RNT Consulting Inc.
823 County Road 35
Picton, Ontario, Canada
K0K 2T0

Phone 613 476 7994
Fax 613 476 0279

Assessment of the Potential Impact of Invasive Mussels on Water System Facilities and Structures and Recommendations for Control - Pueblo Reservoir, Fryingpan-Arkansas Project

Prepared for: Eastern Colorado Area Office, Bureau of Reclamation

Prepared by:

Renata Claudi MSc & Tom Prescott MSc, PEng.

Date: February 23, 2009

Contract Number: 09PG810044

TABLE OF CONTENTS

EXECUTIVE SUMMARY

In November of 2007, the Colorado Division of Wildlife (CDOW) discovered two unconfirmed suspect mussels attached to a substrate sample at the North Marina of Pueblo Reservoir in Colorado. They also conducted a plankton tow in this area and found larvae that were later verified by DNA testing as zebra mussel larvae. This was the first documented finding of Dreissena mussels in Colorado. Since that time quagga mussel larvae have also been confirmed. At this time, the source of veligers collected in the reservoir is not known; however, no adults have been confirmed to date.

In November 2008, RNT Consulting Inc. (RNT) was asked by the Eastern Colorado Area Office, Bureau of Reclamation (Reclamation) to examine the Pueblo Dam and other features of Pueblo Reservoir to provide an assessment on the vulnerability of the dam and recommend possible control strategies.

Although examination of environmental suitability of the Pueblo Reservoir for mussel survival was not part of the contract requirement, some idea of environmental suitability is helpful when assessing the magnitude of risk to facilities and structures. For this reason, RNT examined environmental data for Pueblo Reservoir collected by U.S. Geological Survey (USGS) from 2006 to 2008. RNT also used the summary data available in the Lake Pueblo Zebra Mussel Response Plan and conducted a brief physical survey of a portion of the exposed bed of the reservoir during the site visit. Based on the limited data analyzed, this effort by no means replaces a full scale assessment of environmental suitability.

Based on experience in the Great Lakes and in Europe, data available indicates that there is more than adequate calcium in the water to support a massive Dreissenid population. When calcium data is not available, populations of Asian clams (if present) are taken as an indicator of possible Dreissena success. Asian clams have roughly the same environmental requirements as dreissenids and a high population of Asian clams predicts high likelihood of successful dreissenid invasion. During the brief site visit to the exposed beach of the reservoir, the authors noted that the Asian clam population in this part of the reservoir appeared very low, especially when compared to the massive population present in Bessemer Ditch. The irrigation ditch is downstream of the reservoir which draws water from the reservoir, but is shallow and probably well oxygenated. This leads us to speculate that unless the Asian clams have buried themselves in the sediment or followed the falling water level into deeper parts of the reservoir, environmental parameters other than calcium may have a mitigating effect on the Asian clam population. If there is an environmental parameter which has a mitigating effect on the Asian clams, it may have a similar effect on dreissenids. Dissolved oxygen level appears a likely candidate as a mitigating factor, particularly as the USGS data for dissolved oxygen collected during the last three years indicate very low dissolved oxygen levels. This was especially true during the summer months at depths greater than 20 feet. This hypothesis is based on limited observation and data and should be examined in further detail as it may have implications for reservoir management.

Warm summer water temperatures and large periodic swings in pH may also be contributing to an environment where the mussel populations may not be vigorous. The annual level fluctuation of the reservoir can also contribute to overall mussel mitigation, particularly if the drawdown reaches the elevation of low summer dissolved oxygen. The drawdown in 2008 appears to have reached the depth of low dissolved oxygen based on USGS data.

There was no risk to dam safety identified. While mussels may be able to travel with normal dam seepage into the dam drainage system, the drains are substantial in size, monitored frequently and able to be cleaned in a straight-forward manner. The current dam practices of inspection and investigation should be sufficient to deal with any mussel presence in the drainage system. Extra attention to vent lines is warranted due to possible pipe collapse from plugged vent lines.

We found no signs of Asian clams or snails in any of the open drain gutters within the dam. However, it is important to note that at other times both snails and clams may be present. Reclamation observed snails in the dam drain gutters earlier in 2008.

The main potential effect to the dam from a mussel infestation appears to be accumulation of mussels on the hydraulic structures such as conduits, piping and trashracks. All water conveyance components have some extra flow capacity so that any mussel accumulation can be monitored and cleaning planned accordingly to maintain water delivery commitments. The effect of mussel accumulation on these structures will therefore likely be an economic addition to the operations and maintenance budgets only. There is low probability that a sudden or unplanned water delivery interruption will occur.

Continued monitoring is recommended and is critical to help detect adult mussels and establish the seasonal distribution of dreissenid veligers. Monitoring will help identify the source of veligers, establish the mussel distribution within the reservoir and determine how much effect the mitigating parameters (particularly dissolved oxygen) identified above have on mussel density and population growth. Trends are valuable so that future plans can be developed to best address the mussel issue. This information can also contribute to future maintenance and budget planning. To be most effective, the monitoring program needs to be able to determine if the mussels are alive or dead at the time of sampling.

1.0 INTRODUCTION

Pueblo Reservoir is a component of the Fryingpan-Arkansas (Fry-Ark) Project, which is a multipurpose transmountain, transbasin water diversion and delivery project in Colorado. Fry-Ark makes possible an average annual diversion of 69,200 acre-feet of surplus water from the Fryingpan River and other tributaries of the Roaring Fork River, on the western slope of the Rocky Mountains, to the Arkansas River basin on the eastern slope.

Pueblo Reservoir is approximately 4,646 surface acres in size at the top of the Active Conservation Pool (4880.49 ft) with approximately 60 miles of shoreline. The reservoir has a total storage capacity of 349,940 acre-feet at the top of the Exclusive Flood Control Pool (4,898.7 ft). The water level varies temporally based on natural resupply and management practices resulting in corresponding variations in shoreline distance and surface area.

Pueblo Reservoir is approximately 11.4 miles long and averages a width of 0.8 miles. Based on the top of the Joint Use Pool (elevation 4893.8 ft) and the original streambed elevation of 4725 ft, the reservoir is 169 ft deep at its deepest point. At the North Marina, it is typically 85 ft deep and at the South Marina, it is typically 81 ft deep.

Water stored in Pueblo Reservoir is used by at least 80 different entities. Its largest storage components are water diverted from the Colorado River basin as part of the Fry-Ark Project and water stored for municipal ditch companies east of Pueblo as part of the Winter Water Storage Program.

Flows out of Pueblo Reservoir can range from 50 cubic feet per second (cfs) in the winter months to the maximum downstream channel capacity of 6,000 cfs during spring runoff. Typical summer releases are in the 500 to 2,000 cfs range.

Lake Pueblo State Park is one of Colorado's most popular State Parks. Located on the Arkansas River in northwestern Pueblo County, the park is within two hours of Denver and Colorado Springs. It is about six miles upstream and on the western edge of the Pueblo metropolitan area and abuts the eastern slope of the Rocky Mountains. The major attraction of the park is the lake which sees around 1.6 million visitors each year.

The CDOW found two suspected adult mussels attached to a substrate sampler in November 2007; however, confirmation was not attainable since the samples were not preserved properly. At that same time a plankton tow was conducted in the North Marina area and microscopic analysis of the sample identified dreissenid veligers. In January 2008, DNA analysis confirmed the larvae were zebra mussels. Throughout the summer of 2008, Reclamation and CDOW conducted sampling, which concentrated on the most likely areas for mussel populations. Quagga veligers were first confirmed from samples taken in July 2008. Zebra and quagga veligers were detected on different sampling dates and from different sampling locations. To this point, no adult mussels have been confirmed at Pueblo Reservoir.

Zebra mussels are members of the dreissenid family of bivalves. Together with their sister species, the quagga mussel, these non-native, invasive mussels are an environmental and economic nuisance to North America.

Dreissenid mussels are aggressive bio-foulers. When present in dam infrastructure or the source of raw cooling water, mussels become a serious problem for industrial facilities using this water unless control actions are taken. There are two main types of fouling: acute and chronic.

Chronic fouling occurs when juvenile quagga mussels attach themselves to external and internal structures. The juvenile mussels accumulate and grow in place resulting in reduced water flow rates and in some cases can even cut off the water flow.

