QUAGGA AND ZEBRA MUSSEL CONTROL STRATEGIES WORKSHOP

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April 3-4, 2008

BACKGROUND

On January 6, 2007, quagga mussels were first detected in Boulder Basin of Lake Mead. This range expansion extended the distribution of the quagga mussels from the Great Lakes and other eastern and midwestern systems to this southwestern reservoir without evidence of invasion of water bodies anywhere in between. This was the first confirmed appearance of quagga mussels in the western United States. Within two weeks of the initial report of quagga mussels in Lake Mead, divers from the Metropolitan Water District of Southern California (MWD) found them in fairly low densities (1 to 10 mussels/m^2) on the intake structure for the Colorado River Aqueduct (CRA) 150 miles downstream of Lake Mead. The subsequent spring spawn in Lake Mead produced high densities of settled mussels that have rapidly and significantly increased the population size in Boulder Basin. It is likely that the spring spawn in Lake Mohave allowed the mussels to penetrate further into the CRA. The spread of the mussels has been extremely rapid, with quaggas now detected throughout Lake Mead with mussel densities approaching 500 mussels/m^2 in Boulder Basin. Mussels are now found in several reservoirs of San Diego County, California. Recreation is being severely impacted by this invasive species as Lake Mead is a primary recreation destination for California boaters. There are more than 8 million visitors who recreate at Lake Mead National Recreation Area every year, with a majority of these visitors using the reservoirs. In the summer, the number of vessels on the water averages more than 3,000; on holiday weekends, this number rises to 5,000 vessels. Concerns developed immediately that the adult mussels would attach to the hull of watercraft, or that larval veligers would survive in the craft's ballast water, and be transported from Lake Mead and spread throughout the surface waters of California.

Zebra mussels (Dreissena polymorpha) were introduced into the North American Great Lakes in the mid-1980's by the fresh-water ballasts of transoceanic ships traveling from the Black, Caspian and Azov Seas of Eastern Europe. Although the introduction of new species into drinking water supplies does not typically result in violations of drinking water standards, zebra mussel infestations can adversely impact aquatic ecosystems. Zebra mussel infestations have severely impacted aquatic ecosystems of lakes and rivers; clogged intakes and raw water conveyance systems; reduced the recreational and aesthetic value of lakes and beaches; altered or destroyed fisheries and made lakes more susceptible to deleterious algal blooms. A related species, the quagga mussel (Dreissena bugensis), indigenous to the Dneiper River area of the Ukraine, were introduced to the Great Lakes in the late 1980's through similar means. Dreissenid mussels currently infest much of the Great Lakes Basin, the St. Lawrence Seaway, much of the Mississippi River drainage system and are extending their distribution in the mountain west. It has been estimated that between 1993 and 1999, zebra mussels cost the power industry $3.1 billion, while their impact on broader industries, businesses and communities exceeded $5 billion.

Population densities of quagga mussels typically expand exponentially and as a result they can quickly colonize and dominate new areas. In Lake Mead and the lower Colorado River, the population of quagga mussels has increased more rapidly than predicted. The mussels are distributed from the surface to depths of greater than 150 ft., with the highest densities encountered between 25–35 ft. Surveys done through July of 2007 indicated that the highest densities of quagga mussels were located at the upstream end of Black Canyon, near Hoover Dam, and downstream in the near-dam portions of Lake Mohave. The mussels are quickly expanding their range to the downstream lower Colorado River. Early detection substrates, inspected monthly at Parker Dam (Lake Havasu, downstream from Lake Mohave), did not indicate the presence of quagga mussels until July 2007. At that time they were found not only to be present, but in such large numbers that the mussels were beginning to grow attached to other mussel shells. Some individual mussels identified on the substrate were larger than would have been expected if they had settled as juveniles and grown/developed attached to the substrate, suggesting that adults were traveling or being transported between reservoirs. It appears that less than one month was necessary for the successful invasion of this location by quagga mussels. In Lake Mead, quagga mussels now make up nearly 40% of the macroscopic animal population in Boulder Basin, where none had presently been found as little as 16 months previous (January 2007).

In response to the discovery of quagga in Lake Mead, the California Department of Fish and Game (Fish and Game) created a multi-agency task force to address this issue. The initial objective of the task force was to conduct a survey of the Colorado River to ascertain the extent of the quagga colonization. Divers from Fish and Game, the National Park Service (NPS), and MWD have completed surveys of Lake Mead, Lake Mohave and Lake Havasu. Quagga mussels have been detected at low densities in all of these lakes and in the intake of the Central Arizona Project. The quagga mussels were found at depths between 35 to 40 feet. This partially explains why previous monitoring, focused on zebra mussel detection, had not detected the quagga infestation earlier. Unlike zebra mussels, quagga mussels tend to favor deeper depths and darker environments and previous surveys had not emphasized quaggas preferred habitat. MWD's divers detected quagga mussels at Whitsett Intake Pumping Plant and Gene Wash but not in Copper Basin. MWD divers and maintenance teams recently completed a preliminary survey of the CRA system and reservoirs connected to it. Quagga mussels were not detected at Lake Skinner, Diamond Valley Lake or Lake Mathews (at that time). Based on low colonization levels and the estimated age of the mussels that were detected in MWD's system, Fish and Wildlife biologists believe that the infestation in MWD's system is in its very early stages (i.e. less than one year).

Response to the first sighting of quagga mussels in Lake Mead began quickly following their discovery in the Colorado River system. The 100th Meridian Initiative, a cooperative effort between state, provincial and federal agencies to prevent the westward spread of invasive mussels, sponsored an information meeting and immediately made their website available as an information clearing house. Under the leadership of the NPS Lake Mead National Recreation Area (LMNRA), efforts began immediately to further assess the extent of the invasion. While the jurisdiction of the NPS is limited to the LMNRA, which includes only Lakes Mead and Mohave and the connecting Colorado River, their monitoring and detection template was used in formulating a plan for the broader geographic region. NPS divers performed inspections throughout Lake Mead and Lake Mohave, a Science Advisory Board was created to guide the response and a detailed report, "Lake Mead National Recreation Area Quagga Mussel Initial

Response Plan" was prepared. The California Science Advisory Panel issued a report titled "Report on Zebra/Quagga Mussel Invasion in the West." The report states it is "…critical that aggressive, concerted efforts be undertaken immediately to eradicate, contain and monitor zebra mussel infestation in the lower Colorado River." Response to this report and decisions concerning the actions that are to be taken are pending at this time.

Assessments carried out in Nevada in January through March 2007 focused on characterizing the distribution and density of the population(s) to guide an immediate response. Diver surveys throughout Lakes Mead, Mohave and Havasu were completed and quantitative monitoring at nine transects was implemented. Artificial substrate sampling devices have been installed at seven additional sites in order to evaluate colonization and settling of quagga mussel veligers. Veliger counts are occurring monthly at four sites in Lake Mead, one each basin and four sites in Lake Mohave.

More than 80% of the water used in the Las Vegas Valley is obtained from Lake Mead. The Southern Nevada Water Authority (SNWA) pumping plant was drawing approximately 330 million gallons per day when veliger samples were collected. By simple mathematical extension, more than 750 million veligers per day were being pumped through the plant in March 2007, and more than 30 billion veligers per day two months later in May. Calculations based on surface water samples indicate that there were over 27 trillion veligers in Boulder Basin during this time. Investigations into the age of quaggas present in the system suggest that the main invasion of Lake Mead likely occurred in 2003 or 2004. The age structure also suggests that the population is currently undergoing the rapid increase and range expansion associated with invasive species.

The quagga mussel has become the most serious non-indigenous biofouling pest ever to be introduced into North American freshwater systems. It has the ability to tolerate a wide range of environmental conditions, is extremely adaptable and has very high growth and reproductive rates. It has the potential to significantly alter the ecosystem of any body of water it invades and to degrade water delivery systems that it enters. It has been broadly stated that the invasion of the lower Colorado River is a "giant experiment" as these are the first large reservoir systems invaded by quagga mussels. Experts predict that in this system there will be an explosive growth of the quagga mussel population and depletion of the natural food resources currently being utilized by endemic zooplankton. The negative impact on the zooplankton community is predicted to cause a complete disruption of fishery resources (including endangered species) in the three reservoirs as the established food chain is altered. The quaggas are also expected to result in the replacement of desirable forms of algae/phytoplankton by less desirable forms. Filamentous and gelatinous blue-green algae will dominate the deeper portions of the reservoirs as their growth forms are more resistant to consumption. Simultaneously, there will be an accumulation of large quantities of quagga mussel pseudofeces at the sediment surface which can adversely affect water chemistry, create an inhospitable environment for other aquatic organisms and threaten the quality of the reservoir as a drinking water source. Complete incrustation by mussels of the bottom of the lake, rock walls and any other hard structures in Lake Mead (including water supply intakes and related structures) is predicted to occur in the years following invasion. These high population densities can transform the shoreline into thick rows of dead shells and will require increased and continuing maintenance of structures in and around the lake, marinas, docks and watercraft that are in contact with the water.

The majority of research conducted on mussel infestations and their impacts has been specific to zebra mussels with much less emphasis on quagga mussels. While the two species have many similar characteristics, existing research does not provide reliable information to predict the potential impacts of the current infestation in the Colorado River system or on the water suppliers that draw from this system. What is apparent, even at this early date, is that the quagga invasion is proceeding at a more rapid pace than was experienced in the eastern United States. As a result, water managers have had little advanced notice prior to experiencing serious system impacts.

OVERVIEW AND OBJECTIVE

The Southern Nevada Water Authority (SNWA) and the Metropolitan Water District of Southern California (MWD) received grant funding from the American Water Works Association Research Foundation (AwwaRF) to host a workshop to explore strategies for responding to the presence of quagga mussels in the lower Colorado River. A facilitated two-day workshop was held April 3-4, 2008 in Las Vegas, Nevada, and was attended by approximately 140 people.

The objective was to organize a workshop on quagga mussels involving individuals with direct experience using all of the available control methods, a diverse array of stakeholders, and to provide a forum for a focused exchange of ideas, opinions, research results, technical approaches, applications and future perspectives to technologies and strategies for controlling quagga mussels in water conveyance systems and in source waters used for drinking water, such as rivers, lakes or reservoirs. Workshop attendants discussed information and data gaps, research priorities and implications for “real world” application of quagga mussel control. The workshop involved invited participants with expertise in: current state-of-knowledge on water system protection, exploratory approaches for water system protection, protection and management of lakes and reservoirs prior to and after mussel infestation, management of large natural systems (rivers and lakes), statistical analysis and sampling strategies, ecological and population dynamics and biology of invasive mussels. The overall workshop approach can be found in Figure 1.

The intended goal of the workshop was to utilize suggestions and information exchanged at the conference to develop a report that captures important issues and stakeholder concerns regarding quagga information needs. This report will identify research needs to address invasive mussel control in the Southwest.

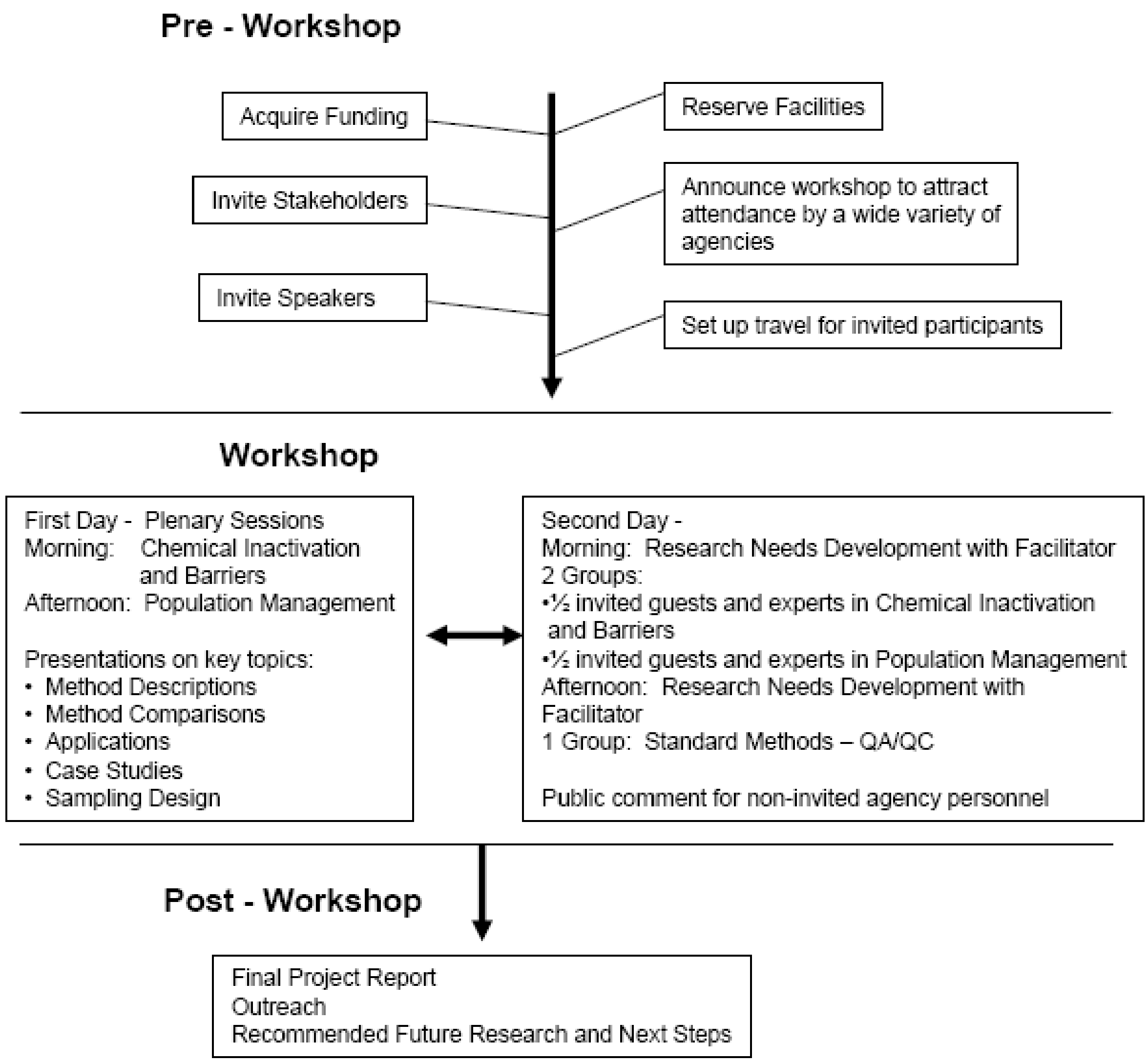

Figure 1: Workshop Approach

WORKSHOP ORGANIZATION

The core of the workshop was a group of 32 invited participants (Table 1) representing a variety of stakeholders, government agencies, academicians, water professionals and limnology and ecological scientists. This panel was made up of individuals with direct experience of invasive mussel management in water systems and in natural systems (lakes and rivers), water industry regulations, water system operations, statistics and ecological sampling as well as limnology and water quality issues. The experts were divided into two groups, Chemical Inactivation and Barriers and Population Management.

