potassium salt required for mussel mortality would cause water quality and dosing concerns, and make this approach impractical for drinking water applications.

7.3.14 Copper Ions

Copper ions have shown distinct toxicity towards mussels. Veliger mortality of 100 percent can be achieved after 24 hours with a dose of 5 mg/L. Copper sulfate levels between 5 and 40 mg/L were effective in adult zebra mussel control, but fish and native mussel species were more sensitive than mussels at these high concentrations. There is also evidence that very low levels of copper ions can produce mussel mortality if a constant residual level is maintained. Copper is a regulated contaminant in both drinking water and wastewater systems.

MacroTech, Inc., has developed a device that distributes copper and aluminum ions to water at low concentrations. The aluminum encourages copper ions to settle and cover surfaces, which then prevents mussels from settling. Veligers are additionally targeted by direct toxicity of copper. MacroTech, Inc. has developed a combined copper / aluminum ion generator which could alleviate disadvantages associated with the use of copper alone. The MacroTech system uses concentrations of 5 ppb of copper and aluminum to control mussel settlement and growth. This method is most effective in small and closed systems. The Bureau of Reclamation is currently investigating using this technology to control mussels and may be able to provide more information for future use.

7.3.15 Organic Molluscicides

Organic molluscicides are often proprietary chemicals that prevent attachment of the mussel, attack the byssal thread, or attack the surface of the mussel. Many of these compounds are registered with the USEPA as effective control agents. They are typically used in closed systems or systems that can decontaminate the water before it encounters aquatic life. While organic molluscicides are effective at controlling mussels, they are also toxic to native fish and mussel species and can be corrosive and harmful to humans. They are not recommended for use in open water systems. Many molluscicides are not approved for use in drinking water applications.

Various organic compounds can also be used for mussel control. Butylated hydroxyanisole (BHA), tert-butylhydroquinone, and tannic acid have been extensively tested based on their costs, solubility in water, anticipated treatment concentrations, and potential environmental and operator safety concerns. Tert-butylhydroquinone was the only chemical that was nontoxic to fish species. At a concentration of 5.8 mg/L for 48 hours, it prevented 90 percent of zebra mussels from attaching to a substrate. Tert-butylhydroquinone must be administered continuously to control zebra mussel attachment or approximately 90 percent of the mussels tend to reattach within 48 hours of exposure ceasing. Tert-butylhydroquinone cannot produce mussel mortality.

7.3.16 Chemical Treatment Considerations

The effectiveness of chemical control strategies for mussels will vary greatly based on the degree of infestation, water temperature, and water quality. Mussels start reproducing when the water temperature is greater than 12°C. It may be possible to chemically treat the water only once annually at the end of the mussel reproductive season, or alternatively periodically (i.e. monthly), intermittently (i.e. daily), semi-continuously (i.e. hourly), or continuously. Multiple applications may be necessary if multiple layers of mussels are attached to a substrate. If utilized on an infrequent basis to kill the mussels that have inhabited the facilities, provisions to clean out the accumulated debris will be necessary.

7.4 Electrical Methods

Electrical fields can be used to proactively or reactively control mussel populations. Low voltage electrical fields can prevent mussel settlement and high voltage electrical fields can kill mussels. The rate of mortality resulting from high voltage fields depends on the intensity of the voltage, the length of time it is applied, and the age of the mussel.

Cathodic protection systems produce a continuous low voltage electrical field that deters adult mussel settlement. Plasma-pulse systems generate sonic waves as a result of an electrical discharge that induces high adult mortalities and reasonable veliger mortalities. Pulse-power systems generate an electric field through a series of electronic pulses and generally target mussels in the settling stage. Low frequency electromagnetism produces an electromagnetic field that kills mussels by decreasing the amount of calcium available for their development.

Similar to the previously discussed technologies, all electrical treatment options require site considerations for constructability, periodic maintenance, and storage for replacement materials. Electrical service is critical for implementation of this control method. In addition, it is very important to post signs alerting the public to the potential of electric shock in the areas of the electrical fields.

7.4.1 Cathodic Protection System

Cathodic protection systems control mussel settlement by creating a continuous low voltage electric field and are not intended to cause mortality. Adult mussels are irritated by the low voltage field and tend to avoid settlement in the area. On the other hand, veligers and juveniles remain relatively unaffected. The settlement of mussels can be completely prevented with an 8-volt AC current and partially prevented with a 6-volt AC current. This type of system is commonly used in the water industry to protect metal in pipelines and structures from corrosion. This technique is only suitable for exposed metal surfaces, as pipelines lined with cement mortar can not be protected due to the insulating affect of the mortar.

Cathodic protection of valves in mortar-lined conduits may provide protection for exposed and vulnerable surfaces. Although cathodic protection of valves is not common, HDR expects it to be feasible for buried conduit.

7.4.2 Plasma Spark System

Phoenix Science and Technology, Inc. is currently in the process of developing a plasma pulse technology that has proven efficient in controlling mussel populations in pipes. The system works by releasing stored energy in a manner that causes intensive shockwaves, steam bubbles, and ultraviolet light in the water being treated. Field and laboratory studies have confirmed the ability of the plasma spark system to kill adult mussels, detach settled mussels, and prevent the settlement of new mussels. During testing, the number of zebra mussels in the control pipe was 10,000 times greater than that in the pipe exposed to electric energy. The electric field also affected the attachment and survival of adult mussels. After five weeks of plasma pulse pressure waves, approximately 20 percent net mortality was observed. At this rate, 100 percent adult mortality would be achieved in just over nine weeks. Plasma pulse technology could be used to proactively and reactively control mussels in pipes and conduits, but is not feasible for use in open water systems.

This technology is currently being tested by the Bureau of Reclamation, and is awaiting technological advances to be implementable on water supply intakes.

7.4.3 Pulse Power Electric Field

Pulse power devices can be used to create an electric field within the area that is confined between two electrodes. The electrical field must span the entire width of the area it is intended to protect to be effective. In comparison to the previously discussed electrical methods, the pulse power electric field is much stronger than a cathodic protection system and covers a greater surface area than a plasma spark system. The electric field generated by the electrodes is essentially designed to stun or kill juvenile mussels.

Very small veliger mussels are typically not killed because they can tolerate greater electrical impulses, while larger mussels with larger biomasses are killed because of the greater amount of electrical energy they come into contact with as they pass through the electric field. Pulse power electric fields can prevent zebra mussel settlement at efficiency of 78-88 percent.

Once established, the technology can control settlement at an efficiency of 80-90 percent. Mussel settlement downstream of the electrical test device was reduced at an efficiency of approximately 40-90 percent, with variability accounted for by equipment malfunction and low mussel densities. Although this technology is designed to target juvenile mussels, veligers are also affected by pulse power electric fields. The mortality rates for umbonal stage veligers consistently ranged from 21-40 percent with a mean of 31 percent. The low mortality rate is likely due to the small size of the mussel, which decreases the electrical exposure. Pulse power electric fields have been shown to consistently provide long-term mussel control by preventing settlement and macro-fouling.

No vendors have been identified for this technology. Further testing and technological development would be necessary before this system could be installed in water supply systems.

7.5 Physical Methods

Physical treatments are typically effective for prevention of mussels in locations that are most likely to impact water system operation (i.e. intake screens, intake pipes, etc.). In addition, many of these methods indirectly cause mussel mortality, necessitating their removal from the water system. All physical treatment options require site considerations for constructability and periodical maintenance access.