Acute fouling occurs when a large build up of adult mussel shells, alive or dead, becomes detached from upstream locations and is carried by the water flow into piping systems. The large quantities of mussel shells quickly plug small diameter pipes, fixed strainers, filters, heat exchangers, and other system components. Such events can occur at unexpected times and, if not anticipated, can have rapid and significant consequences. It is essential that any facility experiencing mussel fouling is prepared to deal with both types of fouling.

When veligers were found in 2008, Reclamation decided to take proactive steps and evaluate the susceptibility of the Pueblo Dam and it appurtenances to mussel fouling. RNT Consulting was engaged to lead the process and to make the evaluation methodology available to Reclamation for use at other facilities.

This report is a summary of the findings on:

1) Brief summary of findings on environmental suitability of Pueblo reservoir to Dreissena infestation

2) Areas of the dam at risk from mussel fouling,

3) Best management practices for coping with mussel invasion and control options for raw water systems.

It is important to note that this report contains what we believe are practical options for dreissenid mussel mitigation at each facility, but this report is not intended to represent an engineering evaluation of these options.

2.0 ASSESSMENT PROCESS and METHOD

Reclamation provided RNT with flow diagrams and general arrangement drawings of raw water piping systems at the dam. RNT studied the drawings prior to commencing the site visit in November 2008. The site visit team consisted of staff from RNT, Reclamation, and the Southeastern Colorado Water Conservancy District. The team inspected all accessible areas from trashracks to discharge, identifying various components and cooling systems previously highlighted on the drawings. During the inspection, the team was able to identify potential threats and impacts to the systems and to individual components.

In addition, a brief shoreline inspection of the reservoir was conducted as well as an inspection of the dewatered Bessemer Ditch just below Pueblo Reservoir, which is used to deliver irrigation water in the summer. The latest three years of USGS water quality data for Pueblo Reservoir were also examined, focusing primarily on dissolved oxygen levels. Summary data available in the Lake Pueblo Zebra Mussel Response Plan was also used.

3.0 RESULTS of the ASSESSMENT

3.1.: General Environmental Suitability for Dreissenid Mussel Infestation

Koutnik and Padilla (1994) used a geographical information system (GIS) to test for associations between predicted lake population density classes and three landscape-scale characteristics (surficial deposits, bedrock type, ecoregions) to predict:

(i) absence or presence,

(ii) categorical population density,

(iii) numerical abundance,

of zebra mussels for inland Wisconsin lakes. Although the models used differed in their predictions of specific lakes that would support Dreissena, they found a significant association between each landscape-scale characteristic and Dreissena density classes. Numerous researchers (Appendix A) have used available lake monitoring data to predict Dreissena density for inland lakes. It is clear that the more information is available, the less uncertainty exists in the predictions.

Some parameters have better correlation with mussel survival and density than others. The most common parameters used (and listed in order of their predictive value from most predictive to least predictive) are:

- calcium content
- alkalinity, total hardness
- pH
- nutrients (total phosphorous, total nitrogen, chlorophyll *"a"* levels), Secchi depth
- dissolved oxygen content
- mean annual temperature
- conductivity (and/or salinity, total dissolved solids).

Although mean annual values of each of the parameters can be used, temporal (e.g. seasonal) and spatial (e.g. depth, horizontal) variations lend more certainty to the predictions of mussel survival and potential densities.

Calcium, alkalinity, pH, and total hardness are considered “chalk” parameters as they are generally related to the water mineral content. Of the chalk parameters, the calcium level is by far the most used and most reliable. The alkalinity informs us of the availability of the calcium. The total hardness consists of temporary hardness (i.e. amount of calcium and magnesium) in carbonate form and is similar to alkalinity values and permanent hardness (i.e. the amount of calcium and magnesium in non-carbonate form that is largely unavailable to mussels). The pH governs the form of carbonates. For pH values below 8.2 all the calcium is in bicarbonate form and values above 8.2 have the calcium in monocarbonate form. Removal of carbon dioxide (e.g. by photosynthesis of plants and algae) results in precipitation of calcium carbonate, making it unavailable to mussels. Hence, while calcium is the key variable, knowledge of the values of the other chalk variables are also important in predicting densities of dreissenids.

The nutrient parameters (e.g. total phosphorous and nitrogen), chlorophyll *“a”* levels, Secchi depth and dissolved oxygen content are known as “trophic indicators” and all are related. The higher the values of the nutrient variables, the greater the biomasses of algae and hence of chlorophyll *“a”*, and dissolved oxygen (at the surface), and the lower the Secchi depth values (i.e. water is more turbid). Since mussels feed on algae, the values of the trophic indicators are also important criteria for predicting dreissenid densities. Total phosphorous should be used when phosphorous is limiting and total nitrogen used when nitrogen is limiting.

Dissolved oxygen in deeper waters of lakes and reservoirs may become a limiting factor during portions of the year. Seasonal oxygen profiles should be verified in all bodies of water examined.

Conductivity and mean annual surface water temperature are the only physical criteria used. Temperature becomes critical when the body of water in question is close to either the upper or lower thermal limit for veliger survival. Conductivity is rarely an issue, but it should be verified in all cases.

3.2.: Environmental Suitability of Pueblo Reservoir for Dreissenid Mussel Infestation

The following table was derived from the values reported by various authors and gives the ranges of values for each of the parameters and the potential risk of invasion. Values for Pueblo Reservoir were added, using data given in the Lake Pueblo Zebra Mussel Response Plan as well as data provided by USGS for 2006-2008. The ranges are shown in brackets. At this point we have to rely on experience collected in the east of North America to predict the behaviour of dreissenids in the west (Table 1). While some slight changes in tolerance of environmental parameters are possible and expected, we do not expect that the basic environmental requirements of the species will drastically change. For example, the key parameter, calcium content and its availability, is not expected to be less in the west than it is in the east. Based on the levels reported for Pueblo Reservoir, there is ample calcium to support massive mussel populations.

Table 1 Criteria used in determining levels of infestation in temperate zone

Parameter	None	Little	Moderate	High	Pueblo
Calcium (mg/L)	<10	<16	16-24	≥24	48.6 (23 – 75)
Alkalinity (mg $CaCO_3$/L)	<35	35-45	45-89	>90	No data
Total Hardness (mg$CaCO_3$/L)	<40	40-44	45-90	≥90	No data
pH	<7.2	7.2-7.5	7.5-8.0 or 8.7-9.0	8.0-8.6	8.2 (7.1- 9.4)
Mean Summer Temperature (^oF)	< 64	64-68 or > 82	68-72 or 77-82	72-75	63 (34-83)
Dissolved Oxygen mg/L (% saturation)	<6 (25%)	6-7 (25-50%)	7-8 (50-75%)	≥8 (>75%)	6.2 (0 - 14.1)
Conductivity (µS/cm)	<30	<30-37	37-84	≥85	164 -542
Salinity mg/L (ppt)	>10	8-10 (<0.01)	5-10 (0.005-0.01)	<5 (<0.005)	No data
Secchi depth (m)	<0.1	0.1-0.2 or >2.5	0.2-0.4	0.4-2.5	No data
Chlorophyll a (µ/L)	<2.5 or >25	2.0-2.5 or 20-25	8-20	2.5-8	0.9-48.8
Total phosphorous (µg/L)	<5 or >35	5-10 or 30-35	15-30	10-15	2 -36
Total Nitrogen (µg/L)	<200	200-250	250-300	300-500	No data

There are a number of parameters that, for at least portions of the year, could limit the survival of mussels (either as adults or veligers) and therefore impact the population density of mussels in Pueblo Reservoir. Evaluating environmental parameters in detail may provide options for various reservoir management strategies to be used in such a way as to assist in reducing the impact of the mussels on the reservoir and associated facilities. For example, if dissolved oxygen is below the survival threshold of mussels in the deeper sections of the reservoir, then by drawing water only from the lowest intakes would result in low populations of veligers delivered to downstream users.

Parameters which should be examined in greater detail are pH, mean summer temperature, chlorophyll *"a"* and dissolved oxygen.

3.2.1: pH levels

The pH levels vary quite dramatically in the reservoir. Although the average value is 8.2, levels as low as 7.1 and as high as 9.4 have been recorded. Depending on the depth and season during which the extremely low/high levels occur, low pH could have negative effects on the capability of dreissenid veligers to settle. Studies by Nierzwicki-Bauer at al. in 2000 documented that adult mussels are able to survive in Lake George, New York water (Ca= 10.5 mg/L, pH=7.15) but veligers fail unless both calcium and pH levels are raised. The study placed healthy veligers, up to two weeks of age in Lake George water. There was 100% mortality within one week. Adding calcium up to 30 mg/L failed to help veliger survival until the pH was increased as well.