Table 1: Workshop Invited Participants

Name	Affiliation
Chemical Inactivation and Barriers	
Renata Claudi	RNT Consulting
Thomas Prescott	RNT Consulting
John Van Benschoten	State University of New York
Everett Laney	U.S. Corps of Engineers
Gerald Mackie	University of Guelph
Fred Nibling	U.S. Bureau of Reclamation
Dan Young	Central Arizona Project
Brian Moorehead	Salt River Project
Lisa Prus	San Diego County Water Authority
Ron Huntsinger	East Bay Municipal Utility District
Ronald Zegers	Southern Nevada Water Authority
Leonard Willit	U.S. Bureau of Reclamation
Douglas Ball	Los Angeles Department of Water and Power
Michael Remington	Imperial Irrigation District
Richard Volpe	Santa Clara Valley Water District
Tom Simpson	City of Aurora
Population Management	
Peter Fong	Gettysberg College
David Britton	U.S. Fish and Wildlife Service
James L. Grazio	Pennsylvania Department of Environmental Protection
Thomas Horvath	State University of New York
Ricardo DeLeon	Metropolitan Water District of Southern California
Michael Anderson	University of California Riverside
Monica Swartz	Coachella Water District
Jon Sjoberg	Nevada Division of Wildlife
Evan Freeman	Utah Division of Wildlife Resources
Kent Turner	National Park Service
Ron Smith	U.S. Fish and Wildlife Service
Gary Hansen	Colorado River Tribes
Larry Riley	Arizona Fish and Game
Susan Ellis	California Fish and Game
Robert Brownwood	Tulsa Metropolitan Utility Authority
Chris Holdren	U.S. Bureau of Reclamation

The workshop took place over a two-day period. The first day was made up of a morning and afternoon plenary session and ended with a summary and assignments for the second day (Table 2). Experts from the U.S. and Canada with experience managing and researching zebra and quagga mussel populations provided presentations on mussel treatment and control, water system protection and natural water ecosystem protection. Presentations were limited to approximately twenty minutes each to allow time for a number of presenters. The presentations were facilitated and the facilitator highlighted areas of commonality as an introduction to April 4th's proceedings.

On the second day, workgroups focused on exchange of ideas and identification of future needs for technologies and control strategies regarding the presence of quagga mussels in water conveyance systems, and in source waters including rivers, lakes and reservoirs.

During the morning sessions, two workgroups were established to address Population Management and Chemical Inactivation and Barriers. Each workgroup was comprised of approximately eight expert speakers and eight invited stakeholders from the lower Colorado River region. Facilitators worked with the respective groups to solicit dialogue and interaction among group members, ensuring all perspectives had an opportunity to be heard and considered. As needed, they suggested appropriate process tools to assist the committee members in various aspects of their deliberations.

Following initial discussions, the facilitators guided the groups through brainstorming and prioritizing exercises to identify the primary needs for research funding among the attending stakeholders. Several priorities discussed were then further developed into research briefs.

During the afternoon session, members from the earlier workgroups reported on their respective discussions. The facilitator then moderated a discussion among the combined group to identify research needs in the area of Standard Methods. The research briefs developed by the group will be used to create a foundation for obtaining necessary funding to complete research required to develop full management plans.

Opportunities were provided during the plenary sessions and breakout groups for input, questions and concerns to be expressed by all attendees to ensure that maximum stakeholder input is captured. Time for public comment was included in each day.

Table 2: Workshop Schedule

Day 1 Plenary Session — Proposed speaker

7:30 – 8:00	Continental breakfast	
8:00 - 8:05	AwwaRF Welcome	Rick Karlin
8:05 – 8:15	Introductions, Logistics and Workshop Objectives	Lewis Michaelson Ronald Zegers
8:15 – 8:45	Background on Quagga/Zebra Mussels in the West	Ricardo De Leon
8:45 – 9:15	Expert #1 - Control and Disinfection - Optimizing Chemical Disinfections	Gerald Mackie
9:15 – 9:45	Expert #2 – Control and disinfection	John Van Benschoten
9:45 – 10:15	Expert #3 - Freshwater Bivalve infestations; Risks to Assets and Available Control Options	Renata Claudi
10:15 – 10:30	Break	
10:30 – 11:00	Expert #4 – Dreissenid Mussel Control for Large Flow, Once Through Systems	Thomas Prescott

11:00 – 11:30	Expert #5 – Dreissenas in Warm Water	Everett Laney
11:30 – 12:00	Expert #6 – Case Study	Fred Nibling
12:00 – 13:00	Lunch	
13:00 – 13:30	Expert #7 – Reproductive Patterns	Peter Fong
13:30 – 14:00	Expert #8 – Population Behavior	David Britton
14:00 – 14:30	Expert #9 – Population Tracking and Monitoring Methods in Lakes	David Britton
14:30 – 15:00	Expert #10 – Role of Modeling in Assessment and Management of Quagga Mussels	Michael Anderson
15:00 – 15:15	Break	
15:15 – 15:45	Expert #11 – Case Study	James Grazio
15:45 – 16:15	Expert #12 – Case Study	Thomas Horvath
16:15 – 16:30	Public Comment	
16:30 – 17:00	Wrap up Ground Rules for Breakout Groups	Lewis Michaelson

Day 2 Plenary Session

7:30 – 8:00	Continental breakfast	
8:00 – 8:30	Outline of Workshop Process, Summary of Previous Day, Workshop Objectives	Lewis Michaelson
8:30 – 10:00	Workgroup 1 – Chemical Inactivation and Barriers Workgroup 2 – Population Management Brainstorming	Lewis Michaelson Laura Lorber
10:00 – 10:15	Break	
10:15 – 12:00	Workgroup 1 – Chemical Inactivation and Barriers Workgroup 2 – Population Management Defining Issues	Lewis Michaelson Laura Lorber
12:00 – 13:00	Lunch	
13:00 – 14:00	Workgroup 1 – Chemical Inactivation and Barriers Workgroup 2 – Population Management AwwaRF Project Development	Lewis Michaelson Laura Lorber
14:00 – 14:20	Break	
14:20 – 14:40	Reports	Lewis Michaelson Laura Lorber
14:40 – 15:00	Public Comment	
15:00 – 16:30	Workgroup 3 – Standard Methods, QA/QC	Lewis Michaelson
16:30 – 17:00	Workgroup reports	Lewis Michaelson
17:00 – 17:15	Workshop summary	Lewis Michaelson

Each workgroup had a designated facilitator charged with leading the discussion, ensuring that all workgroup members adhered to the ground rules and ensuring that all of the specific questions were addressed, along with any other relevant issues that were raised during the workgroup sessions. The roles and responsibilities of workgroup members are described in Figure 2 and the conventional problem solving model that was used for the workgroups can be found in Figure 3. While it was important to specify objectives for the workgroup process, in the form of specific issues to be addressed, the facilitators maintained sufficient flexibility to allow the discussion to stray from specific questions if it appeared that the diversion would be productive to the overall workshop goals. Too often, scientific discussions that are too rigidly constrained falter and fail to yield productive information or recommendations. Each workgroup also had an assigned reporteur responsible for capturing all of the elements of the discussion between participants as well as the input of non-invited stakeholders. The facilitators used flip charts and compiled notes taken by other workgroup members to capture the discussion. In addition, all workgroup sessions were recorded to ensure that no elements of the discussion were overlooked. Non-invited attendees were free to rove between workgroups although there were assigned time slots for input into the workgroup process.

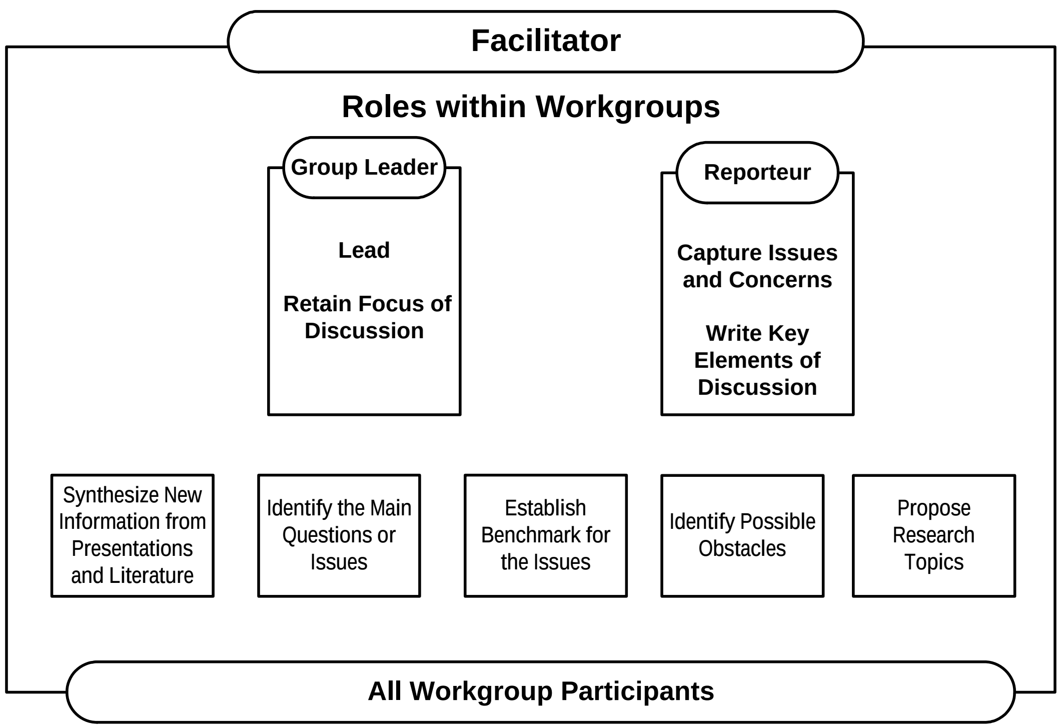

Figure 2: Roles and Responsibilities of Workgroup

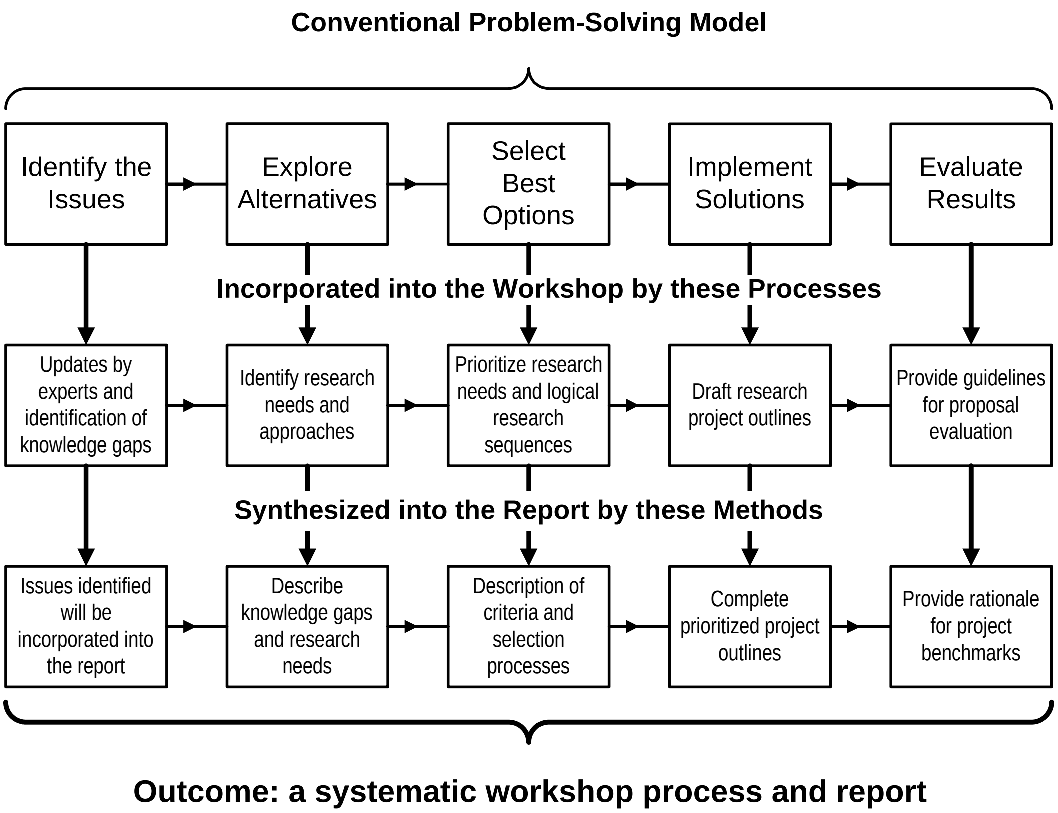

Figure 3: Conventional Problem Solving Model

LOCATION

The workshop was located in Henderson, Nevada. The Day 1 Plenary Session was held at the Sunset Station Hotel - Casino. Out of town attendees had the option of staying at the hotel. The Day 2 Breakout Sessions were held at Southern Nevada Water Authority's River Mountains Water Treatment Facility. The facility has five large conference rooms.

WORKSHOP PROCEEDINGS – THURSDAY, APRIL 3, 2008

AwwaRF Welcome

Rick Karlin

The Awwa Research Foundation (AwwaRF) started the conference by explaining the importance of the quagga mussel workshop. The western states were commended for their proactive approach in disseminating quagga mussel information and their determination to prevent further spread.

AwwaRF is a member-supported, international nonprofit organization that sponsors research to enable water utilities, public health agencies and other professionals to provide safe and affordable drinking water to consumers. With more than 900 subscriber members in the U.S.

and abroad, AwwaRF has funded and managed more than 1,000 research projects to help water suppliers anticipate and effectively deal with emerging issues and regulations. More information on the Awwa Research Foundation is available at www.AwwaRF.org.

Introductions, Logistics, and Workshop Objectives

Lewis Michaelson and Ronald Zegers

The main goal of the workshop was to identify research needs for three main areas: chemical inactivation and barriers for quagga mussels, population management of quagga mussels and development of standard methods for quagga mussel detection. General housekeeping of the meeting was discussed, which included break times, lunch, and restroom locations. The speakers also let the audience know that the National Park Service had brought a boat that was infested with quagga mussels. The Southern Nevada Water Authority (SNWA) shared their experience with quagga mussel control. They implemented chlorination before the treatment process to control quagga mussel growth in the drinking water infrastructure. This addition had a negative impact on the total trihalomethane concentration leaving the treatment plant and a positive impact on the amount of bromate produced in the treatment plant. Bromate is a disinfection byproduct of ozonation, which is used by SNWA. The logistics for the second day were discussed and then the presenters introduced the first speaker for some general background about the quagga mussel.

