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Assessment of the Potential Impact of Invasive Mussels to John Day and The Dalles Projects on the Columbia River.

Prepared for: US Army Corps of Engineers

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EXECUTIVE SUMMARY

The U.S. Army Corps of Engineers (USACE) is the federal government's largest water resources development and management agency. Both The Dalles and John Day Projects belong to and are managed by the USACE. Each project consists of a dam, power generation facilities, navigational lock and fish passage facilities on both sides of the Columbia River. In addition, at the John Day Project there is juvenile fish passage and monitoring facility.

Since 2008, dreissenid mussels have become established at various locations in California. There were additional sightings in other states neighbouring Oregon. There is a concern that dreissenid mussels (quagga and zebra) will be introduced and will become established in the Columbia River.

RNT Consulting Inc. was asked to perform a vulnerability analysis of the John Day and The Dalles projects under contract W9127N-10-P-0127. As part of the contract, RNT briefly examined the environmental parameters of the Columbia River at the location of the projects. Additional data from the USGS NASQAN database, extracted by Thomas Whittier (Oregon State University) in 2007 was also examined. Although determination of environmental suitability for mussel survival was not part of the contract requirement, some idea of environmental suitability is essential when assessing the vulnerability of facilities and structures.

This report covers 4 facilities: The Dalles, Wasco County PUD, John Day Dam, and John Day Smolt Monitoring Lab. Some paragraphs are common between the facilities. These paragraphs are repeated for each facility for the convenience of readers interested in only one facility to have a complete picture of that specific facility without resorting to reading the entire report.

The data available from the Columbia River basin generally shows calcium levels which would be considered adequate to support low population levels of dreissenid mussels (based on data from eastern North American continent and Europe). There is very little pH data and what is available shows oscillating pH values with minimums below the level necessary for dreissenid mussel survival and maximums well within the optimum range for mussel survival. Additional calcium and pH data needs to be collected in various parts of the Columbia watershed if we are to better predict dreissenid mussel levels in this environment. In addition to limitations posed by low calcium and oscillating pH, it is not certain if veligers produced by dreissenid mussels, which may become established in the headwaters of the Columbia, would have adequate time to develop to the settling stage during their downstream transit. It is advisable to calculate the water retention time of various portions of the Columbia River in order to determine the expected time required for newborn mussels to travel from the upper extremities of the Columbia River to Portland.

It is recommended that the current monitoring program be maintained or even enhanced to verify presence/absence of dreissenid mussels in the Columbia River. It is also recommended that USACE invest in all possible activities aimed at preventing dreissenid mussel introduction into the system, particularly lakes and reservoirs which are not on the main stem of the river but discharge into it.

The facilities of both projects were evaluated based on the assumption that mussels could become established in the Columbia River. Elements of the facilities were identified that would be vulnerable to fouling should the mussels survive in sustainable numbers.

Due to the uncertainties in timing of mussel introduction and the uncertainty of them thriving in the Columbia River we suggest a stepwise, graduated approach to asset protection.

Step 1 - Immediate action

- Initiate permitting process with the regulator so you can begin mitigation when required (discuss Zequanox, pH adjustment, oxidizing chemicals)
- Initiate introduction of self-cleaning strainers and filters in areas which currently experience fouling with Asian clam shells and silt

- Install injection points at the start of each raw water system.
- Chlorination of domestic water on continuous basis during the mussel season would be valuable.
- Initiate a non-toxic coating study on the fish grates of the fish handling system to gather first hand performance data.
- Provide senior management back-up to above activities.

Step 2 - Actions recommended when introduction is confirmed

- Evaluate availability of Zequanox (a biological control specific only to dreissenids)
- Confirm which systems continue to require protection.
- Evaluate which systems could be switched from river water to domestic water.
- Update results from non-toxic coating studies.
- Develop an action plan for each system that requires protection.

Step 3 - Actions if population of dreissenids reaches nuisance level

- Prepare to inject Zequanox or alternative chemical into systems which require protection (skid mounted)
- Verify that self cleaning strainers and filters are in service and performing well
- Prepare to coat strategic external structures or develop a cleaning schedule

Step 4 -Actions if dreissenid population continues to flourish in Columbia River

- Convert skid mounted system to permanent installation.
- Increase use of self cleaning strainers and filters.
- Increase use of coatings.
- Continue to monitor new technologies.

1.0 PROJECT DESCRIPTION and BACKGROUND

Quagga and zebra mussels are members of the dreissenid family of bi-valves. These non-native, invasive mussels are an environmental and economic nuisance across North America.

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

Chronic fouling occurs when juvenile dreissenid mussels attach themselves to external and internal structures. The juvenile mussels grow in place and reduce water flow 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 and heat exchangers. 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 be prepared to deal with both types of fouling.