3.2.2: Temperature

Mean summer temperature is more meaningful than an annual average for areas which experience very warm summers. If portions of the reservoir are indeed at 28.5 ^{o}C (83^{o}F) as reported in the Lake Pueblo Zebra Mussel Response Plan, then high summer temperatures could limit settlement in those areas of the reservoir experiencing such temperatures. The data provided by the USGS, however, did not record any temperatures higher than 26 ^{o}C (80^{o}F). Therefore, temperature may only be a mitigating factor in exceptionally warm years.

3.2.3: Chlorophyll

Chlorophyll *"a"* as recorded by USGS, undergoes wild seasonal swings. It seems to vary from too little chlorophyll *"a"* to support any mussels to a value so high that the algal blooms might actually be smothering the gills of mussels causing significant mortality. Again, the timing and the duration of the chlorophyll *"a"* peaks and valleys will determine what impact, if any, it would have on dreissenid populations.

3.2.4: Dissolved Oxygen

Dissolved oxygen is a parameter of great interest (See Figures 1 through 6). The average value given in the Lake Pueblo Zebra Mussel Response Plan is 6.2 mg/L. This would place Pueblo Reservoir in the "little infestation" category. The swings in dissolved oxygen appear to be profound. In the USGS data examined, the levels of dissolved oxygen vary from hyper-saturation at 14.1 mg/L (suggesting heavy algal blooms) to a value as low as 0 mg/L which would result in mussel mortality (see graphs in following pages). It was not in the scope of this report to examine all available historical data to determine if this seasonal variation in dissolved oxygen was historically continuous, although knowing this answer would provide more insight.

The seasonal distribution of dissolved oxygen in Pueblo Reservoir will determine what effect the low dissolved oxygen may have on settlement success of dreissenid veligers. In areas of the reservoir where dissolved oxygen levels fall below the necessary minimum for veliger settlement during the dreissenid breeding season, settlement will be limited.

Our observations on the dissolved oxygen levels are based on data from three stations in the reservoir sampled by the USGS. If doubt exists that the low dissolved oxygen levels are present throughout the reservoir, additional data could be collected.

Following are graphs of data for the three stations which were sampled by the USGS from 2006 to 2008.

T3B station is shallow and probably in the range of the annual reservoir level fluctuations. It is located in mid-reservoir just downstream of where Turkey Creek enters Pueblo. The water appears reasonably mixed in the upper 30 ft. There is downward trend in dissolved oxygen with depth.

TC5 station is deeper. It is located about mid-reservoir, just downstream of where Peck Creek enters the reservoir. The dissolved oxygen (DO) at this site falls off sharply during August of both years sampled at depths of 10 to 20 ft. In 2006, water deeper than 15 ft had less than 4mg/l DO, and in 2007 that level of DO was reached at 30 ft.

T7B is the deepest station sampled. It is located about mid-reservoir near the dam. It shows the same DO pattern as the previous station. In August of 2006, 4mg/L was reached at 36 ft. In 2007, this level was reached at 23 ft and in 2008 at 33 ft.

Data was also available for the dissolved oxygen in the top layer and the dissolved oxygen at greatest available depth for each station.

Figure 1. DO Levels - Pueblo Reservoir at Turkey Creek (T3B)

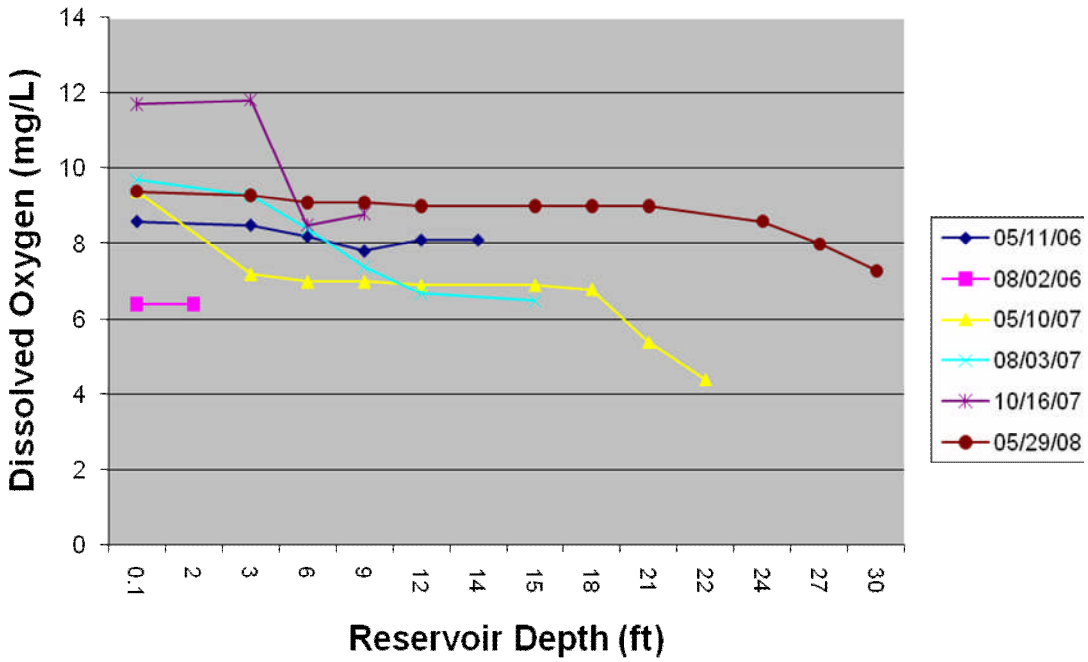


Figure 2. DO Levels - Pueblo Reservoir at Turkey Creek (T5C)

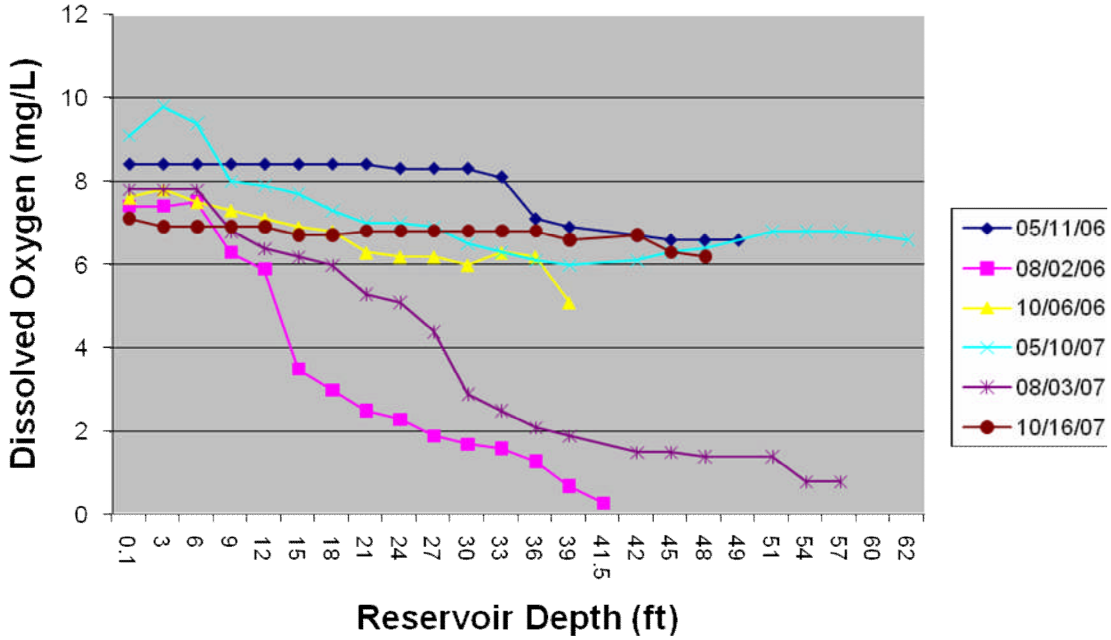


Figure 3. DO Levels - Pueblo Reservoir near Dam (T7B)