Expert #1 - Background on Quagga/Zebra Mussels in the West

Ricardo De Leon

The presentation began by playing a movie clip of adult quagga mussels in a Petri dish. The video showed live mussels filtering water and moving in the Petri dish. The conference attendees were very interested to see how the mussels moved.

After the video clip was completed, background information on the origin of quagga mussels in the southwestern United States was shared. The first discovery of quagga mussels in Lake Mead was on January 6, 2007. The quagga mussels spread to four western states between January and September 2007. A time line was provided that showed in January, quagga mussels were present around the Metropolitan Water District of Southern California (MWD) intake on Lake Havasu, but not confirmed further downstream. In March, they were detected at Colorado River mile marker 21 and by July, quagga mussels had been identified all the way downstream in the Colorado River. Veliger densities increased rapidly in Lake Mead and Lake Mohave between May and July of 2007. Pictures of concrete blocks, floating plastic bottles, PVC coupons and rocks were shown to demonstrate how well the quagga mussels can attach to most surfaces. A picture of 41 quagga mussels growing on top of an Asian clam demonstrates how detrimental quagga mussels can be to other species. The quagga mussels that were removed from the shell represented five different classes, likely correlating to five separate spawning events.

There are some MWD facilities that are at a higher risk of being colonized. Some of the structures at risk are trash racks, idle pipelines, cooling lines, surge chambers, four inch drain pipes, siphons and sand traps.

Settlement of quagga mussels on Hoover Dam Intake tower has already occurred down to 67 ft, but very few have been growing at lower depths. Quagga mussels can change lake dynamics by completely covering the benthic region with shells. The rapid growth and reproduction was illustrated from a picture of a fully colonized substrate sampler that had been retrieved after three months. A movie from divers taken in March of 2007 at Lake Havasu, shows mussel colonization on the intake and a covering of the lake bottom.

Many lakes in California are just being discovered with new infestations, including Lakes Murray, Miramar and El Capitan. Quagga mussels have been detected throughout the Colorado River.

Expert #2 - Control and Disinfection - Optimizing Chemical Disinfections

Gerald Mackie

The second presentation was on control and disinfection of mussels by optimizing the use of chemicals. Timing is key to the process and it is influenced by biotic and abiotic variables. Key biotic variables for infestation include adult filtration rates, body condition, number of generations and factors that affect the larval and adult densities. Abiotic variables include Ca, pH, alkalinity, conductivity, temperature and Secchi depth.

Optimizing the use of chemicals is important for timing the biology of the mussels to the seasonal toxicity of the control agent. Using the biotic and abiotic variables to monitor the conditions that affect the mussels will provide the best guide to determine when to use chemicals. Secchi depth is the cheapest and easiest of these predictor variables and calcium is the most widely used. Seasonal variations in surface temperature are easy to measure and conductivity is useful for estimating some other variables. Reproduction occurs when temperatures reach 12-15 ^{o}C and the rate of larval development increases as water temperature increases. Monitoring the development of the larvae will determine when settlement of veligers begins and ends. The life cycle is one aspect of the biotic factors that can be monitored in order to target chemical treatment.

Graphs of larval densities were shown demonstrating that there are usually rapid increases in density between June and August. After peaking in August, the larval densities decline through December. Adult densities peak between August and September and body condition increases from January to July, with the peak being in April. Adult filtration rates peak between June and July.

The seasonal effectiveness of molluscicides was discussed to illustrate the best and worst times to use various chemicals. Results from three molluscicides were presented to show that different chemicals are more effective at different times of the year. It is important to know the periods of the mussel’s life cycle in order to target toxicity to the most effective time of the year for a given chemical application. The most effective applications avoid using toxins when the mussels are the most fit and when the seasonal effectiveness is limited.

Control strategies for the western states should be modified when using molluscicides. As the water is warmer in the southwest compared to the northern states, the timing will need to be adjusted depending on the water temperature. There is not a single strategy that can be used for treatment with molluscicides. It is important to monitor the abiotic and biotic factors of the system and to understand the limitations of the chemicals involved.

Expert #3 - Control and Disinfection

John Van Benschoten

The third presentation of the morning provided information on controlling Dreissenid mussels using chemical oxidants. The presentation began by detailing some of the known facts about mussel infestations. Quagga mussels have been shown to displace zebra mussels in the lower Great Lakes.

Water intakes are an ideal environment for mussels to inhabit. There are some common control strategies that have been used to prevent or limit infestations. If the intakes have been colonized, an oxidant should be used to kill live mussels. If there are no adults present, then the focus should be to prevent settling of veligers. Most of the known control measures used on zebra mussels should be equally effective with quagga mussels. Even with stringent control measures, some structures may require additional periodic cleaning.

In the Great Lakes, veligers are present in the spring when water temperature reach 10-15 °C. In the fall, veligers continue to persist at low temperatures, but in lower numbers. Veliger densities from the Niagara River were compared and have shown a trend of decreased veliger densities over the past twelve years. It is speculated that this decrease has been a result of the impact of another invasive species, the Round Goby.

In an experiment in 1993, the effectiveness of chlorine, ozone and hydrogen peroxide were tested for their effectiveness in removing veligers from the water column. The results indicated that ozone and chlorine doses greater than 0.1 mg L^{-1} produced a 97% reduction in veliger numbers. Greater removal did not occur at higher doses due to a threshold phenomenon inducing a behavioral response. Hydrogen peroxide was shown to be effective only at high doses, which made this option unfeasible due to cost.

Claudi and Mackie (1994) showed that continuous chlorination did not kill veligers, but prevented them from attaching. Klerks et al. (1993) reported high mortalities of veligers that were exposed to chlorine concentrations between 0.5 and 2.5 mg L^{-1} for two hours. Chlorination can also be useful for adult zebra mussels, with disinfection being a function of contact time, chlorine concentration and water temperature.

An update on plant practices to prevent mussel infestation was provided detailing the activities of nine plants and the oxidants they use. Many of the facilities use oxidants, intermittent chlorine and low levels of permanganate. Oxidants are successful in controlling veligers and adult mussels. Chlorine and ozone are most effective against veligers while hydrogen peroxide and permanganate are less effective. Adults are also successfully eliminated with the use of chlorine and ozone. The control of adult mussels depends on dose, temperature and contact time. It is believed that these strategies for zebra mussels should be effective for quagga mussels.

Expert #4 - Freshwater Bivalve Infestations; Risks to Assets and Available Control Options

Renata Claudi

The fourth presentation of the day addressed risks to assets and available control options for fresh water bivalve infestations. The presentation begins by describing the physiochemical factors that are required for mussels: water temperature less than 29 °C, calcium greater than 15 mg/L, dissolved oxygen greater than 3 mg/L, pH between 7.2 and 9.6, salinity less than 5 ppt and water velocity below 6 ft per sec. Invasive mussels are transferred through recreational boating, aquaculture transfers, pet trade, live bait, live food releases and water ways.

Risks associated with mussel infestations include decreased flow through infrastructure, clogging of essential systems and increased corrosion. Systems that are at risk are external structures and internal piping exposed to raw water that contains veligers or adults. A continuous flow above 6 ft per sec is needed to prevent settlement. Structures that are at risk are intake structures, cooling water systems and civil structures such as locks and dams. During the mussel breeding season, structures that come in contact with large volumes of water are at risk for settlement. Loss of flow can occur through mussel settlement due to increases in friction. Eventually as more shells accumulate, clogging can become a problem.

Fire prevention systems are vulnerable to becoming fouled if strainers are not incorporated into the system. If water in the system is stagnant, then dissolved oxygen levels could fall below 3 mg/L and prevent mussels from surviving. Instrumentation should also be evaluated if it comes in contact with raw water. One example shown was a picture of a thrust bearing sight glass that had mussel growth on the inside of the valve. Level gauges could also pose the same types of colonization risks.

Civil structures that are in contact with raw water can also accumulate mussels. Possible structures at risk include: fire hydrants, irrigation systems, buoys, dams and bridge footings in dams. Structures that are metal can become corroded through the actions of mussels, which could accelerate physical damage.

Ecosystems can undergo significant changes from a mussel infestation. Change in water clarity and removal of particulate matter can occur through mussel filtration. The increased clarity can result in increased rooted vegetation and altered fish habitat. Other species that depend on zooplankton may crash from the removal of planktonic algae by mussels. Increased blue-green algae and taste and odor issues associated with them could also occur as a result of a mussel invasion.

There are two approaches to minimizing mussel fouling. The proactive approach does not allow growth of mussels in a system at all. The reactive approach allows mussels to grow in the system, but subsequently the established populations are periodically treated. When evaluating which approach to use, it is important to decide what level of infestation is tolerable for various parts of the system. If there is a danger of blockage, what are the consequences in terms of economic and safety issues? What will your customers say about a blockage? What will regulators say about your treatment choices? What is your operational preference? When trying to answer these questions it is important to know that not all treatment facilities are the same.

Structures that are in direct contact with the external environment can be approached in two different ways. The reactive approach would be to mechanically clean after infestation by power washing or scraping the mussels from the surface. The proactive approach would be to use antifouling coatings to prevent settlement and colonization. These coatings are reported to last five to seven years and some have not been approved by the EPA. There have been many new formulations brought to the market that cost between $10-40 per sq foot. Unfortunately, tests have shown many of these coatings begin to fail after 12 to 18 months. Examples were shown of *Bioclean* that corroded after four years and copper/beryllium which fouled after two years.

The reactive approach for internal piping involves thermal washing, mechanical cleaning, flushing with weak acids and oxygen deprivation. Non-oxidation and oxidation chemical treatments can be used as a treatment for internal pipes. The proactive solutions for internal pipes include sand/media filtration and mechanical filtration of particles greater than 40 microns. Some situations can make the use of filters difficult. The TSS load in the incoming water and particle size distribution of the TSS needs to be evaluated with regard to filter treatments. Another proactive option for internal piping systems is the use of ultraviolet light (UV) treatment. Before UV is considered as an option, factors that should be considered are the color, hardness, presence of iron and the TSS of the water. The use of low concentrations of oxidizing chemicals as a proactive approach can also be utilized. The chemicals can be added continuously or semi-continuously throughout the mussel breeding season to prevent settlement of veligers. At the Ontario Power Generation Facility, ozone is used as a proactive approach. Ozone is continuously added at 0.03 mg/L during the breeding season. Chlorine is also used continuously at 0.3-0.5 mg/L at the downstream end of the treatment system. Some suggestions for control include installing a rapid response option that can be used if settlement or shells increase dramatically. This can include portable chlorine skids, thermal treatment, weak acids to dissolve shells and cleaning as system performance deteriorates. When determining a long-term strategy, the vulnerabilities of the system and possible approaches need to be determined.

Long-term control strategies could include using thermal treatments when possible. Coatings should be utilized to minimize the need for mechanical cleaning and chemical treatments. Installation of self-cleaning strainers could be used to protect piping from shell debris.

In summary, the characteristics of the mussel in this environment are unknown at this point. It is important to monitor and manage the mussel populations and to know their breeding and growing cycles. Facilities and locations need be evaluated for risks so that control options can be evaluated for feasibility vs. operational preference vs. risk. The best choice of treatment should be based on a combination of regulatory, economic and operational consideration.

The next portion of the presentation discussed monitoring techniques. It is essential to monitor to determine if mussel invasion has occurred, the size of populations, the timing of larval production and settling patterns. One method of monitoring is to focus on the planktonic stages using plankton tows. Plankton tows are an easy way to establish presence or absence of veligers, and they can also be used to determine the beginning and end of the breeding season. One concentration method for veliger counting utilizes large samples and processes them with "density separation" using a sugar solution. The more dense veligers separate from less dense organisms and detritus.

Samples can be taken to perform actual veliger counts for incoming water, but counting is tedious and offers limited insight. Settlement monitoring is the best return on investment as it most closely assesses the actual risk of infestation to infrastructure.

Public awareness programs should be used to prevent the spread of mussels. Working with boaters, hobbyists and anglers can be useful in spreading information to the public. Surveys show that a high percentage of people who have been educated on mussels took precautions to prevent invasive species. The presentation was ended by showing pictures of equipment that had been fully infested with quagga and zebra mussels.

Expert #5 - Dreissenid Mussel Control for Large Flow, Once Through Systems

Thomas Prescott

The fifth presentation covered Dreissenid mussel control for large flow, once through systems. On the Great Lakes, facilities use several methods to control mussels. Preventative chlorine and periodic treatments of proprietary chemicals are used to treat the piping systems. Mechanical cleaning is used on external structures. Other alternatives are being considered because chemicals have environmental risks and the regulatory requirements to use chemicals are extensive. Other technologies that look promising include fine pore filtration, UV light and ozone.

Sites that are considering filtration need a sufficient sized room for the filter pump house. Variations in water quality at the site may challenge the filter. A picture was shown of Nanticoke GS on Lake Erie and the experience using filters at this site was discussed. The system includes a 6 foot diameter self-cleaning filter with a bypass loop for filter maintenance. Several photos on the installed filter were shown. There are two sample panels installed on the inlet and outlet of the filter. Turbidity, pH, conductivity, dissolved oxygen and temperature are all monitored. The filter was tested between 315 to 380 L/sec. The filter operated well when inlet water was below 15 ppm TSS however, when the TSS was high (60 ppm) the backwash system was ineffective. Tests showed that there was greater than 90% veliger removal and most of the surviving veligers were seriously injured. This experiment produced several important insights: the filter requires a large space be available to retrofit older plants, the filter is prone to clogging during periods with high TSS concentrations, and silt load and particle sizes should be quantified to assess the feasibility of this method.

Ultraviolet treatment was also tested in December 1999. Unfortunately, the equipment was plagued with operational problems; lamp trips, leaks and failing tubes. The lamps were able to reduce veligers by 85%, but the costs were higher than chlorine and once per year chemical treatment would still be necessary to effectively remove any mussel settlement that occurred from mussels that manage to pass through the UV lights uninjured.

Intermittent ozone was tested on Bruce Power Plant A on Lake Huron. Ozone was used in two intervals per day injecting 1 kg of ozone for five minutes. Tests have shown that intermittent ozone use is as effective as continuous addition. The tests showed that intermittent treatment had the advantages of lower costs and a smaller footprint for the required equipment. A MABOS (Mitsubishi Anti-Biofouling Ozonation) System can be used, which will allow ozone generation to accumulate in a gel-filled tower that can be injected twice a day into the water system. Ozone usage had a few noticeable negative issues of corrosion and degradation of equipment, compliance of discharge limits and ozone offgassing. The results of intermittent testing showed that some veligers were able to settle between ozonation, but 100% mortality was experienced after subsequent exposures to ozone. Live juvenile and adult mussels in side stream samplers became detached once ozone was applied. The initial capital costs are the biggest factor to consider, but once installed the operational costs are low. The use of intermittent ozone produced 100% control of zebra mussels.