Electrical service is also required for some options and special permits may also be necessary.

7.5.1 Disposable Substrates

Often used in Europe, disposable substrates include bulkheads, pipes, and rope which are installed close to the equipment which is to be protected from mussel colonies. The mussels will preferentially attach to the disposable substrate, which can then be removed (usually after a period of one year) and disposed of. This option is applicable only to juvenile and adult translocating mussels. While disposable substrates are characterized by low maintenance and easy implementation, they are not as effective as other methods. Disposable substrates are typically used in the U.S. for monitoring purposes.

7.5.2 Permeable Barrier

A permeable geotextile barrier with a small mesh size (< 50 µm) installed to extend from the lake bottom to the surface of the water column can block the passage of most veliger and juvenile mussels. Gunderboom, Inc., manufactures fabrics that are used as exclusion systems in marine settings and may be efficient in controlling the spread of mussel veligers. A potential downside of this treatment is that the barrier may serve as a surface for mussel attachment, the barrier may be damaged by icing, and some recreational activities may be restricted, but efficiencies of limiting veligers are very high.

Few studies are available on the long term prevention of mussel infestation using a permeable barrier, however, the vendor indicates it can be effective. The barrier is known to foul in highly turbid and biologically active waters.

7.5.3 Mechanical Cleaning

Adult mussel populations can become large and dense. They thrive by attaching to hard surfaces with byssal threads. If the population is easily accessible, juvenile and adult mussels can be removed from large hard surfaces via the following methods:

- Scraping of surfaces
- Pigging of pipelines
- High-pressure water jetting of surfaces
- Abrasive blast cleaning of surfaces

Mechanical cleaning is a temporary measure and usually requires dewatering of the facility being cleaned, although some components can be cleaned by the use of trained divers to access underwater equipment. Mussel veligers are not targeted with this method and small mussels may avoid removal if they are located in crevices. Infrastructure to be cleaned must be able to withstand mussel accumulation and mechanical abrasion and have the capability to be shut down for extended periods of time to clean mechanically. Additionally, the system and utility must be able to collect and dispose of the removed mussels and shells.

Pipeline pigging is highly effective on smaller conduits; however it is not feasible on conduits larger than 48 inches in diameter. Pigging requires valves that do not obstruct the interior of the pipe, such as ball or gate valves. Conduits containing other valve types that obstruct the flow path, such as butterfly valves, would need to undergo valve replacement in order to employ pigging as a method of mussel control.

7.5.4 Mechanical Filtration

Mussels in all development stages can be contained with filtration systems. Screens with small mesh sizes (~40 μm) or filters with granular media are both efficient for containing mussel veligers. Common granular media include sand, anthracite coal, activated carbon, resin beads, and garnet. Since the filters collect a large amount of suspended solids in addition to 100 percent of zebra mussel veligers, they typically require periodic cleaning. As a result, a large surface area of media must be provided to assume adequate flow through the media. The disadvantage of this method is the difficulty associated with implementation in an open water high flow system. However, this method is very effective in preventing the spread of mussel veligers and offers a nontoxic alternative to other treatment methods that can be harmful to humans and aquatic species.

Sand Filter Intake
Sand filter intake systems have shown to effectively prevent zebra mussel transport into conduits. Multiple waster users along the Great Lakes region of the United States and in Europe have mitigated or avoided mussel infestations by using sand filter intakes. Sand filter intakes would require a large capital cost and will cause lake disturbance during construction. However, after the initial construction, the intake would require minimal operation and maintenance. With a physical barrier to mussels before the conduit, no mussel removal would be expected (i.e., scraping, removal and disposal). Sand filter intakes are not typically designed for systems over 150 MGD. The SLOC peak design flow is 207 MGD.

7.5.5 Light Sources

Mussels typically prefer to attach in dark places or within shadows and will preferentially attach to substrates with these light conditions. Large mussels may prefer darkness while small mussels show no preference although their growth rates may be accelerated in dim locations. Laboratory experiments with strobe lights have shown that mussels move away from the light, but these results have not been duplicated in field studies.

It appears that mussels prefer to inhabit dark places, but there are inconsistent results when direct correlations are examined. There are number of other factors that also affect the settlement and movement of mussels such as substrate color, water flow, and depth. As a result, there is a lack of conclusive evidence that supports the use of light sources as a method to control mussel settlement.

7.5.6 Ultraviolet Radiation

Ultraviolet (UV) radiation is typically an effective method for controlling mussels in all life stages, although veligers are more sensitive to it than adults. Complete veliger mortality can be obtained within four hours of exposure to UV-B radiation and adult mortality can be obtained if constant radiation is applied. More specifically, 100 percent of veligers exposed to 1800W of radiation with a medium pressure mercury lamp for four hours died within 24 hours. UV-B radiation is observed at wavelengths between 280 and 320 nm and is sometimes harmful to resident aquatic species. Furthermore, the effectiveness of UV radiation may be decreased by turbidity and high suspended solids concentrations. Neither Calgon nor Siemens currently market UV systems that can be implemented in large-diameter pipes, however, smaller vendors, including Aquionix, Sollux, and Hanovia, manufacture in-line UV systems for this application. UV systems require a large amount of power to operate, particularly for high flow applications such as at Standley Lake. The Bureau of Reclamation is currently investigating the effectiveness of UV for mussel prevention on a full scale system and results should be available in the coming years.

7.5.7 Z-Alloy Screens

Mussels can rapidly attach to intake screens, eventually blocking flow. Johnson Screens manufactures a passive screen made from Z-alloy, a copper nickel alloy, which discourages attachment of juvenile and adult mussels. Initially tested in Lake St. Clair, the site of the original zebra mussel infestation in the Great Lakes, screens installed for a water treatment plant intake showed no significant attachment over six years of operation compared to 304 stainless steel screens which became plugged. As an alternative to replacing the trash racks with Johnson Screens passive screens, they could be replaced with new trash racks fabricated of Z-alloy. However, Z-alloy screens or trash racks do not prevent veligers from entering the water treatment process.

7.5.8 Coatings

Two types of surface coatings to prevent macrofouling are commercially available. Foul release coatings are non-toxic, low surface energy coatings that allow only weak attachment by mussels. Anti-fouling coatings contain substances that are known mussel irritants, particularly copper, that slowly leach out of the coating over time. Both types of coatings are painted onto the target surface, which generally must be clean and dry during application. One type of cupric coating was identified in research that can be applied underwater, EURO-vinyl AF25, manufactured by Euronavy. The cut sheet indicated zebra mussel prevention for over 30 months, however no independent verification of effectiveness was located in the literature.

Additionally, if the intake structure can be dewatered and cleaned, the US Bureau of Reclamation has conducted research on 20 anti-fouling and foul release coatings, and identified four recommended products. These coatings include E-paint Sunwave Plus (non-copper based antifouling paint), Luminore (copper containing coating), Intersleek 970 (non-toxic foul release), and Fuji (non-toxic foul release). All recommended coatings had minimal or no mussel fouling after four to seven months exposure to quagga mussel infested waters (Parker Dam, California).

8.0 Appendix B - Vulnerability Assessment of Westminster's Watersheds

8.1 Objective of Analysis

The objective of this analysis is two-fold. The first objective is to evaluate the vulnerability of the City of Westminster's watersheds to a quagga or zebra mussel infestation. The second objective is to assess if an infestation in any of the City's watersheds would pose a risk of infestation to Standley Lake.