Since the mussels crossed the continental divide and were discovered in Lake Mead in 2007, dreissenid mussels have become established at various locations in California and several other states neighbouring Oregon. There is a concern that dreissenid mussels will be introduced and will become established in the Columbia River. USACE has taken proactive steps to determine vulnerability of two of their projects located on the lower Columbia River.

The Dalles lock and dam is 192 miles upstream from the mouth of the river. The dam extends 1.5 miles from the Oregon shore to the navigational lock on the Washington shore. The project consists of a navigational lock, spillway, powerhouse containing 22 generators and fish passage facilities on either side of the river. In addition, there is a Wasco County PUD facility located adjacent to the fish ladder on the Washington State side of the river. RNT conducted a brief review of the vulnerability of the PUD facility.

The John Day lock and dam is 24 miles upstream of the Dalles project. The project consists of a navigational lock, spillway, powerhouse containing 16 generators and fish passage facilities on either side of the river. In addition, a juvenile fish by-pass system was completed at this project in 1997 to increase survival rates of downstream migrant fish.

Summarized in this report are the findings on:

- Calcium-based assessment of environmental suitability of the lower Columbia River for mussel establishment
- Areas of the various project facilities vulnerable to mussel fouling
- Best management practices for coping with invasion and control options for raw water systems.

This report is not intended to be a risk assessment for mussel infestation but rather it focuses on identifying those structures and facilities which will be vulnerable to mussel related impacts should an infestation occur in the future. This report does contain what RNT believes are practical options for dreissenid mussel mitigation at each facility, but it does not include an engineering evaluation of these options.

2.0 ASSESSMENT PROCESS and METHOD

USACE provided RNT with flow diagrams and, in some cases, general arrangement drawings of raw water piping systems for both The Dalles and John Day Projects. RNT. staff studied the drawings and visited the projects in March 2010. The site visit team consisted of staff from RNT and USACE. At each facility, the team inspected all accessible areas from water intakes to discharge. During these inspections, the team was able to identify the potential threats and impacts to the systems and to individual components.

Available environmental data pertaining to calcium and pH in the Columbia River was also collected.

3.0 RESULTS of the ASSESSMENT

3.1: GENERAL ENVIRONMENT REQUIREMENTS MUSSEL INFESTATION

Dreissenid mussels need calcium in order to build their shells. The larval forms of dreissenids (veligers) require higher levels of calcium in order to develop than is required by adult mussels for survival. Therefore, adult mussels if introduced into a body of water with low calcium may survive for some time, but the population may fail to reproduce and therefore will be eliminated. Calcium is considered the most essential environmental constituent when assessing the likelihood of long term mussel survival.

When calcium data is not available, calcium levels may be estimated from alkalinity and total hardness data. The alkalinity is an indicator of calcium availability. 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). Hence, while calcium is the key variable, the other chalk variables can be used as surrogates for calcium values if calcium values are not available.

Very low conductivity indicates very low mineral content and can be used to support observations on calcium content.

Values of pH in the range of 7.2 to 7.5 are generally required for veliger development. A pH of 7.5 is usually given as the lower limit for long term veliger survival. As pH tends to vary widely in calcium poor waters, we generally do not use this variable for initial assessment. As calcium increases, the pH becomes more stable.

The following table (Table 1) was derived from the values reported by various authors and gives the ranges of values for each of the parameters as they relate to success of dreissenid mussel populations. The key parameter is calcium content and its availability. Ideally, monthly calcium values collected over several years should be used to assess how dreissenid mussel population may develop in a given environment.

Table 1. Criteria used in determining levels of infestation in temperate zone of eastern portion of North America and Europe (Mackie and Claudi 2009)

Parameter	Adults do not survive long-term	Uncertainty of veliger survival	Moderate Infestation Level	High Infestation Level
Calcium mg/L	<8 to <10	<15	16-24	≥24
Alkalinity mg CaCO3/L	< 30	30-55	45-100	>90
Total Hardness mg CaCO3/L	<30	30-55	45-100	≥90
pH	<7.0 or >9.5	7.1-7.5/ 9.0-9.5	7.5-8.0 or 8.8-9.0	8.2-8.8
Mean Summer Temperature °F	<64	64-68 or >83	68-72 or 77-83	72-75
Dissolved Oxygen mg/L (% saturation)	<3 (25%)	5-7 (25-50%)	7-8 (50-75%)	≥8 (>75%)
Conductivity µS/cm	<30	<30-60	60-110	≥100
Salinity g/L (ppt)	>10	8-10 (<0.01)	5-10 (0.005-0.01)	<5 (<0.005)
Secchi depth m	<0.1 >8	0.1-0.2 or >2.5	0.2-0.4	0.4-2.5
Chlorophyll a µg/L	<2.5 or >25	2.0-2.5 or 20-25	8-20	2.5-8
Total phosphorous µg/L	<5 or >50	5-10 or 30-50	15-25	25-35

3.2: SUITABILITY of COLUMBIA RIVER for DREISSENID MUSSEL INFESTATION

Although examination of environmental suitability for mussel survival was not part of the contract requirement, some idea of environmental suitability for sustaining mussel populations is helpful when assessing the mussel-related vulnerability of facilities and structures.