Another ozone design was shown from Lennox GS. This station uses continuous ozone through a service water pump house. Ozone is injected into an open inlet channel where the channel enters the pump house to achieve concentrations between 50-80 ppb. The results showed greater than a 98% reduction in settlement of veligers in the piping system at 50 ppb. All settled mussels died, and cleaning of the cooling piping and components has been reduced dramatically. The portion of the open inlet channel inside the pump house was capped to eliminate any offgassing issues in the pump house. Off-gas management within the power station building at service water drains was the most significant safety concern encountered. The system is still in service and is within compliance of discharge limits.

Expert #6 - Dreissena's in Warm Water

Everett Laney

The sixth presentation described *Dreissena*'s in warm water. The presentation began by explaining that quagga mussels were historically thought to be a cold water species, but now are known to be very successful in warm water environments. A map of the United States was used to show the distribution of zebra and quagga mussels. There has been an abundance of zebra mussel sightings in the northeast and quagga mussel sightings along the lower Colorado River. A map of the Tulsa District in Oklahoma showed that zebra mussels have spread to most major lakes and water supplies. A mussel native to Oklahoma was shown with zebra mussels growing all over the shell. At Oologah Lake in Tulsa, there is such an abundance of zebra mussel shells on some of the shorelines that it prevents recreational visitors from making use of the areas.

One problem encountered at Corps of Engineers facilities is shells clogging the navigation pumps when water is greater than 30 ºC. Several pictures of water pumping equipment that were completely clogged with zebra mussels were shown. A timeline of El Dorado Lake in Kansas detailed the increase of zebra mussels from 50 to 25,178 per square meter in one year since the infestation was discovered. One attempt to kill the mussels included a three foot draw down of the water level in the lake. Exposed mussels were killed, but there was no affect on the mussels deeper in the water.

A study at the McClellan–Kerr Navigation System by Dr. Jim Schooley, Northeastern State University (1994) showed that the ranges for conductivity and calcium should support moderate to good growth at most lakes in the region. The study also documented that zebra mussels grew 1.19-1.25 mm/week. Zebra mussel growth rates were slower in late summer than early summer, possibly due to differences in water chemistry at the sites and high temperatures limiting growth near the end of summer. Veliger numbers declined rapidly starting in June as water temperatures increased.

Another study from University of Arlington showed that mussels do spawn all summer long if the temperature remains below 30 ºC, and some can spawn above 30 ºC and survive several weeks above this threshold temperature. The mussels are genetically diverse and could possibly adapt to warmer waters in the future.

Zebra mussels are more tolerant of warm water than initially thought and will continue to be a nuisance for many areas. Mussel survivors could produce more warm-water tolerant offspring, which could help increase population sizes further. The U.S. Army Corps of Engineers Tulsa District program will include monitoring, reproduction, adaptation and water tolerant studies in the future.

Expert #7 - Case Study

Fred Nibling

The seventh presentation dealt with a Bureau of Reclamation (Reclamation) case study about the threat of Dreissenid mussels to water systems in the western United States. The presentation began by showing a current United States distribution map that marked the locations of zebra and quagga mussel infestations. The map showed that both Lake Mead and Lake Havasu are infested with quagga mussels. The next slide showed the distribution of Reclamation regions in the western United States, splitting the Colorado River into upper and lower Colorado regions. Reclamation delivers 10 trillion gallons of water to more than 31 million people every year, and is the second largest producer of hydroelectric power in the west. Some of the assets Reclamation manages include miles of diversions, tunnels and pumping plants. Mussels have created several types of problems for these assets across the western states.

One problem has been flow restriction. Quagga and zebra mussels have byssal threads that mussels use to attach to surfaces. Once the mussels are attached, they can be extremely difficult to remove. When mussels attach, flow is decreased due to an increase in friction (roughening) within the pipe. If mussels continue to attach to the pipe the result can be complete blockage. A few slides were shown of pipes, trash racks and intake screens that were completely infested with mussels. Corrosion or chemical degradation is another problem that can result from mussel infestations. When mussels are present in high densities, they release large amounts of pseudofeces which produce bacterial colonies that support corrosive conditions.

Mussel infestations can also impact biological and environmental conditions. Beaches at Lake Michigan have been covered in zebra mussel shells which limit recreation, and mussels can coat surface bottoms that once were catfish habitat.

A diagram of the life cycle of the mussel was presented with control strategies also diagrammed. The proactive strategy or preventative measures focus on the planktonic stages while the reactive approach mainly focuses on the adult stages. The reactive approach includes cleaning of fouled equipment or redesigning equipment to prevent settlement. Some available control methods were listed including chemical treatments, mechanical cleaning, filtration, biological controls, repellants and environmental manipulation. A list of substrate preferences of mussels were discussed; copper, galvanized iron and aluminum are some of the least preferred substrates while stainless steel, polypropylene and asbestos were preferred.

There are many components of a water delivery system that can be compromised by a mussel infestation. A diagram of an irrigation delivery system was shown that highlighted some of the areas which have structures that may be sensitive to mussel infestation. Some examples are the main canal headworks, canal lining, river pumping plant and the check structure. A diagram of the Central Arizona Plan showed extensive pipes and tunnels that could be at risk of a mussel infestation. The project has 340 miles of aqueducts, 19 siphons and 15 pumping plants. Storage reservoirs (often with associated hydroelectric generation facilities), diversion structures, conveyance channels, fields and drains are other areas that need to be protected to prevent mussel infestations. Special consideration should be given to the fouling of instruments, fish protection facilities and inverted siphons. Siphons are of special concern because they are often very long, deep, undrainable and inaccessible.

Water systems in western states have many differences from those in eastern states. The western water systems are used for water dispersal and contain long continuous reaches for water delivery often involving interbasin transfers. Their structures often lack design characteristics and management plans to contend with quagga infestations. There may be new problems arising for which we will be required to develop new management techniques in the future.

Expert #8 - Reproductive Patterns

Peter Fong

The eighth presentation of the day focused on patterns of reproduction in Dreissenid mussels. Temperature, calcium and pH are factors that regulate the timing of reproduction and larval development. A diagram of the life cycle of a zebra mussel was shown. The different stages of the planktonic growth and the development from the juvenile to adult stages were depicted. A series of slides of electron micrographs were shown documenting mature ovary cells and mature oocytes with germinal vesicles. Germinal vesicle breakdown (preceding spawning) was shown along with the released oocytes (diameter of 65-70 micrometers). A slide showing sperm-egg fusion was presented with the entire head of the sperm entering the egg. Pictures of early larval stage zebra and quagga mussel were shown.

A literature review demonstrated the temperature pattern influencing reproduction of zebra and quagga mussels. Zebra mussels have an optimal spawning at a temperature of 12-18 ºC, and larval development is optimized between 17-18 ºC. Research suggests quagga mussels can spawn as low as 9 ºC, but there is insufficient data to suggest optimal temperatures for larval development. Investigations by Ram et al. (1996) showed that the most intense spawning of zebra mussels occurred when temperatures were 13-25 ºC. A Study by Garton & Haag, (1993) showed that zebra mussel veliger abundance was highest in July and August when the temperatures were the warmest. Nichols, (1996) suggested the reproductive cycle varies in locations depending on the climate.

Calcium influences the patterns of reproduction as zebra mussels can be limited at all life cycle stages in the absence of sufficient calcium. It has been suggested that a minimum of 20mg Ca/L is necessary to have a reproductive population and quagga mussels are absent in water below 12 mg Ca/L. Waters low in calcium are most likely the result of a limited upstream source or local geology. A chart from Sprung (1987) showed how increasing calcium concentrations have a positive effect on veliger rearing success. An invasion potential map was presented highlighting the areas of the U.S. that have been sampled and determined to be a high risk because of the abundance of calcium. Lake Mead is categorized as a high risk due to the calcium concentrations.

Another important variable for reproduction in zebra and quagga mussels is pH. Sprung, (1993) has demonstrated that zebra mussels require a pH of 7.4 – 9.4 for veliger development, but there is insufficient data on quagga mussels to determine their pH threshold.
The conclusion to this presentation summarized the ranges of reproduction from an extensive literature search. Zebra mussels require a temperature between 12-25 ºC, a calcium content of greater than 20 mg Ca/L and a pH between 7.4 and 9.4. There is insufficient data for quagga mussels to determine the thresholds for calcium and pH, but they theorize that the temperature requirements are similar for quagga mussels and zebra mussels.

Expert #9 - Population Behavior

David Britton

The ninth presentation dealt with the topic of quagga mussel population behavior. The presentation began by describing North American *Dreissena's*. Zebra and quagga mussels are freshwater bivalve mollusks that can reach about an inch long in the adult stages. Both mussels can have a light, dark or striped shell. The impacts from both can be costly if there is an infestation. Management and control costs are about one billion dollars annually. Municipal water supplies, hydroelectric stations and fossil fuel power plants are facilities of concern.

A study by Ricciardi and Whoriskey (2004) showed that there can be a species shift with time when quagga and zebra mussels are both present. The study suggests that quagga mussels will out-produce zebra mussels (in terms of biomass) over a span of ten years. The study also found evidence to show the quagga mussels had considerably higher densities in the middle and bottom of the Soulanges Canal compared to zebra mussels.

There are five types of cycles that describe population behaviors: lag, boom-bust, cyclic, irregular and equilibrial. A lag, which is characterized by slow growth over time, followed by a sudden increase in population is not commonly seen in quagga mussel infestations. This type of pattern could be observed if quaggas were introduced into a system with a well established zebra mussel population. Another possible stimulus for a quagga lag period would be the introduction of the species into a system with less desirable environmental conditions followed by changes in conditions that favor quagga development. An example is an area of soft sediment that is changed to a shell gravel bottom. Another population behavior is the boom-bust cycle. This is characterized by a rapid increase in population size followed by a quick die off of much of the population. This pattern is commonly observed in many invasive species, but zebra mussels do not commonly exhibit this population behavior. Boom-bust cycles have been observed in Lake Erie and alpine lakes of Europe. This cycle can be caused by a rapid decrease in food availability, predators, disease or an exceedance of the carrying capacity of the environment. Another population behavior is a cyclic pattern which is characterized by fluctuating periods of population growth and decline. This cycle has been observed in mussel populations in the Hudson River. This type of population behavior is more common to quagga mussels as it is driven by dominance of strong year classes. The periods of increasing population size are linked to the lifespan of the dominate year class, which for quagga would be three to five years. These cycles reduce in amplitude over time, but can be "restarted" if a disturbance occurs. Another type of population behavior is irregular, which is characterized by no generalized pattern which makes predictions difficult. The last population behavior discussed is the equilibrial where an equilibrium population density is reached. This population behavior is best suited for making predictions and understanding the long term impacts, unfortunately it is very uncommon.

Simulation models can be used to help determine population behavior. Strayer and Malcom (2006) have produced a long term demographic model of zebra mussels. The model includes parameters for space limitations, larval food limitations and disturbance. Another model by Casagrandi, Marim and Gatto (2007) was designed to show the impact of local dynamics of zebra mussels. Their model includes parameters for age structure, density dependent veliger survival and population filtration rates.

Generally, the zebra and quagga mussels are benthic as adults and planktonic as larvae (veligers) with the planktonic stages persisting in the water column for several weeks. A few pictures of various stages of the life cycle were depicted. Adults attach to hard surfaces with byssal threads, usually forming dense clusters. The mussels use cilia to pull water into the shell via an incurrent siphon, where desired particulate matter (food) is removed by filtration and undesirable matter is bound with mucus and secreted. This secretion from the mussels is called pseudofeces. The adult mussels filter water in proportion to their size with a single adult mussel capable of filtering more than a liter of water per day.

Larval survival can be affected by food limitation and the Strayer and Malcom (2006) model suggested that larval food limited populations should cycle with a period of three to five years and that space limited or disturbed populations would stabilize over time. This would be correct for larger lakes with ample hard substrates and lower phytoplankton concentrations. Irregular disturbances should lead to irregular patterns.

There are a wide variety of population dynamics that could occur. The most commonly observed patterns are cyclical or irregular driven by density dependent factors related to dominate age classes. Limiting larval food and removing larvae could have large impacts on population behavior, unfortunately long term data for Dreissenid populations are rare.

Expert #10 - Population Tracking and Monitoring Methods in Lakes

David Britton

The tenth presentation discussed tracking and monitoring of invasive mussel in lakes. Monitoring programs regarding the larvae (veligers), juveniles and adults should be evaluated. The goal is to determine the presence or absence of the different life stages, their density and their abundance. The most commonly used sampling device is called the Portland sampler, which is PVC tubes filled with netting material hung in the water column. The device is not as effective as desired, but recent upgrades have helped improve its use as a monitoring device for attached life stages.

Plankton samples (63 micron mesh with a slow vertical tow) can be used for monitoring planktonic life stages. Samples should be preserved in a 1:1 ration of 95% ETOH and analyzed using microscopy and Polymerase Chain Reaction (PCR) techniques for identification. Microscopy using a cross-polarized light source is most effective as the veliger shells produce a distinctive “cross” pattern. One problem with using microscopy is that it is prone to false positives. For example, ostracods can be easily confused with veligers because they show a very similar shape and size. Detection using PCR looks for specific DNA sequences in amplified samples. While PCR offers the potential of very early detection (small sample sizes), this method is prone to false negatives, and is expensive (it is becoming more cost-effective as more laboratories adopt the approach).

Plankton samples are also useful for monitoring known infestations as veliger densities may reflect future population densities. It is important to perform plankton tows of known volumes for comparisons between sites and dates. If the identification difficulties can be overcomed, monitoring veligers can be one of the easiest methods for monitoring and tracking

Another method of monitoring juvenile and adult populations is sampling plates. Settling plates are made of PVC and are anchored with a brick or cement block with a buoy, so the plates can be easily located. Several rows of settling plates are attached that allow for settling and growth. Another, less sophisticated method for detection is to use a concrete block or similar material. The advantages of this approach are that it is simple, low cost and readily available. This method is useful, because the area of the block can be easily determined, and counting these areas is easier than other methods. Using quadrats is another method to count adult populations present on natural substrates and surfaces. This method uses a 1/8 m^2 quadrant that is randomly thrown over a bed of mussels. The divers can collect all the animals in this quadrat in order to quantify them out of the water.