8.2 Approach

For Standley Lake to be at risk from an infestation from any of the City's watersheds there must be:

- A credible pathway for importation of mussels into the watershed
- Suitable water quality and environmental conditions to establish and sustain an infestation in the watershed
- A viable means to transport the infestation from the watershed to Standley Lake

The vulnerability assessment for Westminster consists of a number of steps. It starts with understanding the existing water supply system, which is shown in Figure 16. The assessment then identifies the lakes and reservoirs in the supply system that are hydraulically connected to Standley Lake and ranks their susceptibility to the importation of mussels. Next, the assessment considers rivers and streams that are connected to Standley Lake and evaluates their susceptibility to the importation of mussels. From here, the assessment, considers representative water quality of lakes and streams in the supply system and considers if these conditions are suitable for sustaining a mussel population. The assessment then considers the risks of transport of veligers or mussels to Standley Lake by streams and canals in the watersheds. The assessment concludes with an overall evaluation of risk to Standley Lake and recommendations for risk mitigation.

8.2.1 Description of the City of Westminster's Water Supply System

The primary source of the City's water in Standley Lake originates from snow melt and surface waters from the Clear Creek Basin in the mountains to the west. This raw water flows to Standley Lake through three main irrigation canals that divert water from the north bank of Clear Creek near Golden: the Farmers' High Line Canal (FHL), the Croke Canal and the Church Ditch. Over 85 percent of Westminster's water supply comes from Clear Creek through these irrigation canals.

The City also receives high quality water at Standley Lake from Denver Water. This water is delivered from the West Slope through Denver's water supply system into the Kinnear Ditch Pipeline (KDPL). This water, often referred to as "Moffat Tunnel water," is collected from the Williams Fork River and the Fraser River on the western slope and diverted through the Moffat Tunnel into South Boulder Creek. The water is then stored in Denver's Gross Reservoir, released into the South Boulder Diversion Canal, delivered into the KDPL and discharge into in Standley Lake.

The City's portion of Coal Creek water rights is also delivered into the KDPL for delivery to Standley Lake. Westminster's Coal Creek water rights are currently a minor portion of the City's supply, but at one point in time in the 1960's, this was a significant source of water for the City.

Clear Creek Water

The portion of the Clear Creek watershed upstream of the diversion points at Golden, CO was considered for this analysis. The watershed includes land drained by the main stem of Clear Creek up to the Continental Divide. Major tributaries feeding Clear Creek considered in this analysis include the West Fork of Clear Creek, the South Fork of Clear Creek, North Fork of Clear Creek, Chicago Creek, Beaver Brook and Fall River.

Moffat Tunnel Water

For this analysis, Moffat Tunnel Water was considered to contain western slope water from the upper Fraser and upper Williams Fork Rivers, and received by the Moffat collection system. This analysis also includes water collected in the South Boulder Creek watershed extending from the Continental Divide to the point of diversion at the S. Boulder Diversion Canal, located downstream from Gross Reservoir.

Coal Creek Water

For this analysis, Coal Creek Water was considered as water collected in the Coal Creek Basin from the mouth of Coal Creek, to its headwaters, near Wonderview, CO.

Interbasin Transfers that are Hydraulically Connected to Standley Lake

In addition to the Moffat Tunnel water, western slope water can reach Standley Lake via two interbasin diversions. First, Williams Fork Basin water is diverted to the West Fork of Clear Creek via the Gumlick Tunnel. Subsequently, the water is rediverted via the Vasquez Tunnel to the Moffat Tunnel. Hence, water from the headwaters of Williams Fork can ultimately reach Standley Lake via either Clear Creek or the Moffat Collection system. Second, Peru Creek water in the Blue River Basin can be diverted to Clear Creek via the Vidler Tunnel and Leavenworth Creek. Hence Standley Lake is hydraulically connected to Peru Creek. It should be noted that of all of these diversions are at high altitude (> 11,000 feet) and there are no significant lakes or reservoirs above these diversions. As will be discussed later in the report, it is not anticipated that any of these diversion represent an infestation risk to Standley Lake.

8.2.2 Identification of Lake/Reservoirs in the City of Westminster's Watershed

USGS topographic maps were reviewed to create a list of lakes or reservoirs in the Clear Creek, S. Boulder Creek or Coal Creek basins which may be hydraulically connected to Standley Lake. This list is presented in Table 12. A total of 64 lakes/reservoirs were identified. Of the 64 lakes/reservoirs, 49 were determined to be hydraulically connected to Standley Lake. The elevations of these lakes/reservoirs ranged from 7287 ft (Gross Reservoir) to 12,541 ft (Ethyl Lake). Thirty two of the 49 hydraulically connected lakes/reservoirs are above 10,000 ft. The only large lake/reservoir hydraulically connected to Standley Lake is Gross Reservoir, (440 ac surface area, 43,000 ac-ft storage). The next largest lake/reservoir is Guanella Reservoir. Guanella Reservoir's storage capacity is an order of magnitude less than Gross Reservoir, with approximately 2100 ac-ft of storage. The Cabin Creek Reservoirs, operated by Xcel Energy store approximately 1900 ac-ft of water. Other lakes and reservoirs in the Clear Creek, S. Boulder Creek or Coal Creek Basins are even smaller.

To better assess the level of risk posed by these lakes/reservoirs, determinations were made regarding

- Type of public access
- Popularity of boating activities
- Popularity of fishing activities

Type of Public Access

USGS topographic maps and satellite views from Google Maps were consulted to determine the type of access available to the site. Access was defined as by foot or by vehicle. A lake/reservoir was considered accessible by vehicle if a maintained dirt or paved road passed in the vicinity of the site. Of the 49 hydraulically connected lakes/reservoirs, 25 were determined to be accessible by vehicle and the remaining 24 were determined to be accessible by foot only. Many of the 'foot access' sites could be reached by 4WD or off road vehicles by a determined visitor.

Popularity of Boating Activities

None of the hydraulically connected lakes/reservoirs are open to motorized boating. However, motorized boats may occasionally be used on these lakes/reservoirs by public officials, such as the Division of Wildlife. In theory, hand power craft can be used on any of the connected lakes/reservoirs. Given the cold water temperature, small size and remote locations of most lakes/reservoirs, there is minimal exposure to hand powered craft. Gross Reservoir is the only connected water body that promotes the use of hand powered craft as a recreational experience. Hence, this is the only connected reservoir which was designated as boating site in Table 12.

Popularity of Fishing Activities

All of the connected lakes/reservoirs can be fished. Fisherman may not have legal access, but given the remote locations of most of these lakes/reservoirs, the lack of legal access is probably not much of a deterrent. A popular fishing website, *Fishingworks.com* was consulted to evaluate which lakes/reservoirs are considered good fishing destinations. Of the 49 hydraulically connected lakes/reservoirs, 18 were reported to have good fishing. These were designated as "Reported Fishing" in Table 12.