Calcium is considered the most important parameters for mussel establishment as documented by the following studies.

Experience from Lake George in New York State suggests what the borderline conditions for calcium and pH may be for zebra mussels. Hansen et .al 1998 document that calcium of 10.68 mg/L +/-1.17 mg/L and pH of 7.56 +/- 0.18, both 10 year averages, have supported a very low level of zebra mussel presence in Lake George for the last 10 years. A confounding factor in Lake George is the presence of scattered limestone deposits which may be creating microzones for dreissenid survival. This could mean that without these microzones, both the calcium and the pH might not be adequate for long term survival.

Studies by Nierzwicki-Bauer et al. in 2000 documented that adult mussels are able to survive in Lake George water (Ca=12 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 of the veligers within one week.

Hincks and Mackie (1997) tested adult survival, juvenile growth rates and veliger production against different concentrations of calcium, alkalinity, total hardness, chlorophyll and pH, by rearing adults and newly settled juveniles collected from Lake St. Clair in water from 16 Ontario Lakes. Six of these lakes had mean calcium levels below 8.5 mg/L and mean pH of 8.4 or less. In these low calcium waters all adults died within 35 days, juvenile growth rates were near zero or negative, and no veligers were produced. The other ten lakes all had mean calcium levels of 20-48 mg/L and mean pH of 8.2-9.3. In these waters adult survival was 52-100%, juvenile growth rates ranged from 3 to29 µm/day (low compared to rates measured in the field in Lake St. Clair of up to 125 µm/day), and very small numbers of veligers were produced, from 0 to 7 veligers from an initial population of 21 adults.

Cohen and Weinstein (2001) in their extensive review of calcium requirements of the zebra mussel concluded that "*Experimental data suggest that populations cannot be sustained where calcium levels are below 15 mg/L, although there are few reports of zebra mussel veligers from inland lakes with calcium measurements in this range, and adults in Lake George in a small area with possibly higher calcium than the levels usually reported for the lake.*"

The requirement for calcium by the quagga mussels, although not precisely established, is assumed to be in the same range as for zebra mussels.

The following assessment was based on data provided by the Independent Economic Analysis Board (IEAB). The IEAB data on Columbia Basin calcium levels at selected main-stem river sites were from the USGS NASQAN database, extracted by Thomas Whittier (Oregon State University) in 2007.

In general, the data shows significant annual oscillation in calcium levels at all locations sampled (Fig.1 – Fig.6). At the lowest levels, associated with spring run-off, the calcium recorded would not support a thriving population of dreissenid mussels. It is uncertain what would happen to mussels which became established during the summer when calcium levels are adequate at several of these location during these low calcium periods. Much would depend on the accompanying pH levels in these locations. The only pH profile available is Fig.6 which shows significant oscillations in pH at a site in Quincy, Oregon. At this site the calcium fluctuates between 11 and 17mg/L. Oscillation in pH combined with relatively low calcium levels would represent a challenging environment for dreissenid mussels.