The presentation concluded with a description of the monitoring program at Lake Champlain. The program monitors for veligers, juvenile and adult life stages at stations along the lake and areas used for juvenile and adult monitoring.

Expert #11 - Role of Modeling in Assessment and Management of Quagga Mussels

Michael Anderson

The eleventh presentation explained the role of modeling in assessments and management of quagga mussels. Models can offer important insights into management of surface waters, and are often used to improve understanding of the physics, chemistry, water quality and ecology of lakes and rivers. Models have successfully been used to understand the effects of mussels on aquatic ecosystems, including impacts on water quality and dispersal. Models can also help develop and evaluate mussel control strategies.

Models are mathematical representations of physical systems that vary in their complexity. There are several types of models that are available. Zero-dimensional models can be used for calculations of water quality and other properties, assuming well-mixed conditions within the lake. One-dimensional (1-D) numerical models assume that the primary gradients are in a vertical direction and allow for more complex modeling of temperature, light, dissolved oxygen, nutrient concentrations and other properties. Two-dimensional (2-D) models can account for gradients in properties with two directions. This type of model requires more spatial data, but is otherwise similar to 1-D models. Two-dimensional models are particularly useful for run of river reservoirs where gradients in both length and depth are of interest. Three-dimensional (3-D) models can accommodate gradients in three dimensions, require the most extensive input of data and are expensive to create. When these models are calibrated and validated, however, they can provide comprehensive insight into physical, chemical, water quality and ecological processes and properties within lakes, streams and reservoirs.

As an example, a 1-D model was recently used to evaluate control strategies for quagga mussels in Lake Skinner, an important drinking water reservoir for Southern California. One control strategy under consideration was to promote stratification and development of anoxia within the hypolimnion to kill adult mussels there. There were a number of important questions that needed to be answered, however.

A primary question was whether altering the flow regime and operation of the reservoir could induce stratification and allow anoxia to develop within the lake. If so, what volume, area and depth within the reservoir would become anoxic and be potentially cleared of viable mussels? And if successful, how quickly could a diffused aeration system break stratification and restore oxic conditions in the water column? What would the ensuing water quality in the lake be?

The 1-D DYRESM-CAEDYM model was used to answer these questions. The model required information concerning the sediments, water column, reservoir operations and local meteorology to simulate the conditions in the lake. The results were compared with available field measurements as part of the calibration and verification steps. The model predicted under normal operational conditions that some stratification would occur in late May and June, although the model generally predicted isothermal conditions for the lake. Reducing the flow through the reservoir and restricting withdrawal to the upper portion of the water column was predicted to yield strongly stratified conditions throughout the summer. Water quality in the upper portion of the water column was actually predicted to improve as a result of stratification relative to the generally mixed condition found at the lake. The model further predicted rapid loss of DO above the sediments in the hypolimnion, with DO concentrations below levels necessary for mussel survival at 10-18% of the sediment area in the lake. Implementation of a diffused aeration subroutine within the model demonstrated that mixing could be achieved within about one week, thereby rapidly restoring oxic conditions in the lake if necessary. Based upon these model predictions, quagga mussel control via enhanced stratification was pursued at Lake Skinner.

This example is only one use for a water quality model. There are many other options that could be explored. Models can thus serve as important tools for understanding the impacts of quagga mussels in ecosystems and developing and assessing possible management strategies.

Expert #12 - Case Study

James Grazio

The twelfth presentation was a case study of using winter lake drawdown as a strategy for zebra mussel control. Opinions on control options available to managers were shared in the presentation. The case study involved two very different lakes, Lake Zumbro in Minnesota and Edinboro Lake in Pennsylvania. Studies by Paukstis et al. 1996; Waterways Experiment Station, (1995) have shown that freezing air temperatures are lethal to zebra mussels exposed under laboratory conditions. No previous studies had demonstrated that this technique could work as a control strategy, so they decided to conduct an independent experimental drawdown on Lake Zumbro and Edinboro Lake.

The study was initiated on Lake Zumbro on November 20th, 2000. The target drawdown level was 1.5 meters and water was held at that depth for 10 days. During the drawdown, the temperature was below 0 °C. To determine the effectiveness of the drawdown, shoreline substrates were inspected at sites 5, 4, 2.5 and 0 miles above the dam before and after the drawdown. Veligers and settling mussels were collected the following spring and divers conducted surveys for adult mussels. The results showed that extensive mortality occurred in the area of the drawdown, but there were live mussels observed in a few areas influenced by the inflow of meltwater. A map was shown of the areas that had been reported to have zebra mussels present in 2001, and almost ¾ of the lake had high recruitment as indicated by settling plates and diving surveys. The results showed that by August there were high densities of live mussels in the dewatered zones and deeper areas of the lakes. The result of this experiment showed that draw down of lake elevation in freezing conditions is effective for killing zebra mussels, but does not prove to be an effective long-term management tool in Minnesota.

The second experiment took place at Edinboro Lake in Pennsylvania. The goal of this experiment was to understand the distribution of mussels at depth and to obtain a quantitative population estimate. The methodology included sampling along random transects and quantitative samples of mussels at depths of 2.5, 5, 8, 10 and 20 meter depths. Samples were collected from rocks, by the aluminum foil method, to count attached mussels. The results were expressed in terms of surface area. The distribution of zebra mussels was shown to be confined to the shallow depths, no mussels were detected greater than 2.5 m. Peak mussel densities were found shallower than 2.5 m. The experiment targeted a drawdown of ~0.5m for a duration of seven days. The results showed complete mortality for depths 0-1m. Survival occurred at high levels at lower depths. A second draw down was performed in 2001with better success at killing larger, more established zebra mussels.

The experiments concluded that winter drawdown was effective at killing exposed mussels, though some mussels may survive depending on other factors (animal size, snow/ ice cover and exposure time). Winter drawdown can be an effective zebra mussel management tool for some lakes, but drawdown is not recommended if the majority of the population is below the drawdown depth. Control should be the goal, because elimination with this strategy is not possible. Drawdown during summer months should be avoided as the freezing conditions fatal to the mussels will not occur. Drawdown techniques could be incorporated with other strategies to control populations.

Expert #13 - Case Study

Thomas Horvath

The thirteenth presentation was a case study on Dreissenid mussels in riverine ecosystems. The presentation began by describing the preferred habitat of mussels: requiring calcium greater than 20 mg Ca/L, pH between 7.2 to 8.7, salinity at 5 ppt and temperature at the upper tolerance of ~36 ºC. Colonization of inland lakes has occurred primarily from recreational boats that have not been thoroughly cleaned and dispersal into rivers can also occur from veligers carried downstream.

A diagram of the upper Susquehanna sub-basin was provided to show the areas of mussel infestation. Veligers were counted from the lake outlet downward. Veliger counts declined rapidly as the distance approached 5 km, but some veligers were still detected up to 25 kilometers away from the outlet. This dispersal in rivers is a classic source and sink model of dispersal, creating populations further downstream from “parent” populations.

A study by Horvath, T.G. and G.A. Lamberti (1999) showed that exposure to turbulence can inflict a high mortality on veligers during downstream transport. Veliger survival was about 5 percent after 48 hours at 400 rpm. A study by Stoeckel et al. (2004) has shown that in the upper Mississippi River, Lake Pepin is the main source for veligers and that it is unlikely that backwaters and other off-channel sites are driving main channel abundance patterns.

Metapopulation models have shown that if a self-sustaining upstream population occurs, this in-river population provides propagules for the establishment of down-river populations. Strayer & Malcom. (2006) provide evidence that the long-term population demography of mussels exhibit a temporal cycle of population size as increases and decreases in population size were observed. Orlova et al. (2005) demonstrated that passive larval drift allowed quagga mussels to expand range and that increases over a 20 year period were 50%. Other studies have suggested that quagga mussels have replaced zebra mussel populations in stable habitats.

There are many ecological and economic impacts of a mussel infestation. Some ecological impacts are observed on the native species and their habitats. A picture of a native bivalve being completely overgrown by quagga was shown. Indirect impacts of the aquatic ecosystems can occur through changing species and nutrients available in the water. Mussel infestations can also have an effect on water quality. Denkenberger et al. (2007) have documented several problems in the Seneca and Hudson Rivers since their invasion of mussels. Dissolved oxygen concentrations are so low that they violate water quality standards in the Seneca River. Increased cyanobacteria blooms, increased bacterial abundance and reduced primary production have occurred since infestation. Fish distribution and migration patterns have also been shifted.

These infestations have also created many unanswered questions. What is the basic biology and ecology of mussels and what is involved in controlling them? What are the interactions between quagga and zebra mussels and how does the interaction affect the broader ecosystem? One important step in preventing the spread of mussels is to try to prevent the species from being transported to other bodies of water. Boat inspections can be very important in preventing the spread of invasive species. Outreach programs are helpful to educate the people about the dangers of bringing nuisance species on their boats and the damage they can cause to the ecosystem.

WORKSHOP PROCEEDINGS – FRIDAY, APRIL 4, 2008

Expert speakers and invited stakeholders were divided into two subgroups: Population Management and Chemical Inactivation and Barriers. The facilitated workgroups met to synthesize the information obtained from the presentations on April 3rd and work to identify the main questions or issues that were unresolved from previous research and experience. The workgroups were then asked to establish benchmarks and identify proposed budgets and timelines, etc. Ultimately, the subgroups worked to propose main research topics that could be expanded with future information, research and analysis.

WORKGROUP GROUND RULES

The workgroup leaders were expected to maintain a balanced group dynamic so that the maximum benefit could be derived from the various participants. Equal time was provided to all workgroup members who wished to contribute on a particular issue. All participants were instructed that brainstorming sessions were to be non-judgmental and that no one person’s opinion was more valuable than anyone else's. The time and opinion of all people wishing to contribute to the workgroup process was respected.

WORKSHOP QUALITY ASSURANCE/QUALITY CONTROL

To ensure that the workshop was productive and achieved the stated objectives, the following quality assurance/quality control recommendations were followed. Workshop participants often express concerns on workshop processes and outcome. The proposing team discussed the many workshops attended and have summarized the expressed concerns into six categories. These issues are described below along with the mitigating measures used to ensure that they do not become limitations of this workshop:

1. The overall goal, objectives and desired outcome of the workshop were not clearly stated at the onset of the workshop to the participants. Similarly, goals and objectives for the break-out groups are often inadequately stated
2. Lack of a systematic and logical process. The process and its relation to the workshop goal and outcomes are often erratic and inadequately stated. Consequently, the workshop process is erratic and confusing to the participants, which reduces the effective use of the participants' time and the quality of the overall product. Workshops often fail to follow well established and effective models for problem identification and resolution

The workshop process and design was developed based on established problem solving and decision making models (Figure 3). (Decision and Problem Solving. 2002. Federal Emergency Management Agency (FEMA), Emergency Management Institute, Emmitsburg, MD). A specific process was clearly identified, illustrated by means of figures and flow charts, communicated and followed during the workshop. The primary role of the workshop facilitator and workgroup leads were to ensure adherence to the identified process.

3. Issues and concerns by all workshop participants and stakeholders are not adequately acknowledged, recorded nor considered in the overall discussion

There are three major processes for soliciting input, generating options and identifying research needs: brainstorming, surveys and discussion groups. Each of these were incorporated into the process as a means to ensure active involvement by all workshop participants.

A basic ground rule of brainstorming is not to prejudge the value of any idea, concern nor suggestion. Workshop and group leaders were instructed to record issues, ideas or suggestions prior to any discussion. A systematic process was followed later in the workshop for analysis and prioritization.

Discussion groups are a process for benefiting from synergistic interaction between workgroup participants. Three basic ground rules for workgroups were used by dealing with issues in a comprehensive manner, avoiding initial judgment and by focusing on issues or research needs and not on personalities. The facilitators instructed group participants to follow these simple rules.

4. Lack of transparency in the identification of issues and subsequent prioritization process. The rationale behind the critical issues and the ranking process is often inadequately documented. A major concern expressed about workshops is that bias and personality domination are not adequately mitigated in the overall process

More transparency was attained by explaining and following established problem resolution models and by documenting the key elements for issues discussed (Figure 3).

5. Lack of participation by stakeholders early in the process

In this workshop, stakeholder participation was incorporated by two means:

a. Stakeholders were invited as active workshop members who also participated in the workgroups
b. Open attendance during presentations and plenary sessions gave additional stakeholders the opportunity to provide input. Open microphone time slots were included in all of the plenary and workgroup sessions

6. Personality domination. Stronger personalities have a tendency to dominate a group and potentially bias or inhibit active participation by other group members

One of the roles of the facilitator was to minimize the influence of dominant personalities through a process of restating the workshop objectives, reiterating ground rules and encouraging participation by less dominant individuals. The facilitators were responsible for maintaining a balanced group dynamic so that the maximum benefit could be derived from the various participants invited. The oral survey process during workgroups provided an opportunity for all participants to provide input.

POPULATION MANAGEMENT WORKGROUP

The Population Management workgroup included the following individuals:

Michael Anderson	University of California Riverside
David Britton	U.S. Fish and Wildlife Service
Robert Brownwood	Tulsa Metropolitan Utility Authority
Ric DeLeon	Metropolitan Water District of Southern California
Susan Ellis	California Fish and Game
Peter Fong	Gettysburg College (Pennsylvania)
Evan Freeman	Utah Division of Wildlife Resources
James Grazio	Pennsylvania Department of Environmental Protection
Thomas Horvath	State University of New York
Everett Laney	U.S. Army Corps of Engineers
Larry Riley	Arizona Fish and Game
Jon Sjoberg	Nevada Department of Wildlife
Ron Smith	U.S. Fish and Wildlife

Monica Swartz	Coachella Valley Water District
Kent Turner	National Park Service

After summarizing the key themes from the first day of presentations (for example, the uniqueness of the situation and the lack of data on basic biology of the mussels), the group began to identify areas where further research was needed. The group discussed at length the need to determine whether veligers are alive or dead. This determination will provide for more accurate control, management and eradication measures. Because individuals with similar but different interests were participating in this group, there was often debate between which research need should be prioritized. A portion of the group represented the interests of water operators who dealt with the quagga mussels on an infrastructure level. The remaining group represented either a regulator or environmental interest, where managing the invasive species holistically was a common ideal.