Table 12. Lakes/Reservoirs in Clear Creek, and S. Boulder Creek Basins

Basin	Water Body	General Location	Connecting Stream/Ditch	Lat °N	Long -°W	Elevation Feet	USGS Quad Name	Access	Reported Fishing	Boating	Hydraulically Connected to Standley Lake?
CC	Ethyl	West of Alice	Mill Creek	39.8059	105.7223	12541	Empire	Foot	No	No	Yes
CC	Ice	West of Alice	Fall River	39.8424	105.6913	12204	Empire	Foot	No	No	Yes
CC	Murry	West of Naylor Lake	Clear Creek	39.605	105.759	12103	Montezuma	Foot	No	No	Yes
CC	Silver Dollar	West of Naylor Lake	Clear Creek	39.6052	105.7604	11950	Montezuma	Foot	Yes	No	Yes
CC	Caroline	West of Alice	Fall River	39.8352	105.6883	11897	Empire	Foot	No	No	Yes
CC	Lower Urad	West of Berthoud Falls, near Urad mine	Woods Creek	39.7433	105.83	11854	Gray's Peak	Foot	Yes	No	Yes
CC	Bill Moore	West of Alice	Mill Creek	39.8045	105.7118	11718	Empire	Foot	No	No	Yes
CC	Ohman	West of Alice	Fall River	39.8398	105.6849	11533	Empire	Foot	No	No	Yes
CC	Reynolds	West of Alice	Fall River	39.8398	105.6849	11533	Empire	Foot	No	No	Yes
CC	Steuart	West of Alice	Fall River	39.8395	105.6816	11473	Empire	Foot	No	No	Yes
CC	Chicago Lakes	SW Echo Lake	Chicago Creek	39.6157	105.6344	11420	Mount Evans	Foot	No	No	Yes
CC	Slater	West of Alice	Fall River	39.8198	105.7025	11387	Empire	Foot	No	No	Yes
CC	Naylor Lake	Guenella Pass Road	Clear Creek	39.6065	105.7604	11372	Mount Evans	Vehicle	Yes	No	Yes
CC	Upper Urad	West of Berthoud Falls, near Urad mine	Woods Creek	39.75	105.849	11309	Gray's Peak	Foot	No	No	Yes
CC	Loch Lomond	West of Alice	Fall River	39.6776	105.8357	11200	Empire	Foot	No	No	Yes
CC	Upper Chinns Lake	West of Alice	Fall River	39.8166	105.6997	11107	Empire	Vehicle	Yes	No	Yes
CC	Upper Cabin Creek	Guenella Pass Road	Clear Creek	39.651	105.719	11047	Gerogetown	Vehicle	No	No	Yes
CC	Lower Chinns Lake	West of Alice	Fall River	39.817	105.693	11037	Empire	Vehicle	Yes	No	Yes
CC	Fall River	West of Alice	Fall River	39.821	105.691	10840	Empire	Foot	Yes	No	Yes
CC	St Mary's Lake	St Mary's Glacer	Fall River	39.8329	105.6465	10690	Empire	Vehicle	No	No	Yes
CC	Idaho Springs	SW Echo Lake	?	39.645	105.615	10621	Idaho Springs	Vehicle	No	No	?
CC	Echo Lake	Squaw Pass Road	Chicago Creek	39.6582	105.6034	10597	Idaho Springs	Vehicle	Yes	No	Yes
CC	Lake Quivira	North Alice	Fall River	39.826	105.642	10302	Empire	Vehicle	No	No	Yes
CC	Green Lake	Guenella Pass Road	Clear Creek	39.677	105.707	10102	Gerogetown	Vehicle	Yes	No	Yes
CC	Lower Cabin Creek	Guenella Pass Road	Clear Creek	39.662	105.707	9961	Gerogetown	Vehicle	No	No	Yes
CC	Clear Lake	Guenella Pass Road	Clear Creek	39.672	105.701	9876	Gerogetown	Vehicle	Yes	No	Yes
CC	Gerogetown Res	Guenella Pass Road	Clear Creek	39.6919	105.6981	9187	Gerogetown	Vehicle	Yes	No	Yes
CC	Chase Gulch	Northwest of Central City	Clear Creek	39.8187	105.5353	8880	Central City	Vehicle	No	No	Yes
CC	Guanella	South US40 near Empire	Clear Creek	39.7588	105.6947	8620	Empire	Vehicle	No	No	Yes
CC	Beaver Brook #3a	West of Evergreen	Beaver Brook	39.693	105.432	8400	Squaw Pass	Vehicle	No	No	Yes
CC	Georgetown Lake	East of Georgetown South of I-70	Clear Creek	39.7292	105.6908	8448	Georgetown	Vehicle	Yes	No	Yes
CC	Beaver Brook #2	West of Evergreen	Beaver Brook	39.705	105.412	7944	Squaw Pass	Vehicle	No	No	Yes
CC	Beaver Brook #3	Lookout Mountain	?	39.7302	105.2392	7303	Morrison	Vehicle	No	No	Yes
SBC	Iceberg Lakes	West of East Potal Moffat Tunnel	South Boulder	39.8901	105.6969	11651	East Portal	Foot	No	No	Yes
SBC	Heart Lake	West of East Potal Moffat Tunnel	South Boulder	39.8761	105.6934	11322	East Portal	Foot	No	No	Yes
SBC	Arapaho Lakes	West of East Potal Moffat Tunnel	Arapaho Creek	39.9072	105.6809	11139	East Portal	Foot	No	No	Yes
SBC	Rogers Peak Lake	West of East Potal Moffat Tunnel	South Boulder	39.7117	105.6901	11117	Empire	Foot	No	No	Yes
SBC	Clayton	West of East Potal Moffat Tunnel	South Boulder	39.8893	105.6848	10989	East Portal	Foot	No	No	Yes
SBC	Jenny Lake	Rollins Pass	Jenny Creek	39.9335	105.6631	10917	East Portal	Vehicle	Yes	No	Yes
SBC	Yankee Doodle Lake	Rollins Pass	Jenny Creek	39.9377	105.6538	10711	East Portal	Vehicle	Yes	No	Yes
SBC	Forest Lakes	West of East Potal Moffat Tunnel	Arapaho Creek	39.9175	105.6674	10674	East Portal	Foot	No	No	Yes
SBC	Crater Lakes	West of East Potal Moffat Tunnel	South Boulder	39.8973	105.6754	10584	East Portal	Foot	No	No	Yes
SBC	Mammoth Creek Reservoir	South of East Potal Moffat Tunnel	Mammoth Gulch	39.8794	105.6192	9727	East Portal	Vehicle	No	No	Yes
SBC	Teller Lake	South of East Potal Moffat Tunnel	Mammoth Gulch	39.8888	105.6151	9614	Nederland	Foot	No	No	Yes
SBC	Snowline Lake	South Rollinsville	South Boulder	39.8861	105.5091	9001	Nederland	Vehicle	Yes	No	Yes
SBC	Thorn Lake	South Rollinsville	South Beaver Creek	39.8863	105.4501	8963	Tungsten	Vehicle	Yes	No	Yes
SBC	Karl Park Lake	East Rollinsville	South Boulder	39.9001	105.5196	8884	Nederland	Vehicle	No	No	Yes
SBC	Los Lagos Reserviors 1-3	North Rollinsville	South Boulder	39.9321	105.5082	8626	Nederland	Vehicle	Yes	No	Yes
SBC	Manchester Lake	North Rollinsville	South Boulder	39.924	105.4993	8555	Nederland	Vehicle	Yes	No	Yes
SBC	Kossler Lake	Walker Ranch Park	?	39.9786	105.332	7700	Eldorado Springs	Vehicle	No	No	No
SBC	Gross	West of Colo 93 North of Colo 72	South Boulder	39.95	105.362	7287	Eldorado Springs	Vehicle	Yes	Yes	Yes
n/a	Ralston	West of Colo 93	South Boulder	39.832	105.241	6053	Golden	Vehicle	No	No	No
n/a	Rocky Flats Lake	East Colo 93	Smart Canal	39.8724	105.2319	6184	Golden	Vehicle	No	No	No
n/a	Upper Long Lake	West Colo 93	Long Lake Ditch	39.8223	105.2371	6086	Golden	Vehicle	No	No	No
n/a	Lower Long Lake	West Colo 94	Long Lake Ditch	39.821	105.2303	5909	Golden	Vehicle	No	No	No
n/a	Welton	North Colo 72	?	39.866	105.5863	5863	Golden	Vehicle	No	No	No
n/a	Arvada	East Colo 93	Ralston Creek	39.8231	105.2108	5770	Golden	Vehicle	Yes	Yes	No
n/a	Tucker	East Colo 93	Tucker Ditch	39.8278	105.198	5748	Golden	Vehicle	No	No	No
n/a	Leyden	East Colo 93	Leyden Creek	39.8415	105.1709	5614	Golden	Vehicle	No	No	No
n/a	Great Western	NW Standley Lake	Walnut Creek	39.8975	105.1541	5610	Golden	Vehicle	No	No	No
n/a	Fairmount	North Colo 58	?	39.7794	105.1719	5586	Golden	Vehicle	No	No	No
n/a	Hyatt	East McIntyre	Hyatt Creek	39.8052	105.1638	5568	Golden	Vehicle	No	No	No
n/a	Maple Grove	North 20th	Rocky Mountain Ditch	39.7516	105.1373	5525	Golden	Vehicle	No	No	No
n/a	Woman	West Standley lake	Woman Creek	39.1586	105.8793	5220	Louisville	Vehicle	No	No	No