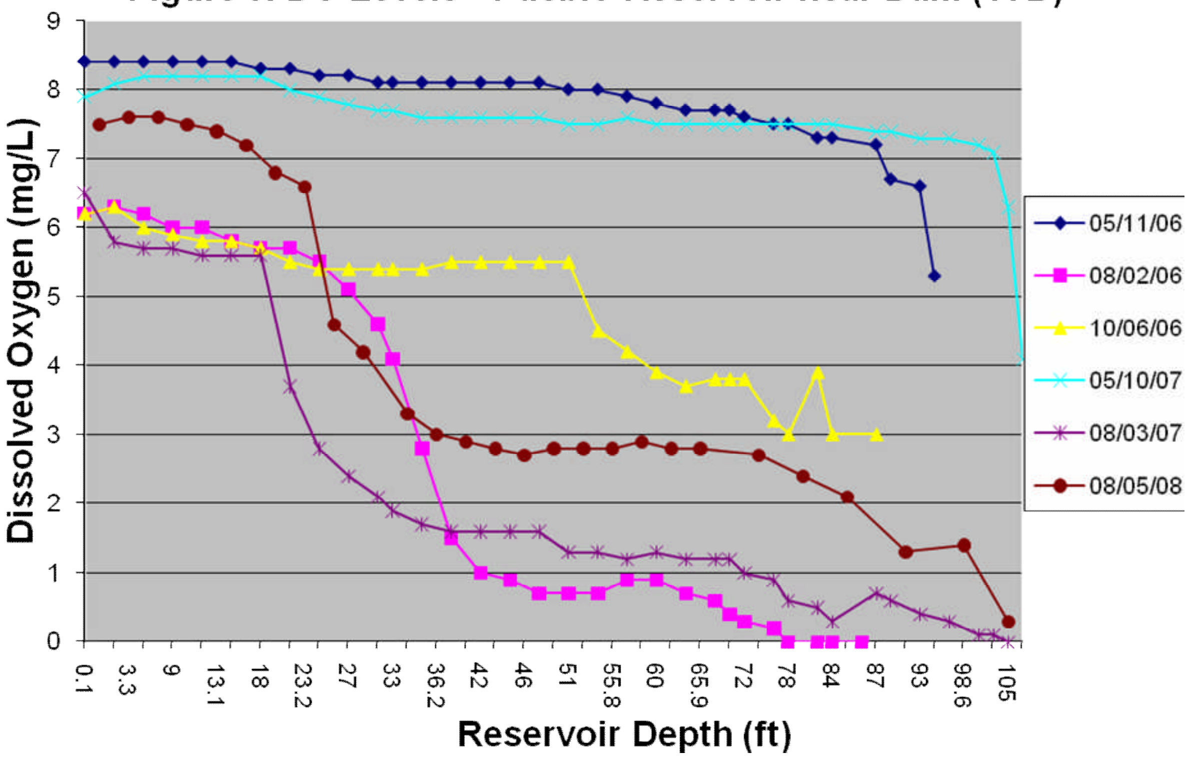
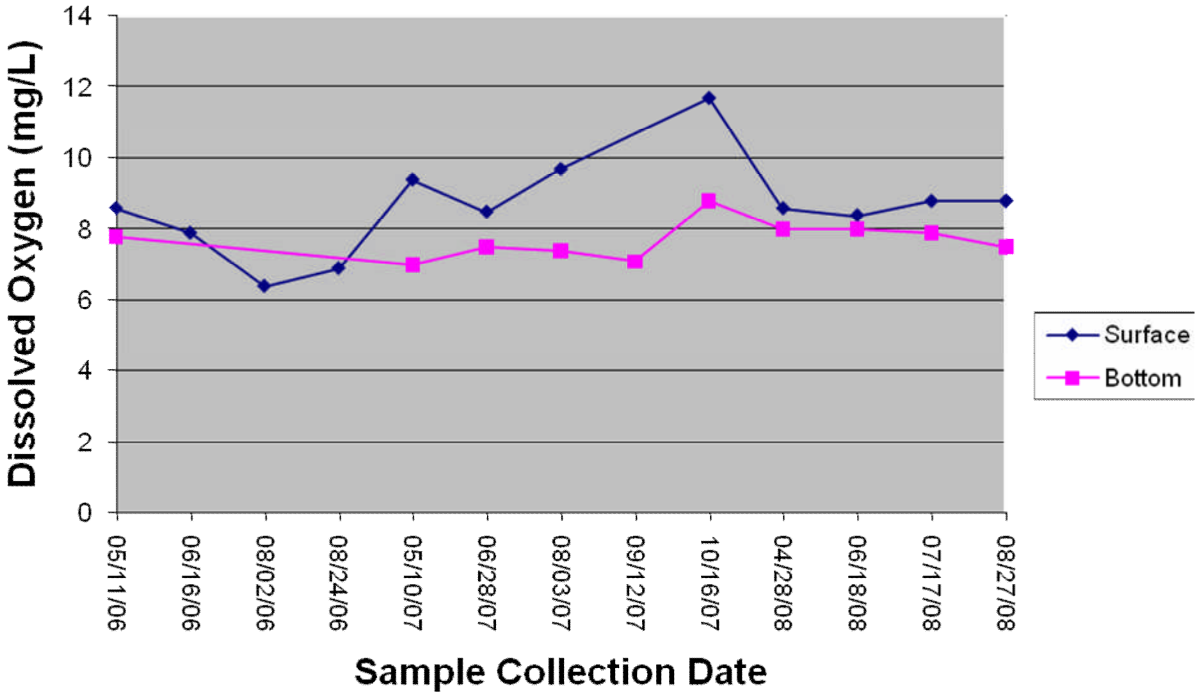


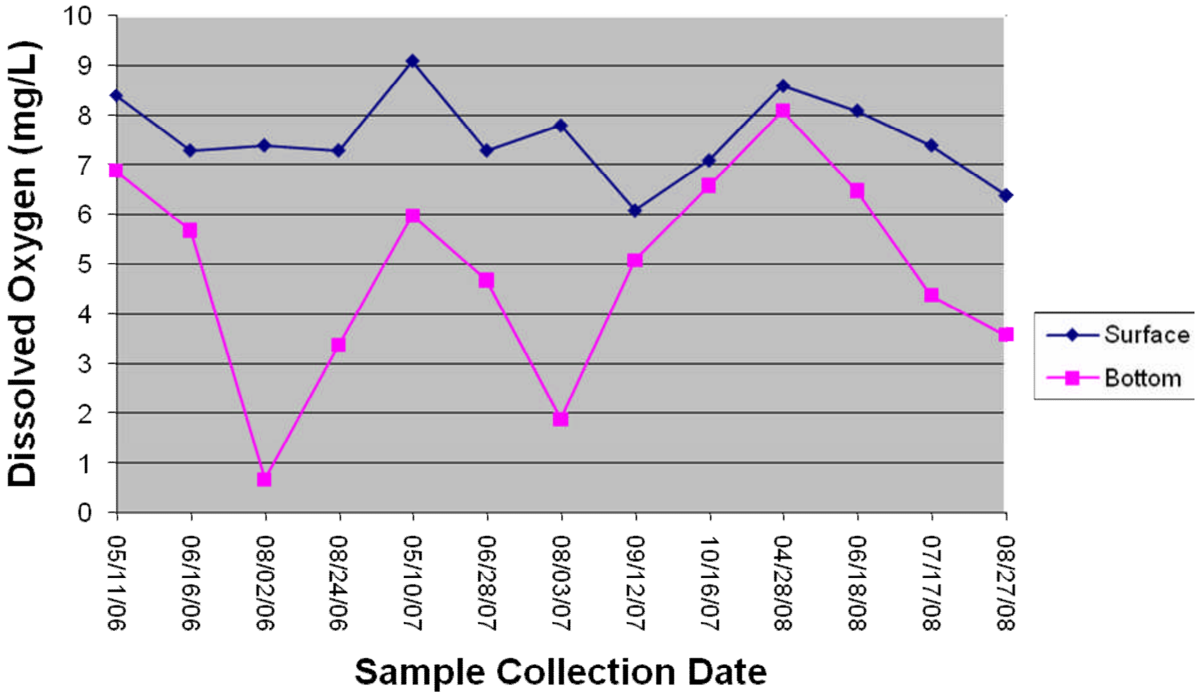
Figure 4. Seasonal DO Profile - Pueblo Reservoir at Turkey Creek (T3B)