Figure 1. Calcium and Temperature, Snake River at Burbank, 1995 to 2000

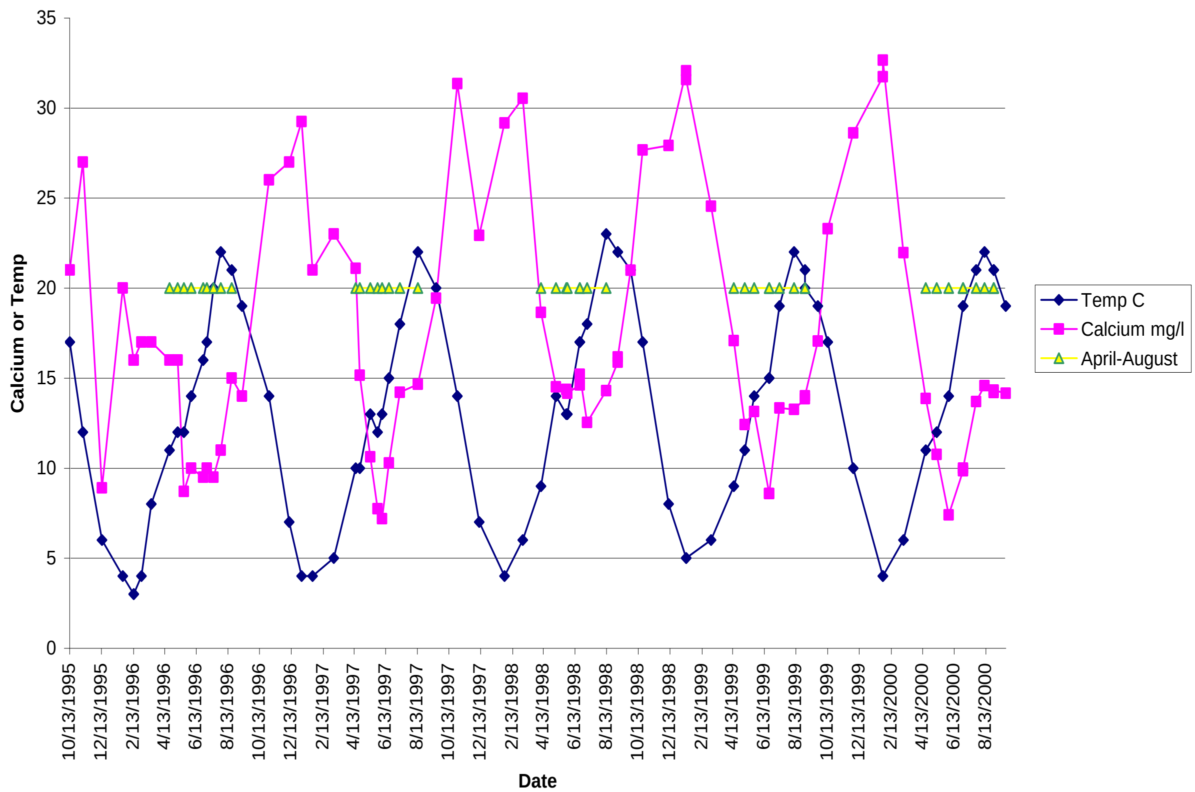


Figure 2 Calcium Data at Revelstoke

(http://www.env.gov.bc.ca/wat/wq/quality/revelstoke/revelstoke-12.htm)