BC = S. Boulder Creek
CC = Clear Creak

8.2.3 Assessment of Vulnerability of Introduction of Mussels to Lakes/Reservoirs in Westminster's Watershed

A relative rating of the risk of mussel importation for the lakes and reservoirs that are hydraulically connected to Standley Lake is provided in Table 13. The four levels of risk are categorized as follows:

- Highest risk – Accessible by vehicle, popular for fishing and boating
- Higher risk - Accessible by vehicle, popular for fishing
- Lower risk - Accessible by vehicle, not popular for fishing
- Lowest risk - Accessible by foot only

Table 13. Relative Risk of Importation of Mussels - Lakes/Reservoirs Hydraulically Connected to Standley Lake

		Highest Risk		
Gross				
		Higher Risk		
Naylor Lake	Upper Chinns Lake	Lower Chinns Lake	Jenny Lake	Yankee Doodle Lake
Echo Lake	Green Lake	Clear Lake	Georgetown Res	Snowline Lake
Thorn Lake	Los Lagos Reserviors 1-3	Manchester Lake	Georgetown Lake	
		Lower Risk		
Upper Cabin Creek	St Mary's Lake	Lake Quivira	Lower Cabin Creek	Mammoth Creek
Karl Park Lake	Chase Gulch	Guanella	Beaver Brook #3a	Beaver Brook #2
Beaver Brook #3				
		Lowest Risk		
Ethyl	Ice	Murry	Caroline	Bill Moore
Iceberg Lakes	Ohman	Reynolds	Steuart	Chicago Lakes
Slater	Heart Lake	Upper Urad	Loch Lomond	Arapaho Lakes
Rogers Peak Lake	Clayton	Forest Lakes	Crater Lakes	Teller Lake

These rankings are relative and none of the hydraulically connected lakes/reservoirs are at a large absolute risk of importation of mussels. Of the 49 hydraulically connected lakes/reservoirs, Gross Reservoir is ranked as being at the greatest risk for the importation of mussels due to its relatively easy access, use of hand powered craft and potential for fishing.

The hand power craft restrictions on Gross Reservoir are as follows:

- Single-hull construction
- < 18 ft
- Hand Launch
- Memorial Day – September 30 only

Gross Reservoir is stocked by the Colorado Division of Wildlife.

8.2.4 Identification and Assessment of Vulnerability to the Introduction of Mussels into Streams in Westminster's Watershed

The major streams in the City of Westminster's watershed include:

- Clear Creek and its tributaries
- S. Boulder Creek and its tributaries
- Coal Creek and its tributaries
- Fraser River Headwaters/Williams Fork Headwaters

Similar to the evaluation of lakes/reservoirs, an attempt was made to assess the level of risk posed to these streams by type of public access, popularity of boating activities, and popularity of fishing activities

Clear Creek and Tributaries

There is excellent vehicle access to Clear Creek and its major forks between the Continental Divide and Golden. Fishing is popular along sections of Clear Creek and its tributaries. Clear Creek is not suitable for motorized boating, but is popular for whitewater rafting and kayaking. Several commercial white water rafting companies offer tours of various sections of Clear Creek. Sections of Clear Creek contain Class IV and V rapids, with vertical gradients of 150 ft/mile.

The City of Golden operates the Clear Creek Whitewater Park, downstream of the US 6 bridge over Clear Creek at the mouth of Clear Creek Canyon. This park is popular with kayakers. Rapids in this section of Clear Creek are classified as Class II or III with a vertical gradient of 45 ft/mile.

S. Boulder Creek and Tributaries

Vehicle access to S. Boulder Creek is much more limited than to Clear Creek. Fishing is popular along some sections of S. Boulder Creek. Whitewater rafting is not commercially developed along S. Boulder Creek, so whitewater activities tend to be limited to private individuals and thrill seekers. The section of S. Boulder Creek between Pinecliffe and Gross Reservoir is highly technical, containing Class V+ rapids, with vertical gradients of 250 ft/mile. The section of S. Boulder Creek between Gross Reservoir and the takeout for the S. Boulder Feeder Canal also contains vertical gradients of approximately 250 ft/mile.

Coal Creek and Tributaries

Vehicle access to Coal Creek is good, and some sections are fished. Coal Creek is not popular with rafters or kayakers. Vertical gradients of up to 200 ft/mile occur betweens its source and the mouth of Coal Creek canyon.

Frazer River Headwaters/Williams Fork Headwaters

Vehicle access to the Frazer River upstream of Moffat Tunnel is excellent. There is some fishing, but the Frazer River is not popular with rafters or kayakers. As discussed above, Moffat Tunnel water is also collected from the head waters of Williams Fork as well as along Vasquez Creek, in the Fraser River Basin. Access to these sources is by foot only, with little to no fishing. There is no rafting or kayaking.

Summary of Stream Vulnerability

Overall, because of access, fishing and boating, the main stem of Clear Creek possesses the greatest risk for the importation of mussels into streams in the Standley Lake watershed. The Golden Whitewater Park on Clear Creek is also a possible point of importation. Because of the proximity of the Whitewater Park to the Farmers High Line Canal and Croke Canal headgates, this Park probably represents the greatest risk for mussel importation and colonization of the watershed. Other streams, including S. Boulder Creek, Coal Creek and the headwaters of the Frazer and Williams Fork Rivers do not appear to be at high risk for the importation of mussels.

8.2.5 Assessment of Lake/Reservoir Water Quality

Obtaining water quality data on all the 49 lakes/reservoirs hydraulically connected to Standley Lake is beyond the scope of this project. However, all the lakes/reservoirs should have similar water quality due to their high mountain location. All are fed primarily by snowmelt, with minimal development upstream. Typically, these types of water bodies are characterized by low temperature, turbidity, hardness and suspended solids. They are also low in mineral and nutrient content. Annual variations in water quality occur, primarily as a result of dilution during run-off events. Most of the high mountain reservoirs are relatively unimpacted by human activities. However, past mining activities along Clear Creek are responsible for the release of some heavy metals.