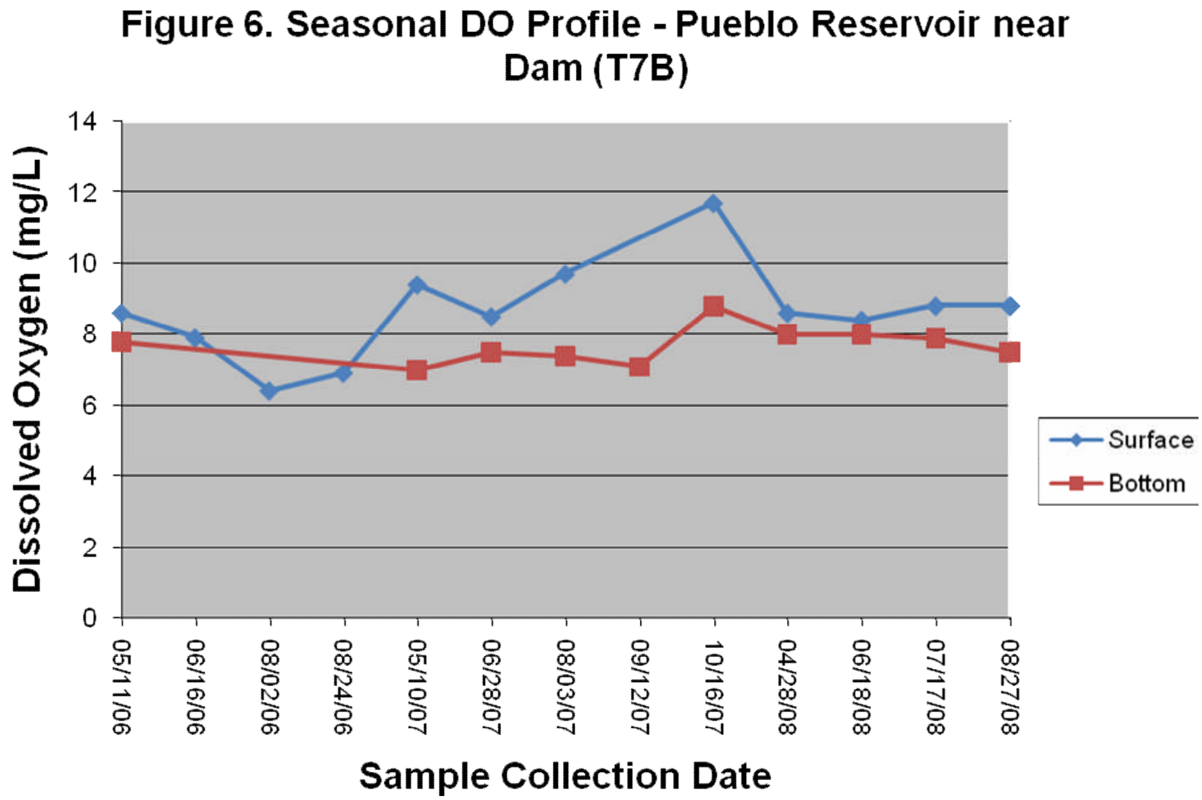
At the shallow station T3B (max. depth 30 ft) the DO shows the late October turnover when bottom DO values seem to peak. It also shows the steady decline in DO from April 2008 to September 2008.

At the deeper station, T5C (max depth 60 feet) the trend is very clear. The bottom layer plummets to near 0 mg/L every August. The decline begins in mid June and continues until the fall turnover in October. Depending on the year, this low oxygen level can start at 15 ft deep or as deep as 30 ft. Below this top layer, for four months on average, there is dissolved oxygen low enough to mitigate veliger settlement. If the reproductive pattern of the dreissenids in Pueblo reservoir follows the reproductive pattern of dreissenids in eastern bodies of water with similar temperature profiles, the period of low dissolved oxygen could coincide with the time of maximum veliger production.

Figure 5. Seasonal DO Profile - Pueblo Reservoir at Peck Creek (T5C)



The deepest station measured T7B (maximum depth 108 ft) shows the same seasonal profile as the previous station. Again, depending on the year, the area of low dissolved oxygen (below 4mg/L) begins in depth between 30 and 45 ft.



Dreissenid mussels are relatively intolerant of low dissolved oxygen concentrations. They have been reported to thrive in water with at least 70%– 80% oxygen saturation. Dreissenids have been found in water with oxygen saturation as low as 50%, but long term survival under those conditions is uncertain.

The following is a schematic of the relationship between dissolved oxygen, temperature and percent saturation at 25ºC (77 ºF) at sea level. By drawing a straight line between the temperatures measured to the oxygen value recorded, oxygen saturation percentage can be read from the inclined line.

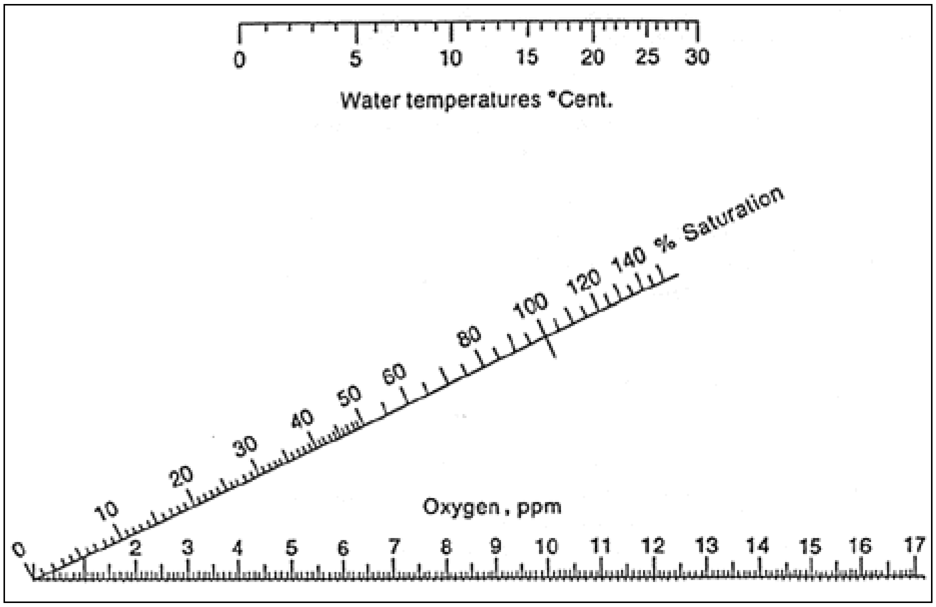


Figure 7: Dissolved Oxygen concentration and %saturation vs ambient temperature.

Dissolved oxygen saturation level needs to be adjusted for elevation. It falls by 4% for every 1,000 feet of elevation. Therefore, if 10mg/L is a 100% saturation level at 11.5ºC at sea level, at 5,000 feet the 100% saturation level will be 8 mg/L.

It is not clear if, or how, altitude will affect the dissolved oxygen requirements of the dreissenids.

On the site visit to Pueblo Reservoir, the reservoir level was approximately 30 feet lower than normal due to the annual drawdown. During a brief inspection of a small portion of the dewatered area of the reservoir, we noted very few Asian clam shells “on the beach” or even in the shallow water. The shells which were present were small and the majority of them did not contain live animals or animal tissue. Of the few dozen we inspected, only one shell contained a live individual. Further inspection for Asian clams around the reservoir is recommended. The inspection should determine if the apparent lack of Asian clams is real or if the Asian clams have burrowed into the sediment or perhaps followed the falling water level during reservoir drawdown to deeper waters.

The Asian clam population was quite different in the Bessemer Ditch just below Pueblo Reservoir. In the ditch, the bottom was covered by Asian clam shells, many of them containing live individuals despite the ditch having been dewatered for some time. Once the water from the reservoir reaches the Bessemer Ditch, it is open to the atmosphere and quickly gains oxygen. As all other water quality parameters are likely the same in the reservoir as in the ditch, the presence of oxygen may be the best explanation for the healthy population of Asian clams in the ditch.

3.3: Pueblo Reservoir Facility Assessment

The main purpose of Pueblo Reservoir is water resource management for the surrounding Pueblo area; although, due to its large size and proximity to populated areas, recreational use of the reservoir is high.

By its nature, water resource management results in annual level fluctuations of the reservoir. The total range of level change is typically 30 ft but this is somewhat variable based on demand and variations in natural run-off replenishment.

Within the 30 ft fluctuation band mussels will not survive. Any structures that become exposed will have, at most, one year accumulation of mussels that can be cleaned if the particular structure needs to be kept free of fouling. Floating structures such as recreational boating facilities will move with the water column and will need to have submerged portions cleaned manually.

As indicated earlier in Section 3.2, there appears to be annual periods of low dissolved oxygen in the deeper portions of the reservoir that could limit mussel survival at these depths. If the timing of the low water level can be matched to the periods of low dissolved oxygen at depth, then a relatively narrow band of mussel survivability will occur. This situation should assist in limiting the density of mussels within the reservoir.