To help focus the group's efforts, the facilitator worked with participants to identify broader topics under which more narrowed questions could be placed. These broad topics included:

- Identifying areas of weaknesses in the mussels' reproductive cycle
- Prioritizing risks and threats of mussels (for example, a day boat is a relatively low risk)
- Developing an effective method to determine whether a veliger is alive or dead
- Making the public aware of the seriousness of the issue without creating panic
- Developing effective sampling methods
- Determining the level of physical destruction

In terms of managing and controlling the quagga mussel population, the group worked to identify broad categories under which more detailed research needs could be categorized. These included biology, ecology, mechanical control (infrastructure), public relations and detection. Following discussion about the prioritization of research needs, the group agreed on the following ranking of research topics based on immediate need:

1. Understanding basic biology of the mussel in the west
2. Identifying how system ecology can be exploited for control purposes
3. Developing a model for lake/river management tools that can model integrated pest management and reduced impacts to ecosystems
4. Determining reliable methods for early detection
5. Using engineering and operational means to reduce the physical destruction to water delivery infrastructure by quagga mussels
6. Anticipating the potential for shifts from planktonic to benthic regimes, resulting in reduced water quality
7. Evaluating existing outreach and education efforts
8. Identifying living veligers from dead veligers, as current methods cannot accurately determine if a veliger is dead or not moving
9. Identifying how mussel growths impact other organisms and operations
10. Developing a rapid assessment index

From this list, four research topics were developed. The group divided and began to develop rough drafts of research proposals for these topics. The results are included in Appendix A. The research topics identified by the group included:

1. System Ecology as a Control Strategy
2. Development of Quantitative Tools for Management of Mussels in the Colorado River System
3. Tolerances in Western U.S. at Water Resource Facilities and Operations. Quantification of Life Histories and Environmental Conditions
4. Assessment of Existing Dreissenid Control Technology. Efficacy, Development and Assessment of New Control Technologies

Seven research topics were ultimately developed and these can be found in Appendix B. The final list of seven research topics from this group included:

1. Response of Quagga Mussel Veligers to Limnological Variables
2. Application of Biological Agents to Control Quagga Mussels
3. Applying Knowledge of System Ecology as a Control Strategy
4. Quantitative Tools for Management of Mussels in the Colorado River System
5. Quantitative Evaluation of Quagga Mussels Outreach and Educational Activities
6. Shifts from Planktonic to Benthic Regimes in Response to Quagga Mussel Invasion
7. Impact of Quagga Mussel Invasion on the Quality of Domestic Water

CHEMICAL BARRIERS AND INACTIVATION WORKGROUP

The following individuals participated in the Chemical Barriers and Inactivation Workgroup:

Doug Ball	Los Angeles Department of Water and Power
Pam Benskin	City of Aurora, Colorado
Renata Claudi	RNT Consulting
Dave Drury	Santa Clara Valley Water District
Ron Huntsinger	East Bay Municipal Utility District (San Francisco)
Gerald Mackie	University of Guelph (Canada)
Brian Moorehead	Salt River Project
Fred Nibling	U.S. Bureau of Reclamation
Thomas Prescott	RNT Consulting
Lisa Prus	San Diego County Water Authority
Michael Remington	Imperial Irrigation District
Leonard Willit	U.S. Bureau of Reclamation
Dan Young	Central Arizona Project
Ron Zegers	Southern Nevada Water Authority

Following a brief review of April 3rd's activities, the facilitator invited participants to introduce themselves and identify research interests or concerns that they consider a priority. These are compiled in the list below:

- Specific information about the quagga versus zebra mussel, such as biology, sensitivity, depths, anoxia, etc
- Non-oxidative molluscicides. Specifically, do the water treatment chemicals that we use now (coagulants) have an effect on mussel control? Does the water treatment process itself have a major effect
- Information about Potassium Permanganate as a strong oxidant
- Information regarding the significant difference between "recovery" and "settlement" as it pertains to raw water transport pipelines
- Basic biological and ecological information for quagga mussels in a warm water environment
- What methods can be used to protect major infrastructure for irrigation and potable use
- Potential impacts for in-lake/reservoir management systems and available non-chemical options
- Potential impact for flow-through systems such as the All-American Canal
- What structures are in place that will damage the larvae to minimize the amount of chemicals used? (Specifically the Mark Wilmer Pumping Station and lift that appears to effectively kill veligers by mechanical means). It is unclear what aspect of the process is attributable for this effect
- What changes in design should be considered for future infrastructure to maximize control of quagga populations
- What are the chemical alternatives to massive chlorination treatments
- How to address quagga control for raw water applications that cannot use or maintain sufficient chlorination levels, such as golf courses, parks or discharges into lakes or streams
- How to differentiate between veliger mortality and non-attachment. What contact times and concentration dosages are required

The facilitator led the group in a discussion to identify commonalities between issues and research concerns. The group concluded that infrastructure differences require a variety of methodologies to be studied. For example, some water managers are only concerned with non-attachment while others with long transmission lines may require veliger mortality. The group identified four categories of threatened facilities, including treatment plants, aqueducts, irrigation systems and reservoirs.

The group discussed the potential differences between quagga and zebra mussels that must be understood prior to establishing treatment methodologies. For example, survival depth varies between species and is a major consideration for infrastructure placement. Adult mussels close and sink after coming into contact with chlorine. It is unclear whether quaggas survive after being exposed to chlorine and sinking to depths lower than their known settlement tolerance. This will become an important piece of information for intake placement. Several group members agreed that the lower-level intakes in the west represent an important difference between western and eastern water infrastructure. However, low intakes may not address the issue if the quagga is able to settle at greater depths. Ron Zegers noted another important infrastructure difference, that many western facilities do not use sedimentation basins that are common in the east.

One group member noted that Metropolitan Water District of Southern California (MWD) had difficulty identifying an acceptable means of disposing of quagga waste following the cleaning of their trash racks. Renata Claudi said MWD has a specialized system that could be addressed as an independent case study. It would be particularly ideal to analyze post-treatment viability and re-settlement within the closed system of the California Aqueduct.

Participants discussed potential options that will require additional research before the feasibility of their application would be understood. Some of these measures included UV treatment, natural filtration for small systems, oxidants, pseudomonas fluorescence or predatory fish that can be bred as a non-reproductive triploid.
Renata Claudi emphasized the importance of exploring the effect of the hydraulic pumping station and lift at the Central Arizona Project. She said this type of physical barrier has not been observed anywhere else and was enthusiastic about the potential for an effective non-chemical barrier.

Ron Zegers expressed concerns regarding water quality and taste (geosmine, MIB, algae blooms, etc.). He said research should be conducted regarding the impacts of zebras or quaggas in these areas.

Following this discussion, the facilitator helped the group to identify broad categories that encompassed the various research suggestions. These categories were: chemical, physical, biological and integrative management. The group then participated in an exercise that helped them to prioritize research needs. From this list, four research topics were developed. The group divided and began to develop rough drafts of research proposals for these topics. The results are included in Appendix C. The research topics identified by the group included:

1. Demonstrate Alternative Technologies to Chemical Control of Dreissenid Mussels
2. Dreissenid Mussel Vulnerability Assessment and Response Management Tool
3. Hydraulic Effects on Veliger Mortality from Engineered Systems
4. Develop Method to Determine Quagga Mussel Veliger Viability as it Applies to Chemical Treatment for Removal, Non-Attachment or Mortality

Seven research topics were ultimately developed and these can be found in Appendix D. The final list of seven research topics from this group included:

1. Determination of Viability in Quagga Mussel Veligers and Assessments of Chemical Treatment Efficacy
2. Hydraulic Effects on Veliger Mortality in Engineered Systems
3. Quagga Mussel Vulnerability Assessment and Response Management Tool Development
4. Demonstrate Alternative, Non-Chemical Control Technologies for Quagga Mussels for Deployment at Water Treatment Facilities
5. Molluscicides and Biocides for Control of Dreissenid Mussels in Water Resources
6. Coating and Materials for Control of Dreissenid Mussel Attachment in Water Resource Projects
7. Early Detection Methodology and Rapid Assessment Protocols for Quagga Mussels

STANDARD METHODS WORKGROUP

The final workgroup consisted of the combined membership of both subgroups. One of the facilitators conducted a group discussion based on a set of potential questions regarding procedure and standardization. The group discussed methodologies and documentation as it relates to surveillance, sampling and reporting. Specific issues were identified including the standardization of coupons or substrate surfaces and methods to determine veliger mortality in the lab and in the field. It was noted that early-stage monitoring (presence/absence testing) does not require sophisticated sampling methodologies.

The group also discussed the need for reviewing and accessing shared information. There were differing opinions regarding the level of review required. Some suggested that the 100th Meridian Website could be a potential site; however it hasn't been updated recently. The group concluded that something like a Wikipedia system may work to disseminate information rather than waiting for a webmaster to post.

Appendix A: Population Management – Research Needs Developed at Workshop

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: System Ecology as a Control Strategy

Background: Using a system-wide ecological approach to control could minimize the impact to existing ecological resources and simplify compliance. Takes advantage of existing resources for system self-correction.

Objectives:

- Want to identify components that make the community resistant to invasion. Biotic/ abiotic components
- Identify system vulnerabilities
- Identify roles and relationships to introduced species
- Relationship between quagga and T and E species
- Identify where controls would be most effective in an ecological system-wide context

Approach:

- Identify system pathways which expose both vulnerabilities in ecological sustainability, and possible vulnerabilities in quagga ecology
- Evaluate potential resilience of existing biota/ecology to provide some level of long term control
- Evaluate management of abiotic inputs and system operations (e.g. disturbance regimes, temp, nutrient inputs) to identify positive and negative effects on quagga distribution and abundance
- Evaluate ecological overlap and relationship between quagga and T and E

Recommended Budget: Possibly $250,000.00

Recommended Schedule: 5 year project

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: **Development of Quantitative Tools for Management of Mussels in the Colorado River System**

Background: Models can provide important insights into the physics, chemistry and biology of lakes, rivers, reservoirs and other conveyances, and can be used to assess suitability of different management alternatives on water quality.

Objectives: Development of modeling tools to identify vulnerabilities of quagga mussels in the Colorado River system; develop, simulate and evaluate treatment strategies to control populations and mitigate negative effects; and identify adverse effects on ecology, facilities, conveyances and assets.

Approach: Refine existing models of Lake Mead, develop additional models for other components of the system, with particular focus on Lake Havasu. Integrate ecological, hydraulic, chemical and limnological factors in a comprehensive management tool.

Recommended Budget:

Recommended Schedule:

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: Tolerances in Western U.S. at Water Resource Facilities and Operations. Quantification of Life Histories and Environmental Conditions

Background: Any type of control strategy requires knowledge of the basic biology of the target organism. The western population of quagga mussels have life history traits in stark contrast to those populations studied in the Great Lakes. Moreover, temperature regimes in large western reservoirs are very different from these in the northeast Great Lakes and populations of quagga mussels.

Objectives: Quantify and characterize quagga mussel life history traits and environmental tolerances for the purposes of supporting control of quagga mussels in warm water environments. This information is necessary to minimize impacts of quagga mussels at water resource facilities in the western U.S.

Approach: A combination of field and laboratory work that examines environmental tolerances, routine sampling and examination of wild populations in various western habitats.

Recommended Budget: Estimated $500,000.00

Recommended Schedule:

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: Assessment of Existing Dreissenid Control Technology. Efficacy, Development and Assessment of New Control Technologies

Background: Limited options are currently available to control Dreissenid populations in open water systems and associated, at-risk infrastructure. Existing control options must be identified and evaluated for applicability to western populations and new, effective options developed in order to mitigate the impact of established Dreissenid mussel populations on water supplies and infrastructure.

Objectives: To evaluate the effectiveness of existing Dreissenid control technologies and develop new and effective target-specific technologies for the control or elimination of Dreissenid mussels in open water systems.

Approach:

- Literature review of existing technology and efficacy (successes and failures)
- Development and assessment of new control technologies (e.g. biological, physical, chemical)

Recommended Budget:

Recommended Schedule: Evaluate existing options and fund proposals for new technologies within 8 months. Technology, development and testing up to 3 years

Appendix B: Population Management – Final List of Research Projects

PROJECT TITLE:

RESPONSE OF QUAGGA MUSSEL VELIGERS TO LIMNOLOGICAL VARIABLES

Background: Relatively little is known about the life, history, ecological and environmental requirements of quagga mussels with regard to their success or failure at invading new systems or as these conditions influence population densities. Most of the information that has been developed in the United States is derived from the Great Lakes region, where the genus was first introduced to the continent. Temperature regimes and other limnological conditions in this region of the country can differ significantly from the southwestern and Pacific Coast states that have been invaded more recently or are currently threatened with invasion. Among the primary environmental variables that need to be considered is temperature. At both ends of the spectrum, temperature needs to be addressed within the context of these western systems. Aquatic systems located in desert regions will have water temperatures that far exceed those of the Great Lakes, while the hypolimnion of some of the deep reservoirs and their associated tailwaters will have temperatures that are less variable than natural systems. Limnological variables (e.g. salinity/specific conductance, ionic composition, ecosystem productivity, retention time, depth, irradiance) need to be considered in the context of this recently invaded region.

Objectives:

1. Develop a comprehensive understanding of the biology and ecology of quagga mussels in western reservoirs in order to develop properly designed treatment strategies to maximize success
2. Determine through the literature what environmental/ecological variables have been suggested as important determinants of quagga mussel invasion success
3. Integrate these literature findings into the context of environmental/ecological conditions likely to be encountered in western systems
4. Experimentally assess the response of quagga veligers to expected western conditions

Approach:

1. Conduct a series of laboratory experiments to assess the range of environmental conditions (e.g. temperature) potentially encountered in the west under controlled conditions
    a. Temperature
        i. Persistent cold temperatures representative of deep reservoir, hypolimnetic waters
        ii. High, fluctuating temperatures representative of desert streams, channels and conveyances
2. Literature review of previous works documenting environmental/ecological condition requirements

    a. Where overlap exists, extrapolate findings from previous studies to these western systems
    b. Where data exists, compile life history and environmental tolerances for Dreissenid in the southern segments of the Mississippi River Basin
3. Where data is lacking or environmental/ecological conditions do not overlap, collect data from western systems that have already been invaded to expand the overall understanding of the relationship between quagga mussels and limnological conditions

Recommended Budget:

1. Laboratory experiments: $1,000,000.00
2. Literature review: $250,000.00
3. Field data collection: $1,750,000.00

Recommended Schedule:

1. Laboratory experiments: 2 years
2. Literature review: 1 year
3. Field data collection: Up to 3 years

PROJECT TITLE:

APPLICATION OF BIOLOGICAL AGENTS TO CONTROL QUAGGA MUSSELS

Background: Biological control of invasive species can be one of the most effective means of preventing or mitigating the impacts of these species if an effective candidate can be identified, an application procedure developed and if it can be demonstrated that the proposed control agent does not pose a separate threat to the native or desired flora and fauna. Aquatic ecosystem management has a mixed record in the use of biocontrol agents. Too often, the organisms selected fail to control the target species to the extent desired or the control agent itself becomes a nuisance. These failures are most often a result of having too little background information prior to release.