Existing water quality data for one of the larger upstream lakes/reservoirs, Georgetown Lake (elevation 8448 ft), is available from a past USGS study. Georgetown Lake is on the main stem of Clear Creek, and is one of the lowest elevation hydraulically connected lakes/reservoirs in the City's supply system. Since the tendency is for mineral content and temperature to increase as Clear Creek descends from its headwaters, Georgetown Lake is probably has a higher colonization potential than other lakes/reservoirs in the watershed.

Table 14 compares water quality data collected at the outlet of Georgetown Lake for a one year period and compares this information to the colonization potential related to specific parameters. Calcium levels and temperature are key parameters with respect to colonization potential. Calcium levels are at the low end of conditions suitable for the establishment of a mussel population, while the water temperature will only support a short breeding season.

Georgetown Lake is at approximately the same elevation as Grand Lake, Lake Granby and Shadow Mountain Reservoir, all of which have detected quagga mussel veligers. Calcium concentrations in these lakes vary between 4 – 9 mg/L, which is lower than in Georgetown Lake. At this point, however, it is unclear if a thriving population of quagga mussels has established itself in these reservoirs. Lakes with water quality similar to Georgetown Lake are at apparent low risk of colonization. A significant infestation could only occur if quagga mussels exhibit a greater degree of adaptability to survive in marginal water quality conditions than currently accepted.

Table 14. Water Quality of Georgetown Lake, 1997-1998

Key Parameters	Units	Range in Values	Colonization Potential
Conductance	uS/cm	87 - 230	High
Calcium	mg/L	9.2 - 21	Very low - low
Total Hardness	mg/L $CaCO_3$	40 - 82	Low - moderate
pH	-	7.8 - 9	High - low
Temperature	^0C	0.1 - 13.5	Very low - low
Dissolved Oxygen	mg/L	7.8 - 11.2	High

Ref: USGS 00-4109 (Water quality data)

8.2.6 Assessment of River/Steam Water Quality

Similar to the lake water quality assessment, obtaining water quality data for all the major streams in the City's watershed were beyond the scope of this project. However, water quality data were obtained for Clear Creek, which supplies the majority of the City's water. Data were available for two locations, the first location was for USGS Station 06715000, near Empire and the second, USGS Station 06719505, at Golden.

Figure B2 shows the average monthly temperature of Clear Creek at Empire for the period extending from 1994 – 2003. Superimposed on the figure are bands labeled 'Observed' and 'Favorable'. These bands indicate the range in which mussels survive. For mussels, as with all living things, there is a range in which the conditions are optimal for reproduction and growth. There is also a broader range in which mussels will survive, but the conditions are not ideal for their reproduction and growth. Outside of this broader range of conditions, mussels are unable to survive. In Figure B2 and subsequent figures, the band labeled 'Observed' indicates the range in which mussels have been observed to occur. The narrower band titled 'Favorable' is the range most conducive to their reproduction or growth.

As can be seen in Figure 17, temperature levels in Clear Creek never reach a level that is favorable for supporting a mussel infestation, although temperatures are warm enough to support breeding between July and mid-September.

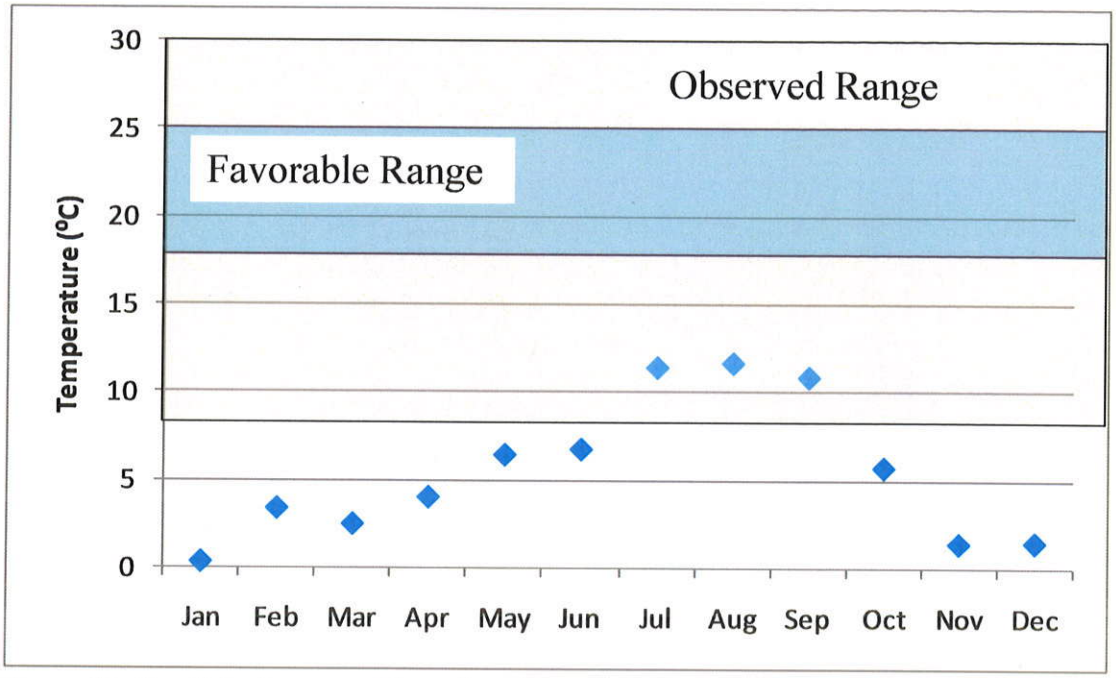

Figure 17. Monthly Average Clear Creek water temperature at Empire, 1994-2003. Superimposed on the figure are the temperature range that mussels have been observed to survive and the narrower temperature range most favorable for growth.

The average monthly temperature of Clear Creek at Golden for the period extending from 1978 – 2004 is shown in Figure 18. Monthly average water temperatures at Golden are approximately 2-3 ^{0}C warmer than at Empire. Similar to the data for Empire, Clear Creek at Golden never reaches a level that is favorable for supporting a mussel infestation. The time period suitable for breading is longer than at Empire, lasting from mid-June to late September.

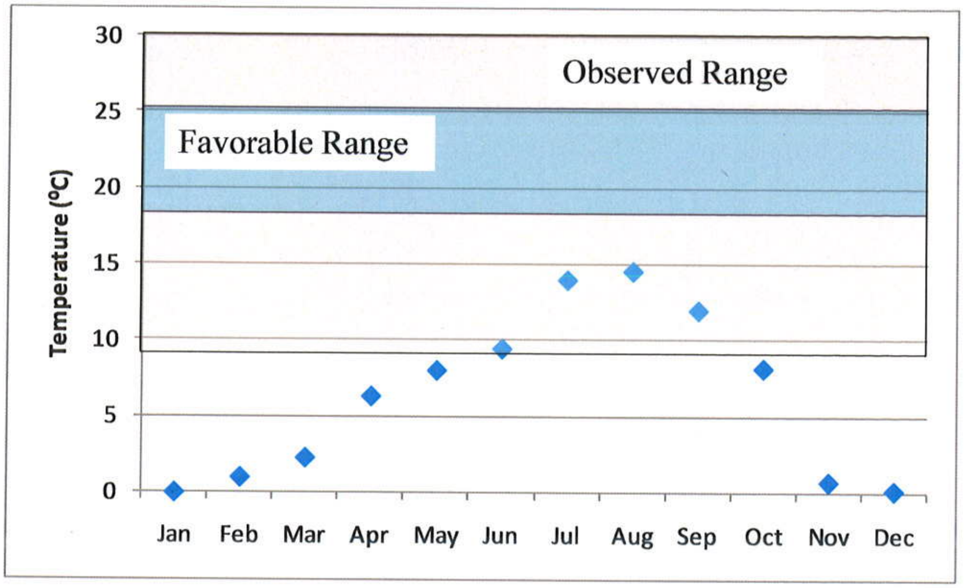

Figure 18. Monthly Average Clear Creek Water Temperature at Golden, 1978-2004.