All water leaves the reservoir through outlets in the dam designed for specific purposes. The outlets are described in subsequent paragraphs, but in general the risks associated with mussel settlement increase as the outlets become smaller. A single layer of mussel settlement has a greater relative effect on smaller openings.

Presence of mussels requires greater vigilance to ensure timely response to clean structures to maintain performance. Inspection frequency of structures needs to be related to the rate at which the mussels accumulate and the tolerance of the particular structure to mussel growth. At this time, the number of breeding cycles and rate of growth of mussels in this particular environment has not been established by measurement. Based on the environmental parameters, including some that may have mitigating effects, quarterly structure inspections should be acceptable together with monthly observations of monitoring stations. It is suggested that once the presence of settling mussels is detected, that all structures be inspected to establish the baseline and that quarterly inspections continue until the accumulation pattern is established on each structure. Once a degree of comfort is reached that the rate of accumulation is known, inspection frequencies can be adjusted accordingly. Cleaning cycles may be timed to coincide with other normal operations tasks such as cleaning trashracks when the water level is lowered and maintenance access is easier.

There is an existing program of regular dam inspections that occur at various timings typically monthly or annually. Where practical, mussel inspections should be combined with the regular dam inspections to make most effective use of dam labour resources.

3.3.1: Pueblo Dam

Pueblo Dam is a composite concrete and earth fill structure, about 10,200 ft long at the crest elevation of 4,925 ft. The concrete section has a structural height of 250 ft and a hydraulic height of 191 ft. The earth fill portions consist of the left and right abutment embankments, totaling 8,450 ft in length. The concrete dam consists of 23 massive-head buttresses which total 1,750 ft in length. It has a 550-foot overflow spillway section and a 1,200-ft non-overflow section. The uncontrolled overflow spillway section has a crest elevation of 4,898.7 feet and is located almost in the center of the concrete dam in buttresses 8 through 14. The spillway consists of a concrete ogee crest, training walls, flip bucket, stilling basin, and an outlet channel. The spillway design flow is 191,500 cfs at reservoir elevation 4,919 ft.

3.3.2: Dam Outlets

Five separate outlets operate at Pueblo Dam. These are described below.

3.3.2.1: River Outlet Works

The river outlet consists of one metal trashrack on the upstream face of the dam, one 4 ft by 4 ft stainless steel conduit, and two 4 ft by 4 ft high pressure slide gates in tandem located in Buttress 16 over the streambed. The maximum discharge of the River outlet is 1,120 cfs.

Trashracks are common areas for mussel settlement and can accumulate large populations quickly. The inlet trashrack at Pueblo Dam is almost always submerged and should be inspected remotely or by divers. Cleaning of submerged trashracks is usually done by divers using manual scraping tools. Manual scraping is usually accompanied by a hydraulic vacuum to collect the mussel debris. Typically, waste disposal permits are required for the removed debris.

Cleaning of trashracks that can be conveniently removed or exposed by lowering water levels is usually done by high pressure water jet tools. Underwater hydro-cleaning can also be done. In-situ cleaning of trashracks or other structures by pressure water jet techniques over open water does not allow the debris to be collected.

Should cleaning of trashracks, inlet grates or other metallic structures become an economic burden, consideration could be given to coating the surface with anti-fouling or foul release paints. Experience in the Great Lakes suggests a 7 to 10 year life expectancy for the coatings. Current coating tests underway in the southwest show promising results, especially for silicone based foul release coatings (See Research Note ZQMRP-2009-RN-04 on USBR Mussel website).

The walls of the conduit upstream of the slide gates could be settlement areas for mussels. Mussels will settle on surfaces where the water velocity is less than 6 ft/sec. The presence of mussels on the walls of a pipe or tunnel creates a roughness that increases flow resistance. Increased hydraulic roughness is an issue for pumping plants and electricity generating plants as pumping costs rise to achieve the same pumping rate and electricity production drops when there is an increase in roughness. Outlet works should have greater tolerance to mussel accumulation on walls as the tunnels are generally oversized and there is no economic penalty to achieve desired flow rates. As mussel accumulation increases on the walls, adult mortality increases on the layers adjacent to the wall surface and sloughing of mussel clumps will occur. The sloughing will be larger during periods of high velocity water flow through the conduit. Persistent accumulation will need to be manually removed if the desired flow rates cannot be achieved. The time required for an unacceptable or intolerable accumulation of mussels to deposit on the walls of a large tunnel such as the River Outlet Works cannot be predicted based on the current level of knowledge of mussel behaviour in the southwest environment but will likely be greater than 2 years.

If possible, it may be helpful to establish a baseline of flow versus reservoir level for various slide gate positions. Should mussels begin to accumulate on the tunnel walls lower than anticipated flow rate may allow prediction of tunnel infestation.

Attached mussels, particularly the byssal threads, can be sources of pitting corrosion on stainless and carbon steel as well as aluminum materials. Mussels, if left attached for lengthy periods of time, may result in some increase in pitting corrosion of the conduit walls.

The air vent at the conduit inlet should be checked for proper operation and cleaned of any accumulated mussels prior to draining the inlet conduit. Venting requirements for emergency valve closure and pipe draining are a potentially significant issue.

This should be a critical element of any facilities assessments. Plant engineers should evaluate which vents require clean passages for proper performance and verification of these vents should be added to plant operating procedures.

If the lower portion of the air vent between the slide gates is kept wetted, then the vent pipe may become colonized. The air vent should be inspected and cleaned periodically to ensure proper operation and vent capacity.

Any trashracks or intake screens in the river downstream of the dam, such as those for turnouts or level control gates, would be at risk of mussel fouling. Trashracks at these locations should be monitored periodically until cleaning is required and then cleaned manually, either by removing them or cleaning in situ. Fish screens will require special consideration as even low levels of fouling can adversely affect performance.

3.3.2.2: Spillway Outlet Works

The spillway outlets consist of three 6 ft by 6.5 ft conduits located in Buttresses 9, 11, and 13 of the spillway section. Each spillway outlet works consist of one metal trashrack structure on the upstream face of the dam, one 6 ft- by 6.5 ft steel conduit, and two 6 ft by 6.5 ft high pressure gates in tandem located in the gate chamber in the dam. The combined maximum discharge capacity is 8,190 cfs.

All comments in the above section on the River Outlet Works are applicable for the Spillway Outlet Works.

3.3.2.3: Fish Hatchery Outlet Works

The fish hatchery outlet works located in Buttress 8 consists of four intakes at various elevations, three metal trashracks structures protecting the intakes, two butterfly valves on each line in the gate chamber, and four 30-in mortar lined pipes merging into a single 30-in pipe that extends 2,000 ft to the fish hatchery. The maximum discharge capacity is 30 cfs.

The upper level trashracks may become exposed during periods of normal reservoir level fluctuations. Any attached mussels will die through desiccation or can be scraped manually. The lower trashrack remains submerged at all times and will need to be inspected remotely or by divers and cleaned by divers as necessary.

There are several vent lines, some fill lines, and air release valves. These components are at risk of mussel settlement. Of particular concern would be plugging of vent lines as plugged vent lines can result in pipe collapse. The condition of vent lines and/or proper operation of vent lines should be verified before draining or filling the piping. Vent lines are typically cleaned by steam or hydro blasting or by mechanical rotary cleaners.

As the speed of flow in the main pipes will be at 6 ft/sec when operating at maximum discharge, the intake piping and delivery piping to the fish hatchery will be at risk of mussel settlement only when flows are less than the maximum. The accumulation of mussels on the pipe walls will reduce the discharge capacity of the system. As the mussel accumulation increases, the valves will need to be opened a greater amount to achieve the same flow as compared to a clean pipe. The amount of mussel fouling that can be tolerated will be a function of the minimum flow required by the fish hatchery when the reservoir levels are low.

Monitoring the position of the flow valves for a particular flow rate and tracking this position over time can be one means to indicate that the piping is becoming fouled.

Mussel attachment on the steel pipe walls is known to increase corrosion. The plant engineer responsible for corrosion and pipe wall thinning should be alerted to this additional problem for the piping runs.

Periodic cleaning of the piping may become necessary if levels of fouling prevent desired flows to be achieved. Remotely-piloted, flow-powered pipe wall cleaning robotic equipment is available. Typically, hydro-jetting equipment is used where pipe runs are less than 1,000 ft. Some exploration should be done by plant maintenance staff to determine if equipment exists to clean runs as long as the fish hatchery piping (2,000 ft). Pigging equipment is also an option given the length of the piping in this case.