Attempts to control mollusks and other biological problems in aquaculture ponds has resulted in the release of several species of Asian carp (grass carp, silver carp, black carp and bighead carp) into the Mississippi River Basin. When care is exercised in stocking, sterile grass carp can be effective at managing aquatic plant growth, but can also easily denude systems of all vegetation when overstocked. The silver carp has been known to injure boaters as it "leaps" into the air in response to boat traffic, but has had little success in algal control. The black carp has been used successfully to control snails in aquaculture, reducing parasitic infections, but it has also been implicated in damage to native mollusk communities.

The introduced Round Goby may be an effective predator on quagga mussels in the Great Lakes, but the broader ecosystem impacts are yet to be quantified.

Bacteria-based biocontrol of Dreissenid mussels has been demonstrated using a ubiquitous soil bacterium, Pseudomonas fluorescens. A toxin produced by this species, has been up to 90% effective at killing Dreissenid mussels in controlled experiments with limited impact on other trophic levels and did not impact other mussel species.

Objectives:

1. Identify potential biocontrol agents
2. Quantify the likelihood of successful control using the identified agents
    a. Define successful control (e.g. percent reduction)
3. Identify biocontrol agents that have potential for success, but are in early stages of development
4. Quantify the likelihood of these control agents becoming problematic

Approach:

1. Literature review of existing biocontrol agents
    a. Identify successful and unsuccessful applications
    b. Identify applications that resulted in the biocontrol agent becoming a nuisance. If possible, identify the cause of these failures
    c. Identify potential biocontrol agents that should be considered following additional development
2. If promising biocontrol agents are identified through the literature review, propose treatment levels that likely would be required
3. Proceed to small scale experimental trials if a promising biocontrol agent is identified through the literature review

Recommended Budget:

1. Literature review: $250,000.00
2. Experimental trials: $1,750,000.00

Recommended Schedule:

1. Literature review: 1 year
2. Experimental trials: 3 years

PROJECT TITLE:

APPLYING KNOWLEDGE OF SYSTEM ECOLOGY AS A CONTROL STRATEGY

Background: Using an ecosystem approach to quagga mussel control could reduce the impact on existing ecological resources, simplify compliance and contribute to the resilience of the overall ecosystem. This approach takes advantage of existing ecosystem resources, encouraging self-correction.

Objectives:

1. Identify components that make communities resistant to invasion by quagga mussels. These components include both biotic and abiotic ecosystem components
2. Identify vulnerabilities that could make the ecosystem susceptible to invasion
3. Identify the roles and relationships filled by introduced species and the native/endemic species that were displaced
4. Identify any relationships between quagga mussels and threatened or endangered species
5. Identify controls that would be most effective in an ecosystem context

Approach:

1. Identify pathways that expose vulnerabilities in ecological sustainability and possible vulnerabilities in quagga mussel ecology
2. Evaluate potential resilience of existing biota/ecology to provide some level of long term control if quagga mussels can be reduced
3. Evaluate management of abiotic inputs and system operations (e.g. disturbance regimes, temperature, nutrient inputs) to identify positive and negative effects on quagga mussel distribution and abundance
4. Evaluate ecological overlap and relationships between quagga mussels and threatened and endangered species

Recommended Budget:

1. Overall integrated project: $3,000,000.00

Recommended Schedule:

1. Overall integrated project: 3 years

PROJECT TITLE:

QUANTITATIVE TOOLS FOR MANAGEMENT OF MUSSELS IN THE COLORADO RIVER SYSTEM

Background: Models can provide important insights into physical, chemical and biological processes occurring in lakes, rivers, reservoirs and other conveyances. These models can be used to predict the outcomes of alternative management activities on water quality prior to actual implementation. Most models developed to date have been able to make reasonable predictions about physical and chemical water quality parameters and mixed results with regard to changes in biological conditions. A limited number of models have been implemented in northern states that attempt to quantify the water quality impacts of quagga mussels.

Objectives:

1. Development of modeling tools to identify vulnerabilities of quagga mussels in the Colorado River System
2. Develop, simulate and evaluate treatment strategies to control quagga populations and to mitigate negative impacts
3. Identify and model adverse impacts on system ecology, facilities, conveyances, etc

Approach:

1. Refine the existing Lake Mead model to incorporate quagga mussel activity
2. Develop or adopt additional models for Lake Mead and other ecosystem components (e.g. Lake Havasu)
3. Integrate ecological, hydraulic, chemical and limnological factors in a comprehensive model for use as a management tool

Recommended Budget:

1. Refine the existing model: $350,000.00
2. Models for other ecosystem components: $350,000.00
3. Integrated comprehensive model: $300,000.00

Recommended Schedule:

1. Refine the existing model: 1 year
2. Models for Lake Mead: 1 year
3. Integrated comprehensive model: 1 year

PROJECT TITLE:

QUANTITATIVE EVALUATION OF QUAGGA MUSSEL OUTREACH AND EDUCATIONAL ACTIVITIES

Background: Extensive efforts have been undertaken in an attempt to communicate to the public the risks associated with quagga mussel invasion as well as the actions that can be taken to reduce the spread of this invasive organism. While these programs have been widely disseminated, it is unclear what impact they are having and which programs are more or less successful. In order to determine the success of these programs, a quantitative evaluation must be undertaken using appropriate survey techniques.

Objectives:

1. Determine the success of outreach and educational activities in reaching target audiences
    a. Boaters, fishermen and other aquatic recreation groups
    b. Water supply, conveyance and distribution officials
    c. Water supply customers

Approach*:*

1. Conduct surveys to develop quantitative measures of outreach and educational program success
2. Survey techniques should be adjusted to best capture the impacts on specific target audiences (e.g. survey boaters on lakes, at boat ramps and away from lakes)

Recommended Budget:

1. Surveys to develop quantitative measures of success: $1,000,000.00

Recommended Schedule:

1. Surveys to develop quantitative measures of success: Up to 3 years

PROJECT TITLE:

SHIFTS FROM PLANKTONIC TO BENTHIC REGIMES IN RESPONSE TO QUAGGA MUSSEL INVASION

Background: The arrival of quagga mussels in western reservoir systems has the potential to significantly alter the food web. Food resources currently used in the water column by zooplankton could be consumed by quagga mussels at the sediment-water interface. While some of the organic matter consumed by quagga mussels will be returned to the water column during reproduction, overall the introduction of the mussels could reallocate resources away from the water column, resulting in major changes throughout the food web.

Objectives:

1. Determine the source of nutrition for adult and juvenile quagga mussels
2. Determine the source of nutrition for zooplankton
3. Assess the impact of overlapping diets of quagga mussels and zooplankton on overall food web energy flow
4. Assess the vulnerability of quagga mussel veligers to planktivores and determine if they represent a supplemental, replacement or reallocation of energy within the food web

Approach:

1. Stable isotope analysis of carbon source utilization and trophic positioning based on nitrogen fractionation
2. Analysis of gut contents for diet analysis
3. While the primary interest of the proposed research is an assessment of phytoplankton, zooplankton, quagga mussel and planktivore interactions, both stable isotope and diet samples should be analyzed from upper trophic levels in order to assess the need for expanded research

Recommended Budget:

1. Stable isotope analysis: $400,000.00
2. Gut content analysis: $400,000.00
3. Higher trophic levels: $200,000.00

Recommended Schedule:

1. 3 years

PROJECT TITLE:

IMPACT OF QUAGGA MUSSEL INVASION ON THE QUALITY OF DOMESTIC WATER

Background: Lake Mead is the source of domestic water used by over 22 million people. About 90% of the domestic water supply for southern Nevada comes from Boulder Basin of Lake Mead. Quagga mussels have heavily invaded the lake and the population density continues to escalate. Findings from other locations where both quagga and zebra mussels exist indicate the potential for their dense population to alter certain water quality parameters, especially in deeper portions of lakes and reservoirs. Quagga mussels provide a waste byproduct of filtration called pseudofeces that have the potential to significantly impact water quality. It is essential that we learn as much as possible about the potential changes to water quality in order that treatment processes may be developed, changed or both based on future conditions.

Objectives:

1. Determine the potential changes to water quality features of the sources of domestic water supply due to the invasion and increasing density of quagga mussels in Lake Mead

Approach:

1. Field and laboratory work to identify potential water quality issues related to dense populations of quagga mussels
2. Development of in-lake micro/mesocosms in reservoirs of concern to isolate populations of known densities of quagga mussels in order to identify and quantify water quality changes
3. Laboratory investigations to provide refined supporting data on water quality issues related to quagga mussel invasion

Recommended Budget:

1. Determine the potential changes to water quality features: $1,500,000.00

Recommended Schedule:

1. Determine the potential changes to water quality features: Up to 3 years

Appendix C: Chemical Inactivation and Barriers – Research Needs Developed at Workshop

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: **Demonstrate Alternative Technologies to Chemical Control of Dreissenid Mussels**

Background: Alternative technologies such as small pore self-cleaning filtration and UV disinfection have been demonstrated as effective controls for Dreissenid mussels. There is a need for a method of non-chemical exclusion of veligers from entering water treatment facilities. The above technologies are not being widely used, primarily for two reasons:

1. Perceived novelty of the technology/ lack of confidence in the product
2. Higher cost of application compared to chlorination

- The advantage of these technologies is ability to treat large volumes of water while maintaining a small footprint for installation with minimal or no waste of water
- These technologies do not interfere with the quality of the final product (i.e. production of THM's in drinking water) and they do not involve hazardous materials. Further, these technologies do not generally require regulatory approval for installation
- In the case of the small pore self-cleaning filter technology, additional benefit would be the removal of silt particles from the incoming water. In many applications, the silt can cause operational problems in the plant or damage to the equipment

Objectives:

- The objective is to demonstrate that the technology is mature and reliable under field installation and normal operating conditions
- Evaluate the associated costs of installation and operation of these technologies compared to chlorine/chemical treatment using a full cost-benefit analysis

Approach:

Phase 1 - Starting with a pilot sized, fully instrumented installation (i.e. treating approx. 500 gpm) operating in an actual facility, demonstrate that the technology meets the required criteria (veliger removal/inactivation, log removal credits for UV, silt removal, longevity, maintainability, operability). As the top three manufacturers should be tested for each technology, the technology would be skid mounted to facilitate the testing of various candidate manufacturers under identical conditions.

Phase 2 **–** The most successful pilot sized installation would be scaled up to demonstration size (5,000gpm) and perform the same evaluation as above.

- Opportunity to integrate these technologies with other water treatment technologies/methods

Recommended Budget:

Phase 1 - Top three manufacturer's products tested under identical condition (3 filters, 3 UV installations) $450K

Phase 2 – One installation of filter and UV, each $520K

Recommended Schedule:

Phase 1 – Immediate

Phase 2 – 18 months later

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: **Dreissena Mussel Vulnerability Assessment and Response Management Tool**

Background: Water systems in the west transport water over long distances and from multiple sources using a variety of structures, processes and conveyance systems. These systems are at risk and many are already experiencing Dreissenid mussel infestations. Water systems need to respond to this emerging issue in a timely and effective manner and currently no concise guidance is available. Agencies need to consider which tools for monitoring and control are most effective given their particular situation and risk tolerance.

Objectives:

Determine VA tool based on type of water system or facility considering beneficial water uses:

- Types of systems
- Extent of vulnerability based on component
- Regulatory constraints
- Options available for combating vulnerability
  - Potential effect of integrated management choices on subsequent users
  - Reactive and proactive approaches
  - Enforcement potential
  - Unintended consequences

It is envisioned that the guidance would include checklists and other decision matrices to assist in management strategy development.

Approach:

Develop a guidance document that evaluates the following:

- Define the physical/chemical/biological characteristics of the water
- Characterize conveyance and downstream affected infrastructure
- Define infestation vectors and infestation vector control strategies
- Develop and apply vulnerability/risk assessment tools
- Define chemical/physical control strategies
- Define a monitoring program
- Develop a containment/mitigation/eradication response plan
  - Short term (emergency)
  - Long term

Recommended Budget: $275,000.00.00. Utility partners are available

Recommended Schedule: 6 months

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: **Hydraulic Effects on Veliger Mortality from Engineered Systems**

Background: Central Arizona Project, Mark Wilmer Pumping Station, has confirmed large quantities of veligers at the plant intake. The plant pumps water in a single pumping stage with a single impeller pump for a total lift of 824 feet. No veligers have been settling between the top of the lift and the Bouse Hill Pumping Station 25 miles east. It is unknown if the veligers are experiencing complete mortality or injury. The mechanism of the veligers damage is unknown, but hypothesized to be a possibility of shear forces, rapid pressure change, gas embolism, cavitation or rapid velocity change. Furthermore, the level [pump lift] at which the injury to the veligers occurs is not known.

The MWD pump lift plant, in close proximity to Mark Wilmer, has a lift of approximately 200 feet and takes veliger rich water from the same water source as Mark Wilmer. The MWD plant is experiencing heavy mussel infestation in the pump discharge in the canal. (Need to confirm that the MWD pumping information is correct).

While the pumping process at the Central Arizona Project is somewhat unique, there are sufficient instances of pump lifts of similar magnitude in the western United States which would make investigation of this apparent veliger control mechanism of interest to other water utilities.