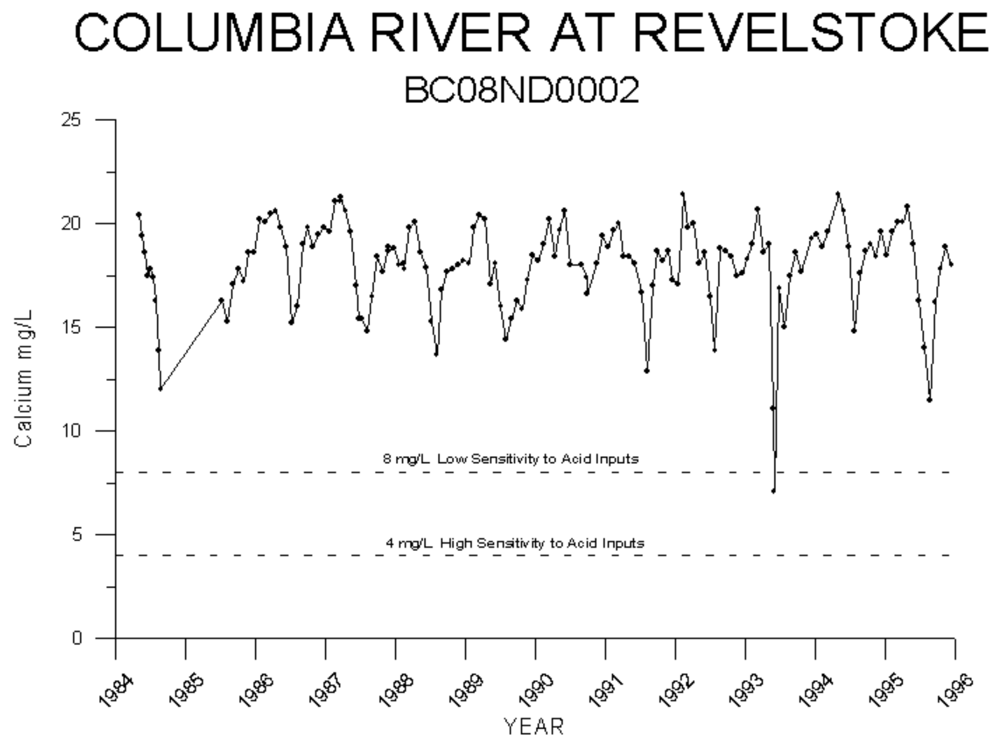


Figure 3. Calcium and Temperature, Northport WA, 1996 to 2000

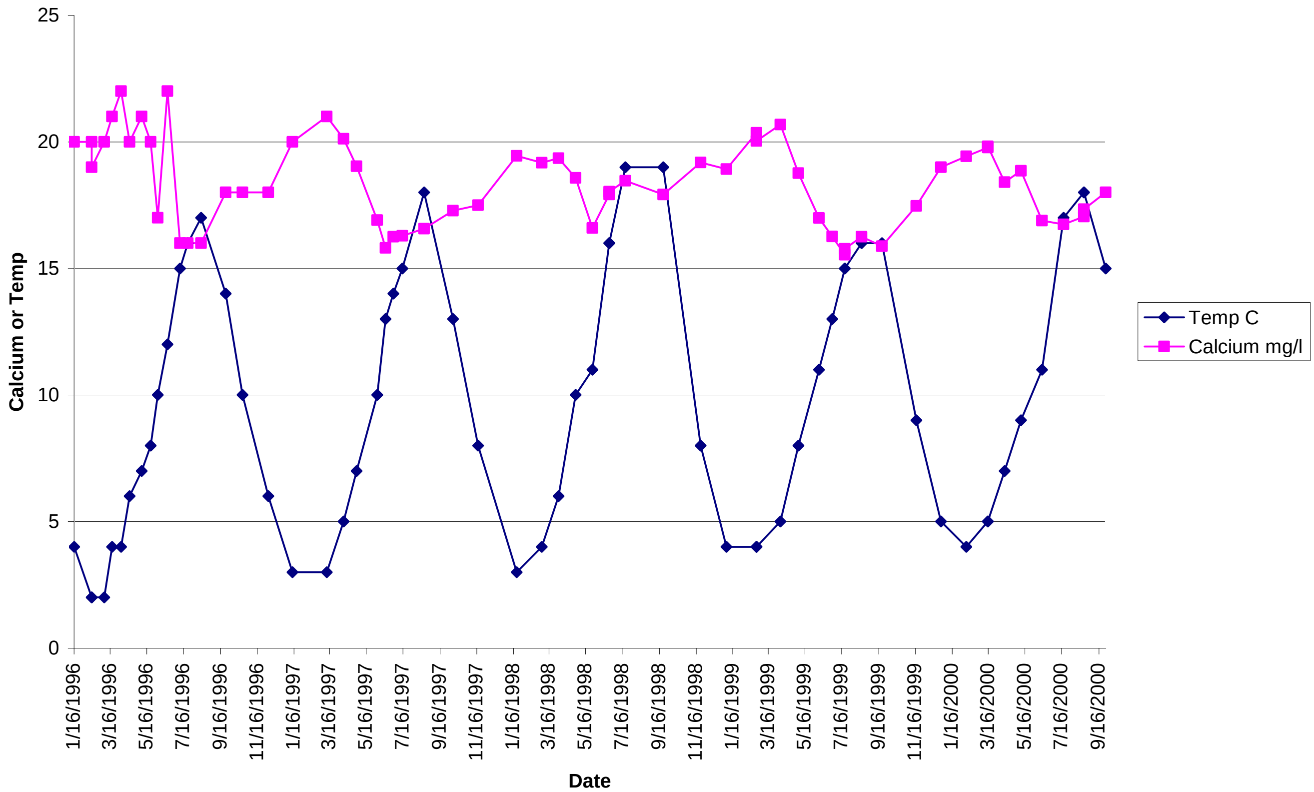


Figure 4. Calcium and