As an alternative, the piping could be cleaned by periodic chemical treatments. Permits to use chemical treatments usually take a long time to obtain and should be explored well in advance of anticipated need. In addition the timing of the chemical application would need to be coordinated with the fish hatchery requirements for chemical free water. Promising technology based on a dreissenid specific bacterial toxin is currently being tested and may become an option in the future. The bacterial product may require permitting. Hot water treatment or draining and drying are also methods used to kill mussels. All of these methods leave the dead mussels in place to slough off with time and regular water flow.

3.3.2.4: South Outlet Works

The south outlet works consists of four intake lines at different levels. Three intakes are controlling water quality and a fourth intake is available for emergency use. All four intakes are located in Buttress 7. The three main intakes include a metal trashrack structure at each intake, two slide gates on the upstream face of the dam for the upper two intakes, one butterfly valve in each of the upstream and downstream gate chambers, and one 48-in diameter pipe. The single level intake line consists of a metal trashrack structure at the intake, one butterfly valve in the upstream gate chamber, and 48-in diameter pipe. The 48-in lines run into a 120-in manifold that supplies a maximum discharge of 359 cfs to municipal and industrial water users.

Comments on the components at risk of mussel settlement in the section 3.3.2.3 regarding the Fish Hatchery Outlet Works are applicable to this outlet works. Should accumulations of mussels reach unacceptable levels, the diameter of the piping is large enough such that a piping outage with manual cleaning is likely to be the most effective maintenance method.

Continuous or semi-continuous methods that prevent settlement and reduce or eliminate the need for an outage could be considered. This approach is usually based on chlorination for industrial users although techniques using other chemicals, UV or filtration are also used.

3.3.2.5: Bessemer Ditch Outlet Works

The Bessemer Ditch, located in the right embankment, consists of an inlet trashrack structure, an upstream 7 ft diameter pressure conduit, four 3.6 in by 3.6 in high-pressure gates, and a downstream horseshoe shaped conduit. The maximum discharge of the Bessemer outlet is 393 cfs.

Comments on the components at risk of mussel settlement in the section 3.3.2.1 above on the River Outlet Works are applicable to this outlet works. Should accumulations of mussels reach unacceptable levels, the conduit is large enough such that an outage with manual cleaning is likely to be the most effective maintenance method. The portion of the outlet that is downstream of the pressure gates may be accessible when the ditch outlet is not flowing and consideration should be given to inspecting this area as part of any general inspection plan.

Any trashracks in the Bessemer Ditch downstream of the dam such as those for turnouts or level control stations would be at risk of mussel attachment. Typically, trashracks that cannot be removed and in an area that cannot be dewatered are monitored periodically until cleaning is required and then cleaned manually.

3.3.3: The Dam Internal Structures

Other than the outlet works piping, there is very little piping within the dam structure that is exposed to raw water or requires raw water to function. The fire protection system is provided by means of chemical extinguishers. Instrumentation is typically only for pressure measurement. These instrumentation lines would have no flow and would not be likely settlement areas for mussels due to low oxygen and lack of nutrients. Level gauges that are float based should have the floats inspected and cleaned periodically.

Each buttress of the dam incorporates a formed drain tube covering the full height of the dam. The drain terminates in the inspection gallery where water is then directed via floor gutters to the sump area. The drain will collect dam water that manages to pass the dam seal and percolate through the control joints of adjacent concrete buttress structures. Mussel veligers may be able to travel with the normal dam seepage into the drain tube where they could settle and grow. The occurrence of such attachment is likely to be rare but has been documented at other facilities.

In the unlikely event that sufficient mussels should accumulate to restrict the drain flow, the reduced drainage should be picked up during the frequent routine inspections by dam staff. The drain structure has an access cap near the top of the drain. An accumulation of mussels could be removed using a cable operated pipe cleaner through the access cap opening or, alternatively, could be killed by temporarily closing the drain and introducing a biocide or other agent such as hot water which will cause mortality quickly. Non-valved drains can be temporarily closed by pressurized bladders, freeze plugs or by modifying the drain pipe to add a blind flange.

Each buttress section incorporates several foundation uplift pipes. Water in these pipes is generally expected to be seepage and not likely to transport mussels. In addition, reservoir seepage from the dam making its way to the pipes passes through the base material in the dam, which will normally suffocate any mussels. Drain pipes are monitored frequently by Reclamation staff and any changes from the norm need to be noted and investigated further.

All of the seepage through the dam drains to a sump evacuated by two 500-gpm sump pumps. The sumps should be inspected periodically for presence of mussels. Mussels typically settle on the external portions of submerged pump casings and on the walls of the sump at levels below the level shut off switch.

4.0 RECOMMENDATIONS

The following recommendations are made for monitoring, research and future actions:

1) Continued monitoring of key environmental parameters, primarily dissolved oxygen, temperature and pH by depth, date and location, is recommended to detect any trends that may place the reservoir at greater or lesser risk.

2) Continued monitoring for both veligers and settled adults is recommended to determine how the infestation by dreisenids is developing and how the environmental parameters do, or do not, mitigate settlement. At a minimum, strings of sampling plates for adult dreissenid mussels should be placed at various locations in the reservoir. The first sampling plate is suggested at 5 feet below the surface with subsequent sampling plates every 5 feet.

3) Seasonal patterns of settlement in the Reservoir need to be determined in order to maximize potential benefit from reservoir level changes. For example, if low dissolved oxygen limits the settlement of mussels below 30 feet and reservoir drawdown begins only after most of the annual settlement has taken place, the newly settled mussels in the upper 30 feet will be eliminated by exposure to air.

4) If monitoring stations establish that the veligers are originating from upstream of Pueblo Reservoir from a single or limited number of sources, then additional study should be done to locate and characterize the source(s) to assess if mussel source eradication is practical. If it is determined that the reservoir itself has sufficient mitigating environmental parameters to substantially limit mussel populations, then elimination of the upstream inoculation source could prove beneficial to downstream users of the water from Pueblo Reservoir. If that upstream inoculation source is localized and small, its eradication may be practical.

5) Require floating facilities to inspect their floating structures and require the facilities to carry out a thorough cleaning if mussels are found on floating structures.

6) Once the presence of vigorous mussel populations is established by detection of adult settlement, conduct an inspection of all facility components to establish a baseline condition. Facility components or structures that are part of a regular inspection program and have been inspected within the previous 3 months would be considered to have the baseline already established. Only structures not recently inspected need to form part of a baseline inspection. Repeat inspections quarterly until mussel accumulation patterns are established. Extend inspection cycles as confidence in the growth patterns and tolerance of various components is established. As no control technology may be required immediately, waiting till mussels are established in the reservoir, time and resources may be targeted more appropriately.

7) Integrate observation of mussels into normal dam inspection cycles and routine walk arounds to minimize the operational burden of inspection. For example, components checked on a monthly basis need not be included in a dedicated quarterly mussel check as the inspection would be deemed to have occurred in the normal course of work. Provide staff training on mussel identification and likely locations inside the dam such as drain gutters and the sump.

8) Develop non-intrusive techniques to predict mussel accumulation such as matching flow to control valve position or ultrasonic inspection of piping. (Note: mussels are difficult to distinguish from corrosion products using ultrasonic so a baseline inspection is necessary).

9) Prepare and test operational procedures to clean critical areas of the dam such as the seepage collection pipes and vent pipes. Vent lines should be inspected prior to draining pipe lines.

10) For any trashracks that are approaching the end of their life cycle, consider application of a foul release or antifouling coating for the new racks to extend the time between cleaning cycles.

11) For any trashracks that are removable but normally submerged, consider removing and coating the racks with foul release or antifouling coating to extend the time between cleaning cycles.

Literature Cited

Ashby, S.L., W.A. Boyd and R.H. Kennedy. 1998. Assessing the potential for zebra mussel habitat at U.S. Army Corps of Engineers Water Resources Projects using GIS techniques and water quality data. Pages 300-305 in: Proceedings: Eighth International Zebra Mussel and Aquatic Nuisance Species Conference, March 16-19, 1998, Sacramento CA

Baker, P., S. Baker and R. Mann. 1993a. Criteria for Predicting Zebra Mussel Invasions in the Mid-Atlantic Region. School of Marine Science, College of William and Mary, Gloucester Point VA. Not seen, cited by Cohen 2001.