A wide variability in calcium concentrations over the year is evident in the average monthly calcium concentration in Clear Creek at Golden (1978 – 2004) as seen in Figure 19. Calcium concentration exceeds 25 mg/L in late winter and early spring, corresponding to periods of low flow. As runoff occurs, the calcium levels drop dramatically as low mineral content snow melt dilutes the calcium contained in the base flow. In June and July calcium concentrations drop to about 10 mg/L, the minimum level of calcium needed to support a mussel population.

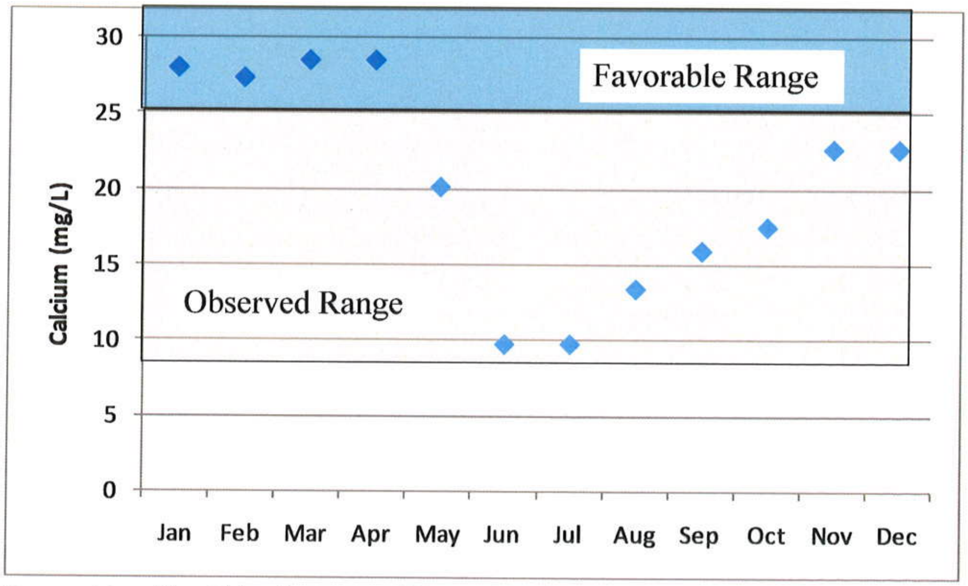

Figure 19. Monthly Average Clear Creek Water Calcium Concentrations at Golden, 1978-2004.

Comparing Figures 18 and 19, it can be seen that favorable water temperature and calcium concentration move in opposite directions, as water temperature increases, calcium level decrease and vice versa. Hence periods that are most favorable to spawning, from a temperature perspective, have a less than optimal level of calcium to support settlement and growth. Overall it appears that water quality conditions in Clear Creek are marginal for supporting a thriving population of mussels.

8.2.7 Assessment of Mussel Growth and Transport in Streams

Studies of zebra mussel infestations in Europe and the Midwestern United States have indicated that viable mussel populations are much more likely to become established in lakes or reservoirs than in rivers or streams. Studies of European river bodies have concluded that zebra mussel infestations are limited to large rivers (>30 m wide). However, infestations of smaller rivers have occurred in the Midwest, and probably exist in Europe. None the less, when populations have become established in rivers or streams, the population densities are far less in rivers or streams than in nearby infested lakes or reservoirs. Many factors are thought to play into this situation. Rivers and streams are physically, chemically and biologically more unstable than lakes and reservoirs. Shifting river beds probably provide a less desirable location for mussel settlement and growth. Water velocities in streams can easily exceed levels suitable for settlement or efficient feeding by adults. The movement of silt and suspended solids can interfere with the feeding of mature adults. Hydraulic forces and turbulence can also increase veliger mortality. All of these factors and others combine to make rivers and streams less susceptible to infestations than lakes/reservoirs.

Midwestern experience with small rivers (< 30 m wide), indicates that small rivers or streams do not develop self sustaining populations of zebra mussels. Sustained populations in small rivers are believed to be supported by what is termed a Source - Sink relationship, where an infested parent body of water (lake or reservoir – "the Source") supplies larval mussels to the stream ("the Sink"). In other words, small rivers and streams need an upstream infested lake or reservoir to maintain a population of mussels.

A key factor behind the source – sink relationship is thought to be the high rate of veliger mortality in moving water. Observations of streams fed by infested lakes have shown that the concentration of live veligers decreases exponentially with the distance down stream from the lake. It is believed that turbulence and shear in moving water is responsible for killing veligers by physically pulling them apart and damaging them due to impacting objects in the streams. Because of the exponential veliger mortality, the transport distances of live veligers is limited. In the case of Midwestern streams, the maximum distance is on the order of 10 - 20 km downstream from the source. Prediction of travel distances for live veligers in mountain streams is difficult due to their higher turbulence. On one hand, faster velocities in mountain streams will move veligers further downstream in the same time period, on the other hand, mortality from physical forces will be far greater.

Other pathways besides the release of larva from a source lake or reservoir maybe contribute to downstream infestations. The translocation of mature zebra mussels from an infested lake to an out flowing stream by attachment to aquatic plants has been shown to be an important means of transport. But the distances over which translocation can occur appears to be limited. In the case of Midwestern streams, the distance is 1 km or less.

Unfortunately, the migration of quagga or zebra mussels in mountain streams, as compared to relatively slow moving Midwest Rivers, has not been studied. (Until recently there has been no need for this type of study.) High gradient, rocky rivers with strong erosive forces are likely to be unsuitable for the establishment of thriving mussel communities. Clear Creek, S. Boulder Creek and Coal Creek possess extreme gradients and boulder filled channels which both preclude the establishment of mussel colonies and are destructive to veligers. Even if a community were to colonize in slow moving backwaters, it seems unlikely such a colony would provide a sufficient source of veligers or translocated adults to endanger downstream locations.

8.2.8 Assessment of Mussel Growth and Transport in Canals/Pipelines

A combination of canals and pipelines are used to move water from Clear Creek, S. Boulder Creek and Coal Creek to Standley Lake. Table 15 summarizes the important features of these canals/pipelines.