Temperature, Warrendale OR, 1996 to 2000

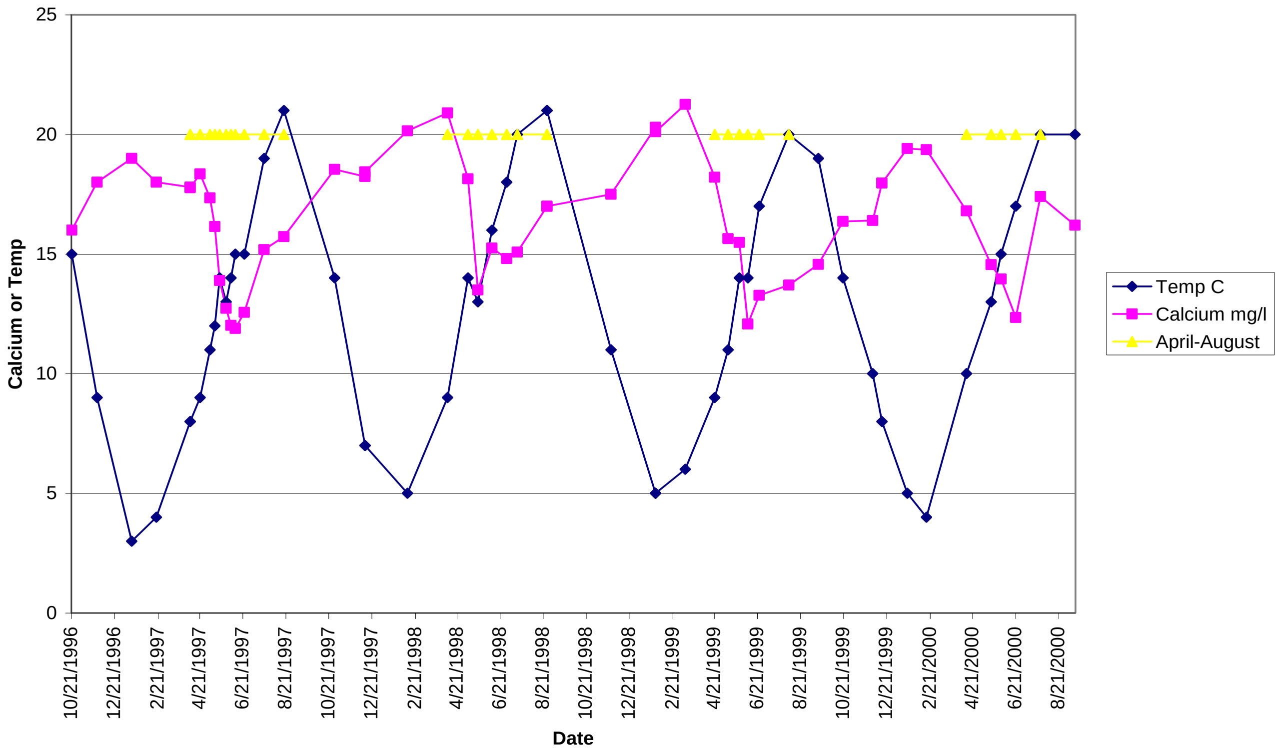


Figure 5. Temperature and Calcium, Columbia River at Quincy (near Beaver Army Terminal), 1995 to 2010