Carlton, J. T. 1993. Dispersal mechanisms of the zebra mussel *Dreissena polymorpha. In* T. E Nalepa and D. W. Schloesser, editors. Zebra mussels: biology, impact, and control. Pages 677-697. Lewis (CRC Press), Ann Arbor, Michigan, USA.

Claudi, R. and G. Mackie 1994. *Zebra Mussel Monitoring and Control*. Lewis Publishers, Inc. Boca Raton, FL.

Cohen, A. N. 2001. Zebra Mussel's Calcium Threshold and Implications for its Potential Distribution in North America, San Francisco Estuary Institute Richmond, CA.

Cohen, A.N. and A. Weinstein. 1998. *The Potential Distribution and Abundance of Zebra Mussels in California*. San Francisco Estuary Institute, Richmond, CA.

Cohen, A.N. and A. Weinstein. 2001 Zebra Mussel's Calcium Threshold and Implications for its Potential Distribution in North America. San Francisco Estuary Institute, Richmond, CA.

Doll, B. 1997. Zebra Mussel Colonization: North Carolina's Risks. Sea Grant North Carolina, University of North Carolina, Raleigh, NC (UNC SG-97-01).

Hansen A.S, S.A.Nierzwicki-Bauer, M.E.Frisher 1998, Presence, Growth and Survival of Zebra Mussels in Lake George, New York Eighth International Conference on Zebra Mussels and Other Aquatic Nuisance Species

Hayward, D. and E. Estevez. 1997. Suitability of Florida Waters to Invasion by the Zebra Mussel, *Dreissena polymorpha*. Florida Sea Grant College Program, Mote Marine Laboratory, Sarasota, FL. Tech. Rept. No. 495.

Hincks, S. S. and G. L. Mackie. 1997. Effects of pH, calcium, alkalinity, hardness, and chlorophyll on the survival, growth and reproductive success of zebra mussels (*Driessena polymorpha*) in Ontario lakes. Can J. Fish. Aquat. Sci. 54: 2049-2057.

Johnson, L. E. and J. T. Carlton. 1996. Post-establishment spread in large-scale invasions: dispersal mechanisms of the zebra mussel, *Dreissena polymorpha.* Ecology 77: 1686-1690.

Johnson, L. E., and D. K. Padilla. 1996. Geographic spread of exotic species: ecological lessons and opportunities from the invasion of the zebra mussel *Dreissena polymorpha.* Biological Conservation 78:23-33.

Kilgour, B. W., M. Baker, and G. L. Mackie. 1993. Effects of salinity on growth and condition of adult zebra mussels (*Dreissena polymorpha*). Estuaries 17: 385-393.

Koutnik, M. and D.K. Padilla. 1994. Predicting the spatial distribution of *Dreissena polymorpha* (zebra mussel) among inland lakes of Wisconsin: modeling with a GIS. *Can. J. Fish. Aquat. Sci.* 51: 1189-1196.

Mackie, G.L. and B.W. Kilgour 1992. Effects of salinity on growth and survival of zebra mussels (*Dreissena*

Mackie, G. L. 2004. Applied aquatic ecosystem concepts. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Mackie, G.L., W.N. Gibbons, B.W. Muncaster and I.M. Gray. 1989. The Zebra Mussel *Dreissena polymorpha*: A Synthesis of European Experiences and a Preview for North America. A report for the Ontario Ministry of the Environment, Water Resources Branch, Great Lakes Section, Queen's Printer, Toronto.

Mackie, G. L. and C. A. Wright. 1994. Ability of the zebra mussel, *Dreissena polymorpha*, to biodeposit and remove phosphorous and B.O.D. from diluted activated sewage sludge. Wat. Res. 28: 1123-1130.

McMahon, R. 1996. The physiological ecology of the zebra mussel, *Dreissena polymorpha*, in North America and Europe. *American Zoologist* 36: 339-363.

Mills, E. L., J. H. Leach, J. T. Carlton and C. L. Secor. (1993). Exotic species in the Great Lakes: A history of biotic crises and anthropogenic introductions. J. Great Lakes Res. 19: 1-54.

Murray, T.E., P.H. Rich and E.H. Jokinen. 1993. Invasion Potential of the Zebra Mussel *Dreissena polymorpha* (Pallas) in Connecticut: Predictions from Water Quality Data. Connecticut Institute of Water Resources, University of Connecticut, Storrs, CT. Special Report No. 36.

Neary, B. P. and J. H. Leach. 1992. Mapping the potential spread of the zebra mussel (*Dreissena polymorpha*) in Ontario. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 406-415.

.Nierzwicki-Bauer S.A., B.R.McGrath, A.S. Hansen, J.Wimbush 2000, Bioassay for Predicting Survival of Zebra Mussel Veligers 10th International Aquatic Nuiscance Species and Zebra Mussel Conference

Padilla, D.K., M. A. Chotkowski, and L. A. J. Buchan. 1996. Predicting the Spread of Zebra Mussels (*Dreissena polymorpha*) to Inland Waters Using Boater Movement Patterns**.** Global Ecology and Biogeography Letters, Vol. 5, No. 6 (Nov., 1996), pp. 353-359

Ramcharan, C. W., D. K. Padilla and S. I. Dodson. 1992. Models to predict potential occurrence and density of the zebra mussel, *Dreissena polymorpha*. *Canadian Journal of Fisheries and Aquatic Sciences* 49(12):2611-2620.

Sorba, E.A. and D.A. Williamson. 1997. Zebra Mussel Colonization Potential in Manitoba, Canada. Water Quality Management Section, Manitoba Environment, Report No. 97-07.

Tammi, K.A., L.T. Green, E. Herron, M. Kerr and M. Rice. 1995a. Likelihood of invasion of the aquatic exotic zebra mussel, *Dreissena polymorpha* (Pallas), into Rhode Island freshwater systems. Proc. Northeast. Conf. Nonindigenous Aquatic Nuisance Species, Connecticut Sea Grant College Program, Groton CT. Not seen, cited by Cohen 2001.

Appendix A

Studies using various parameters to assess risk potential of dreissenid invasion and densities. The parameters are listed alphabetically.

Parameters	**References**
Alkalinity	Claudi and Mackie 1994; Mackie 1994; Hincks & Mackie 1997; Ashby et al. 1998
Calcium	Mackie *et al*. 1989; Neary & Leach 1992; Baker *et al.* 1993; Murray *et al.* 1993; Claudi and Mackie 1994; Mackie 1994; Koutnik & Padilla 1994; Tammi *et al.* 1995a,b; Doll 1997; Hincks & Mackie 1997; Sorba & Williamson 1997; Hayward and Estevez 1997; Janik 1997; Cohen 2001; Cohen & Weinstein 1998, 2001
Chlorophyll *"a"*	Claudi and Mackie 1994; Mackie 1994; Hincks & Mackie 1997
Conductivity	Claudi and Mackie 1994; Mackie 1994; Sorba & Williamson 1997
Dissolved oxygen	Mackie 1994; McMahon 1996; Doll 1997; Sorba & Williamson 1997; Hayward and Estevez 1997; Ashby et al. 1998; Cohen 2001; Cohen & Weinstein 1998, 2001
Nitrogen, total	Mackie 1994; Koutnik & Padilla 1994; Claudi and Mackie 1994;
pH	Mackie *et al*. 1989; Neary & Leach 1992; Koutnik & Padilla 1994; Claudi and Mackie 1994; Mackie 1994; Doll 1997; Hincks & Mackie 1997; Sorba & Williamson 1997; Janik 1997; Hayward and Estevez 1997; Ashby et al. 1998; Cohen 2001; Cohen & Weinstein 1998, 2001
Phosphorous, total	Mackie *et al*. 1989; Mackie 1994; Koutnik & Padilla 1994; Claudi and Mackie 1994;
Salinity	Strayer & Smith 1993; Kilgour *et al.* 1995; Sorba & Williamson 1997; Doll 1997; Hayward and Estevez 1997; Cohen 2001; Cohen & Weinstein 1998, 2001
Secchi depth (or turbidity)	Claudi and Mackie 1994; Sorba & Williamson 1997; Hayward and Estevez 1997
Temperature, mean annual	Strayer 1991; Cohen 2001; Armistead 1995; McMahon 1996; Doll 1997; Janik 1997; Sorba & Williamson 1997; Hayward and Estevez 1997; Roe & MacIsaac 1997; Ashby et al. 1998; Cohen & Weinstein 1998, 2001
Total hardness	Baker *et al.* 1993; Claudi and Mackie 1994; Mackie 1994; Hincks & Mackie 1997; Sorba & Williamson 1997