Table 15. Canals and Pipeline Supplying Standley Lake

Canal/Pipeline	Source Water	Inlet Location	Outlet Location	Comments
S. Boulder Feeder Canal	S. Boulder Creek	Between Gross Reservoir and Eldorado Springs	KDPL	Continues to Ralston Reservoir
Kinnear Ditch Pipe Line (KDPL)	Coal Creek	Mouth of Coal Creek Canyon	Wetlands west of Standley Lake	KDPL carries both S. Boulder Feeder Canal and Coal Creek water
	S. Boulder Feeder Canal	East of Colo 93 at Colo 72		
Church Ditch	Clear Creek	West of US 6 bridge, Golden	Standley Lake south shore, near Indiana St.	Take out from Clear Creek is upstream of Golden Whitewater Park
Farmers Highline Canal (FHL)	Clear Creek	East of Ford Street, Golden	Standley Lake south shore, near Kipling St.	Take outs from Clear Creek are downstream of Golden Whitewater

Croke Canal	Clear Creek	Near Colorado Railroad Museum	Same	Park

Unlike the mountain streams discussed in the last section, the canals and pipeline in Table 15 operate at hydraulic velocities which are more conducive to transport of viable veligers as well as their settlement and growth. If an infestation were to occur, it is more likely that it will occur in these features than in Clear Creek, Coal Creek or S. Boulder Creek proper. Unlike mountain streams, these seasonally operated canals can be taken out of service and permitted to desiccate, either killing or stressing any established mussel populations. No attempt was made to inspect these canals, but they inherently contain features which mussels can settle on. Overall, their operation would be impacted by a mussel infestation.

If an infestation were to occur, the canals/pipeline also do not pose equal risks to Standley Lake. Qualitatively the degree of risk to Standley Lake is likely to be:

FHL Canal = Croke Canal > Church Ditch > KDPL

The FHL and Croke Canals are considered to be the highest risk to Standley Lake. These canals take water out of Clear Creek down stream of the Golden Whitewater Park. The popularity of kayaking at this park represents a small, but conceivable risk for the importation of veligers or aquatic plants with attached adults. The vertical gradient of Clear Creek, while severe, is substantially less at that location than upstream. Veliger or aquatic plants with attached adults could potentially survive the relatively short distance to the takeout points for the FHL or Croke Canals, where they would enter an environment more suitable for survival and transfer to Standley Lake.

Church Ditch appears to pose a lower risk to Standley Lake than FHL and Croke Canals since it is supplied by water taken out of Clear Creek upstream of the Whitewater Park. This eliminates the Whitewater Park as a potential point of importation. As discussed above, it is considered unlikely that a sustained population can survive in Clear Creek above the mouth of Clear Creek Canyon, or that veligers could survive transport in Clear Creek from any potentially infested upstream reservoir.

The KDPL appears to pose the least risk to Standley Lake. Similar to Church Ditch, there does not appear to be a probable mussel source for this system. While Gross Reservoir was ranked as having the greatest risk of infestation of all the reservoirs evaluated, the steep gradients and extreme turbulence of S. Boulder Creek downstream of Gross Reservoir probably provides an effective barrier to the transport of live mussels or veligers. The other source carried by the KDPL, Coal Creek, is only occasionally used and highly unlikely to be infested. Lastly, the water delivered by the KDPL passes through wetlands that are likely to provide an additional barrier to the movement of mussels into Standley Lake.

8.2.9 Overall Assessment of Risk in City of Westminster's Watershed

Evaluation of overall risk of mussel infestation for each water body is related to whether there is a credible pathway for importation, suitable water quality and conditions for growth, and means of transport from point of infestation to Standley Lake. Table 16 presents a qualitative assessment of the level of risk for each of these criteria by water body for each basin in the City's watershed.

Table 16. Summary of Infestation Risk by Basin and Water Bodies

Water Body	Vulnerability to Mussel Importation	Suitability of Water Quality for Survival	Suitability of Environment for Survival	Potential for Transport to Standley
Clear Creek Basin				
Clear Creek and Tributaries				
Above mouth of canyon	Moderate	Poor – Marginal	Poor	Unlikely
Below mouth of canyon	Moderate	Marginal	Marginal	Possible
Lakes/Reservoirs	Low	Marginal	Poor - Marginal	Unlikely
Canals				
Church	Low	Marginal	Fair	Possible
FHL	Low	Marginal	Fair	Possible
Croke	Low	Marginal	Fair	Possible
Moffat/S Boulder Creek Basin				
Moffat Water, S Boulder Cr and Tributaries	Low	Poor	Poor	Unlikely
Lakes/Reservoirs				
Gross	Moderate	Marginal	Poor- Marginal	Unlikely
Others	Low	Poor – Marginal	Poor	Unlikely
Canals				
S. Boulder Feeder	Low	Marginal	Fair	Unlikely
KDPL	None	Marginal	Fair	Unlikely
Coal Creek Basin				
Coal Creek and Tributaries	Low	Poor	Poor	Unlikely

Lakes/Reservoirs	Low	Poor	Poor	Unlikely
Canals				
KDPL	None	Marginal	Fair	Unlikely

Creek Basin appears to be at risk of importation of mussels because of the excellent vehicle access to streams and water bodies in the basin as well as extensive recreational opportunities that are available. The possibility of successful colonization is low however, due to unsuitable water quality and habitat. The steep stream gradients and resulting turbulence in Clear Creek, most likely precludes survival of veligers or adult mussels swept down the creek.

The Golden Whitewater Park probably presents the greatest risk of successful importation and transport of mussels to Standley Lake. In absolute terms the risk that Whitewater Park poses to Standley Lake is low, but the risk is credible. Although Gross Reservoir is at the greatest risk for importation of mussels of all the reservoirs in the City's watersheds, the overall risk that water from the Moffat Tunnel/S. Boulder Cr water posses to Standley Lake appears to be small. This is due to the marginal water quality in Gross Reservoir for mussel survival, and two potential barriers to the transport of mussels between Gross Reservoir and Standley Lake. These barriers are the turbulent nature of S. Boulder Creek downstream of Gross Reservoir and the wetland at the terminus of the KDPL.

Water from the Coal Creek Basin poses the least risk to Standley Lake of any basin in the City's watersheds. The basin is small, recreational activities are limited, and the wetland at the terminus of the KDPL provides a barrier to the transport of mussels into Standley Lake.

8.3 Recommendations

While the conclusion of this assessment is that the City's watersheds are at a relatively low risk of infestation, there are specific actions that the City can take to reduce the risk of mussel infestations.

Promote protection of Clear Creek basin from the importation of mussels

Recreational activity in the Clear Creek Basin provides many pathways for the importation of mussels. The City should support informational and outreach activities to better inform Clear Creek users of the risks mussels' pose and methods for preventing their spread. These efforts should be performed in concert with other interested parties in the basin.

Perform in-depth assessment of risks posed by Golden Whitewater Park

Intense recreational activities at the Golden Whitewater Park provide a credible pathway for the importation of mussels. The City should more closely evaluate the actual risk of importation of mussels at the Whitewater Park and their possible colonization in the FHL or Croke Canals.

Continue to assist in monitoring of Gross Reservoir

As Gross Reservoir was identified as the reservoir most at risk upstream of Standley Lake, the City should continue to assist in monitoring Gross Reservoir for the presence of quagga or zebra mussels.

Monitor and support research into understanding the adaptability of quagga mussels to mountain environments

Overall, water quality and environmental conditions that exist in the City's watersheds above Standley Lake are marginal for the successful colonization of zebra or quagga mussels. The City should monitor and possibly support research clarifying the minimal conditions necessary for the survival of quagga mussels in low calcium, low temperature, or high flow rate environments. The City should also monitor and possibly support research into Source – Sink relationships for mussel propagation in mountain streams and irrigation canals.

These recommendations should be considered in the appropriate context. The broader context is that recreational activities on Standley Lake, particularly motorized boating, by far represents the largest and most creditable pathway for the introduction and growth of a viable population of quagga or zebra mussels in to the City of Westminster's water system. The City should consider implementing the above recommendations for reducing infestation risk in its watersheds, but its primary focus should remain on the protection of Standley Lake from infestation risks posed by recreational activities.