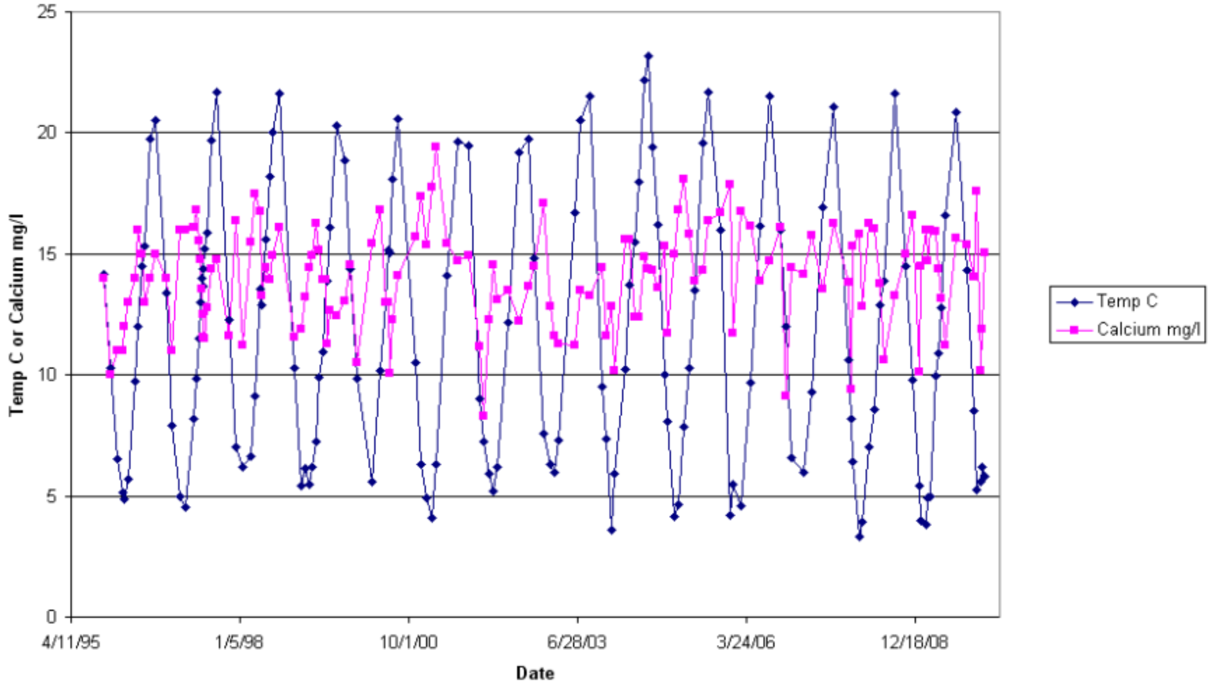


Figure 6. pH Columbia River at Quincy near Beaver Army Terminal, 1996 to 2004

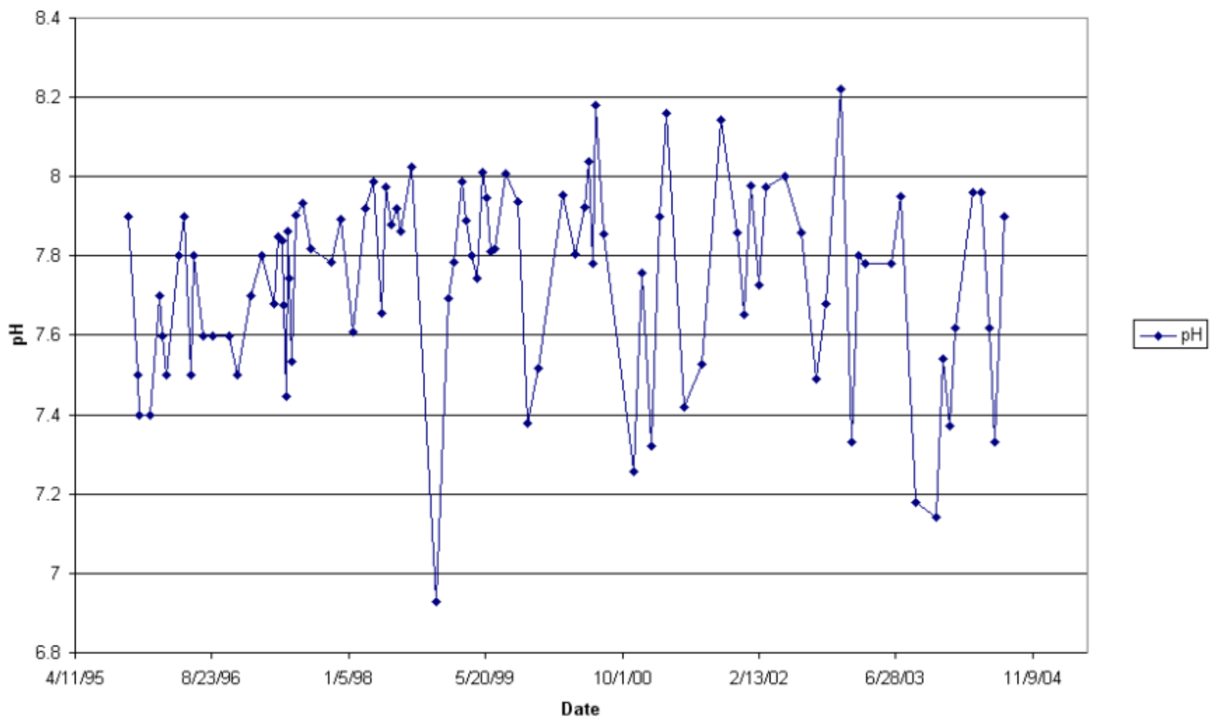
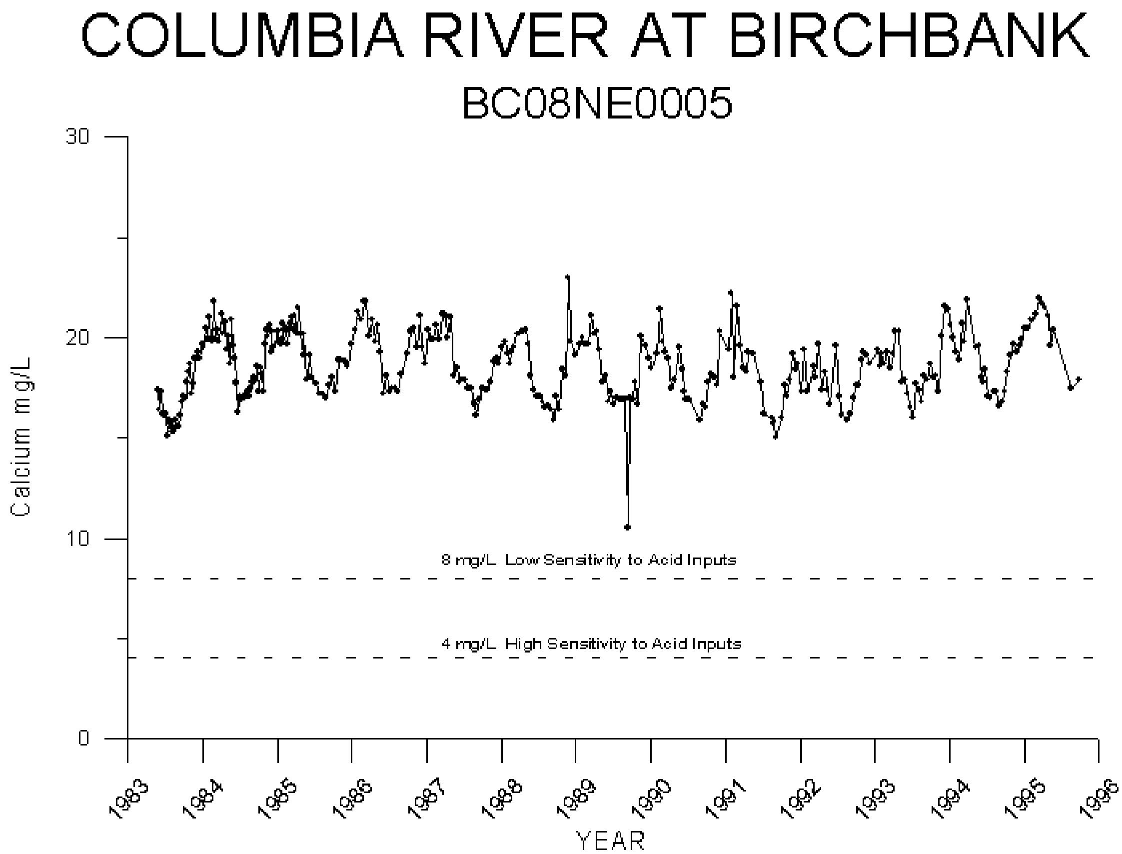