Objectives:

1. To determine if veligers are damaged/killed as a result of the pumping processes like those found in the Central Arizona Project and determine the mechanism causing veliger injury or mortality
2. To determine the threshold at which the "mechanism" becomes effective
3. To determine if the "mechanism" of veliger injury/mortality be practically reproduced/applied in other settings

Approach:

Determine possible mechanism of injury/mortality in CAP case study:

1. Identify the relevant pumping parameter values causing veligers injury/mortality, such as:
    a. Rotational speed
    b. Impeller diameter and design
    c. Volute design
    d. Exact differential pressure
2. Investigation of the time over which the pressure change is occurring within the pumping system

3. The test facility will have the capability to duplicate on a small scale the flow conditions up to and including those at Mark Wilmer Pumping Station
4. The test facility will have the capability of measuring all possible injury mechanism, including but not limited to the mechanisms identified in the background
5. The test facility will have the ability to identify the injury mechanism in detail through laboratory analysis, including the threshold pumping values under which injury occurs
6. Identify suitable test locations where the CAP pump system can be replicated under similar conditions to those found at the original pumping location

Recommended Budget: $300,000.00 to $500,000.00

Recommended Schedule: 18 months

RESEARCH PROJECT TEMPLATE

PROJECT TITLE: **Develop Method to Determine Quagga Mussel Veliger Viability as it Applies to Chemical Treatment for Removal, Non-Attachment or Mortality**

Background:

- The existing methods for determining veliger viability are inaccurate and non-standardized
- Little or no data is available for disinfection criteria (i.e. CT) for quagga mussel veligers
- Little or no data is available for non-oxidizing chemicals (i.e. polymers) available for quagga mussel veliger control or eradication
- Solutions would allow water officials to develop cost-effective control technologies for their facilities

Objectives:

- Method development that would lead to standardized protocols to determine with certainty quagga mussel viability (non-attachment versus mortality)
- Determine the fate of surviving quagga mussel veligers in terms of growth, development and reproduction
- Determine dose, contact time and the effect of environmental variables (pH, temperature and water quality) for oxidizing chemicals to achieve quagga mussel veliger viability (at swimming and settling stages) for desired end-points
- Determine dose, contact time and the effect of environmental variables (pH, temperature and water quality) for non-oxidizing chemicals to achieve quagga mussel veliger viability (at swimming and settling stages) for desired end-points
- In-field verification (conveyance and treatment systems) of chemical dosing results

Approach:

- Procedure development that would ensure the observation of certain quagga mussel mortality
- Testing of oxidant and other non-oxidizing chemical dose applications
- In-lab testing with field verification

Recommended Budget:

- (Phase 1) – Method development - $300,000.00
- (Phase 2) – Oxidizing chemicals (CT) - $150,000.00 per oxidant
- (Phase 3) – Non-oxidizing chemicals - $150,000.00 per chemical
- (Phase 4) – Pilot plant and in-field verification of results - $400,000.00

Recommended Schedule:

- (Phase 1) – 1 year
- (Phase 2 and 3) – 1 year
- (Phase 4) – 1 year

Appendix D: Chemical Inactivation and Barriers - Final List of Research Projects

PROJECT TITLE:

DETERMINATION OF VIABILITY IN QUAGGA MUSSEL VELIGERS AND ASSESSMENTS OF CHEMICAL TREATMENT EFFICACY

Background: Existing methods for the determination of viability of quagga mussel veligers are not standardized and lack sufficient accuracy and precision to have confidence in results from different sources. As a result of the non-standard approaches employed to determine viability, there has been few attempts to determine criteria for either oxidizing or non-oxidizing chemicals that are available for the eradication or control of quagga mussel veligers. The development of a standardized method would allow water officials to assess the effectiveness of control strategies and to determine cost-effective approaches for their facilities.

Objectives:

1. Development of a standardized protocol to determine with certainty quagga mussel viability. This method would distinguish between non-attachment and actual mortality of quagga mussel veligers
2. Determine the fate of surviving quagga mussel veligers in terms of growth, development and reproduction following exposure to (non-lethal) chemical treatment
3. Determine dose, contact time and the effect of environmental variables (pH, temperature, and other water quality parameters) for oxidizing and non-oxidizing chemicals to achieve quagga mussel veliger removal, non-attachment and mortality (at swimming and settling stages)
4. In-field verification (conveyance and treatment systems) of chemical dosing, contact time and environmental variable results from laboratory studies

Approach:

1. Procedure development that would ensure the development of a method that will determine quagga mussel mortality, removal and non-attachment
2. Testing of oxidant and other non-oxidizing chemical applications to determine dosage and contact time requirements with consideration of the effects of environmental variables. Outcomes should be expressed in terms of mortality, removal and non-attachment
3. In-lab testing with field verification

Recommended Budget:

1. Method development: $250,000.00
2. Testing of oxidizing chemicals (CT): $250,000.00
3. Testing of non-oxidizing chemicals: $250,000.00
4. Pilot plant and in-field verification of results: $500,000.00

Recommended Schedule:

1. Method development: 1 year
2. Testing of oxidizing and non-oxidizing chemicals: 1 year
3. Pilot plant and in-field verification: 1 year

PROJECT TITLE:

HYDRAULIC EFFECTS ON VELIGER MORTALITY IN ENGINEERED SYSTEMS

Background: Quagga mussel veligers are found in water pumped from Lake Havasu by the Central Arizona Project through the Mark Wilmer Pumping Station. The plant pumps water in a single pumping stage with a single impeller pump for a total lift of 824 feet. No veligers have been observed to have settled between the top of the lift and the Bouse Hill Pumping Station 25 miles to the east. It is unknown if the veligers are experiencing mortality or injury and if so, the mechanism of damage is unknown. It has been hypothesized that shear forces, rapid pressure change, gas embolism, cavitation or rapid velocity change encountered during pumping could be impacting the veligers. If pumping is impacting the veligers, the pump lift stage at which injury occurs is not known.

The MWD pump lift plant is close to the Mark Wilmer Pumping Station, but has a lift of only 200 feet. Both pump stations take veliger rich water from Lake Havasu, but the MWD plant is experiencing heavy mussel infestation in the pump discharge within the canal, while the Central Arizona Project is not. While the pumping process at the Mark Wilmer Pumping Station is somewhat unique, there are sufficient instances of pump lifts of similar magnitude in the western United States. The investigation of this apparent control mechanism should be of interest to other water utilities.

Objectives:

1. To determine if veligers are damaged/killed as a result of the pumping processes like those found in the Central Arizona Project and determine the mechanism causing veliger injury or mortality
2. To determine the threshold at which the "mechanism" becomes effective
3. To determine if the "mechanism" of veliger injury/mortality should be practically reproduced/applied in other settings

Approach:

Determine possible mechanism of injury/mortality in CAP case study:

1. Identify the pumping parameter causing veligers injury/mortality. Factors may include:
    a. Rotational speed
    b. Impeller diameter and design
    c. Volute design
    d. Exact differential pressure
2. Investigation of the rate of pressure change occurring within the pumping system
3. Development of a test facility that will have the capability to duplicate on a small scale the flow conditions up to and including those at Mark Wilmer Pumping Station

4. The test facility will have the capability of measuring all possible injury mechanisms, including but not limited to the mechanisms identified in the background
5. The test facility will have the ability to identify the injury mechanism in detail through laboratory analysis, including the threshold pumping values under which injury occurs
6. Identify suitable test locations for replication of the CAP pump system under similar conditions to those found at the original pumping location

Recommended Budget: $1,000,000.00

Recommended Schedule: 18 months

PROJECT TITLE:

QUAGGA MUSSEL VULNERABILITY ASSESSMENT AND RESPONSE MANAGEMENT TOOL DEVELOPMENT

Background: Water systems in the west transport water over long distances and from multiple sources using a variety of structures, processes and conveyance systems. These systems are at risk and many are already experiencing quagga mussel infestations. Water systems need to respond to this emerging issue in a timely and effective manner and currently no concise guidance is available. There are numerous tools for monitoring and control and agencies need to consider which are most effective given their particular situation and risk tolerance.

Municipalities, water supply agencies and natural resource managers throughout the country/world have experience with Dreissenid species under a wide range of environmental and operational conditions. There is great potential to learn from the successes and failures of these groups in their efforts to address prevention, treatment and remediation. Summarizing these case studies in a central document would facilitate the dissemination of these results.

Objectives:

1. Determine a vulnerability assessment tool, development should consider:
    a. The types of system
    b. Extent of vulnerability
    c. Regulatory constraints
    d. Options available for combating vulnerability
        i. Potential effect of integrated management choices on subsequent users
        ii. Reactive approaches
        iii. Proactive approaches
        iv. Enforcement potential
        v. Unintended consequences
2. Development of case studies to guide future activities based on a more comprehensive understanding of past successes and failures
3. Development of guidance documents that would include checklists and other decision matrices to assist in management strategy development

Approach:

1. Develop a guidance document that guides the evaluation of the following factors:
    a. Define the physical/chemical/biological characteristics of the water
    b. Characterize conveyance and downstream affected infrastructure
    c. Define infestation vectors and control strategies
    d. Define chemical/physical/biological control strategies
    e. Define a monitoring program
    f. Develop and apply vulnerability/risk assessment tools

   g. Develop a containment/mitigation/eradication response plan
      i. Short term (emergency)
      ii. Long term
2. Identify areas/managers that have confronted Dreissenid invasions in the past and develop case studies based on their experiences (e.g. Metropolitan Water District)
3. Develop detailed case studies of these invasions including but not limited to:
   a. System description
   b. Preventive measures
   c. Initial detection
   d. Initial response
   e. Modified response and actions taken
   f. Measures of success or failure

Recommended Budget: $500,000.00

Recommended Schedule: 1 year

PROJECT TITLE:

DEMONSTRATE ALTERNATIVE, NON-CHEMICAL, CONTROL TECHNOLOGIES FOR QUAGGA MUSSELS FOR DEPLOYMENT AT WATER TREATMENT FACILITIES

Background: Alternative technologies such as small pore, self-cleaning filtration and UV disinfection have been demonstrated as effective controls for Dreissenid mussels. There is a need for a method of non-chemical exclusion of veligers to keep them from entering water treatment facilities. These technologies are not being widely used, primarily for three reasons: perceived novelty of the technology, lack of confidence in the product and higher initial cost of application.

The advantage of these technologies is the ability to treat large volumes of water while maintaining a small footprint with minimal or no waste of water. These technologies do not negatively interfere with the quality of the final product (i.e. production of THM's in drinking water) and they do not involve hazardous materials. Further, these technologies do not generally require regulatory approval for installation. In the case of the small pore self-cleaning filter technology, an additional benefit would be the removal of silt particles from the incoming water.

Objectives:

1. Demonstrate that these alternative control technologies are mature and reliable under field installation and normal operating conditions
2. Using a full cost-benefit analysis, evaluate the installation and operation of these technologies compared to other treatments

Approach:

1. Start with a pilot sized, fully instrumented installation (i.e. treating approx. 500 gpm). Operating in an actual facility, demonstrate that the technology meets the required criteria (veliger removal/inactivation, log removal credits for UV, silt removal, longevity, maintainability, operability). As the top three manufacturers should be tested for each technology, the technology would be skid mounted to facilitate the testing of various candidate manufacturers under identical conditions
    a. The most successful pilot sized installation would be scaled up to demonstration size (5,000 gpm). Perform the same evaluation as above
2. Investigate the opportunity to integrate these technologies with other water treatment technologies/methods
3. Conduct a detailed cost-benefit analysis of alternative and traditional treatment approaches

Recommended Budget:

1. Top three manufacturer's products tested under identical condition (3 filters, 3 UV installations): $600,000.00
2. Demonstration project of one installation of filter and UV: $1,000,000.00
3. Cost-benefit analysis: $150,000.00

Recommended Schedule:

1. Manufacturer tests should begin immediately
2. Demonstration project should begin within 18 months
3. Cost-benefit analysis to follow completion of manufacturer tests

PROJECT TITLE:

MOLLUSCICIDES AND BIOCIDES FOR CONTROL OF DREISSENID MUSSELS IN WATER RESOURCES

Background: Various molluscicides and biocides have been used in attempts to control the spread of these invasive species, to reduce the impact of molluscan species on man-made structures and to reduce and prevent the spread of diseases that require a molluscan intermediate host. The mode of action for these pesticides varies, as compounds as diverse as metal salts to complex organic compounds have been used successfully. Some require detoxification/inactivation by adsorption onto clay particles, while others can be allowed to dissipate naturally. A comprehensive synopsis of available molluscicides and biocides is needed to aid resource managers attempting to address Dreissenid mussel invasions. Recent success in identifying bacteria and bacterial toxins that destroy Dreissenid mussels should be enhanced and applied to western waters.

Objectives:

1. Develop a comprehensive review of available molluscicides and biocides that might be used to mitigate or eliminate the impact of Dreissenid mussels in water supply and distribution systems
2. Support ongoing efforts to develop microbial control technology for Dreissenid mussels

Approach:

1. Prepare a comprehensive literature review of existing peer-reviewed and governmental reports and documents
2. Review should include information addressing:
    a. Available molluscicides and biocides
    b. Permitted and excluded uses of identified molluscicides and biocides
    c. Evidence of efficacy, with identification of relevant environmental variables
    d. Additional conditions (e.g. detoxification) required for use
3. Supplement and coordinate ongoing biocide investigations and apply these results to stations on the lower Colorado River

Recommended Budget:

1. Comprehensive literature review: $250,000.00
2. Support of ongoing biocide research: $1,500,000.00

Recommended Schedule:

1. Literature review: 1 year
2. Biocide research: 3 years

PROJECT TITLE:

COATINGS AND MATERIALS FOR CONTROL OF DREISSENID MUSSEL ATTACHMENT IN WATER RESOURCE PROJECTS

Background: Various coatings and materials have been used in attempts to control fouling of surfaces by these invasive species and to reduce the impact of molluscan species on man-made structures. The mode of action for these coatings and materials varies, but can generally be classified as either ablation/erosion or non-adhesion. Ablative coatings slowly scour from the applied surface, limiting colonization, while non-adhesion coatings prevent successful attachment. A comprehensive synopsis of available coatings and materials is needed to aid resource managers attempting to address Dreissenid mussel attachment.

Objectives:

1. Develop a comprehensive review of available coatings and materials that have been used to prevent or minimize attachment by Dreissenid mussels in water supply and distribution systems

Approach:

1. Prepare a comprehensive literature review of existing peer-reviewed and governmental reports and documents
2. Review should include information addressing:
    a. Available coatings and materials
    b. Permitted and excluded uses of identified coatings and materials
    c. Evidence of efficacy, with identification of relevant environmental variables
    d. Additional conditions (e.g. flow velocity) required for successful use

Recommended Budget:

1. Comprehensive literature review: $250,000.00

Recommended Schedule:

1. Literature review: 1 year

PROJECT TITLE:

EARLY DETECTION METHODOLOGY AND RAPID ASSESSMENT PROTOCOLS FOR QUAGGA MUSSELS

Background: Rapid responses and early detection of invasive species has been helpful in reducing the impact of these species and could be useful in preventing successful colonization of quagga mussels invading new areas. Early detection requires two components: analytical techniques for the rapid processing of samples and a proactive monitoring protocol to collect those samples. To facilitate early detection, the analytical technique(s) must be refined and tested to the point that they require a reasonable skill level to perform with confidence. The protocol for assessing systems must not be so cumbersome so as to limit its use.

Objectives:

1. Development of analytical tools to aid in the identification of quagga mussel invasions
2. Develop a rapid assessment protocol to enable managers to identify invasions or potential invasions in an efficient manner

Approach:

1. Preparation of a literature review of existing Dreissenid and other molluscan detection methods to identify protocols that could be implemented or improved upon
2. Exploration of the use of biotechnological approaches similar to those developed for Cyanobacterial toxins to detect chemical signatures of the presence of quagga mussels (e.g. ELISA techniques)
3. Development of a comprehensive rapid assessment technique integrating detection methodologies as well as sampling requirements

Recommended Budget:

1. Literature review: $250,000.00
2. Detection method development: $500,000.00
3. Rapid assessment technique: $250,000.00

Recommended Schedule:

1. Literature review: 1 year
2. Detection method development: 2 years
3. Rapid assessment technique**:** Preliminary results after literature review, integrated protocol within 1 year of method development