Fig. 7 Calcium Data at Birchbank

Source:http://www.env.gov.bc.ca/wat/wq/quality/birchbank/birchbankreport-03.htm



The IEAB also mentions that the Hells Canyon reach of the Snake River has variable calcium levels. In 1999, the USACE measured a median concentration just above the Clearwater confluence of 29.7 mg/l based on samples from June into October (USACE 1999). Concentrations were highly seasonal, being less than 10 mg/l in June, 10 to 20 mg/l in July through August 15, and near 30 to 40 mg/l in the second week of September through October 10.

In addition to the above data, Steven Well from the Center for lakes and Reservoirs, PSU has provided the following data points;

	Dissolved Calcium (mg/L)						**pH**				
Water Body	**Mean**	**SD**	**Min**	**Max**	**n**	**# yrs**	**Mean**	**Min**	**Max**	**n**	**# yrs**
Columbia River, Lake Celilo	17	0.5	16.3	17.3	3	1	8.1	8.1	8.1	7	1
Columbia River, Lake Umatilla	17.8	1.3	16.9	19.7	4	1					
Columbia River, Lake Wallula	17.4		17.4	17.4	1	1					

There is a concern that large concrete structures may provide dreissenid mussels with the calcium they need in calcium poor water bodies. Concrete structures contain calcium largely in the form of insoluble calcium silicates. Liquid water moving through concrete can cause a steady deterioration of these materials by leaching out the calcium from the calcium silicate bonding materials. Leaching of calcium from the concrete reduces the concrete strength and is undesirable. The calcium that is leached out is soluble in water and therefore available to mussels. This leaching action is most pronounced with soft or mildly acidic waters such as are found in reservoirs fed from swampy areas. The rate at which leaching occurs is a function of many variables including the pH of the water, and the presence of additives that improve the performance of concrete in water environments. Civil structures such as dams are typically designed to have a life of 100 years so the leaching process is believed to be very slow and the additional calcium which may be available to dreissenids would be minimal. Any leaching that would provide sufficient calcium to support mussel growth would likely be in quiescent areas that are not flushed continuously. It is important to note that water conditions that promote leaching of concrete (low pH) also promote leaching of calcium from the mussel shell. This requires the mussel to have access to an ongoing supply of calcium to maintain its shell. Otherwise the shell will thin and eventually dissolve mussel and mortality will occur. Further, the developing dreissenid veliger is free swimming in the plankton and therefore unable to take advantage of possible microzones of calcium in and around concrete structures.

Given all of the above information, it is not possible to assume that dreissenid mussels could not survive in some portions of the Columbia River Basin; however, it is unlikely that there would be a thriving population. Additional data on calcium and pH would greatly firm up this conclusion. In addition to limitations posed by low calcium and oscillating pH, it is not certain if veligers produced by dreissenid mussels, which may become established in the headwaters of the Columbia, would have adequate time to develop to settling stage during the downstream transit. It is advisable to calculate the water retention time of various portions of the Columbia River in order to determine this variable.

3.2.1: Inspecting for Mussel Accumulation

There are existing programs of regular equipment, dam, and other structural inspections that occur at various times. Where practical, inspecting for the presence of adult mussels should be combined with these regular inspections to make the most effective use of labor resources.

We suggest that once the presence of settling mussels is detected, all structures should be inspected to establish the baseline condition. Quarterly inspections should be performed until the accumulation pattern is established on each structure or component. Once a degree of comfort is reached that the rate of accumulation is known, inspection frequencies can be adjusted accordingly. The presence of adult mussels requires vigilance to ensure a 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. There is a significant diversity of structures and equipment at the projects so it would be a poor use of resources to give a single inspection interval. In addition, the number of breeding cycles and rate of growth of mussels in the Columbia River environment has not been established and can only be speculated on.

Cleaning cycles may be timed to coincide with other normal operations tasks such as cleaning trashracks and grates when the structure is dewatered for inspection or maintenance.

With effective monitoring programs in place, implementation of protection for systems using raw water can usually wait until mussel presence is confirmed and an estimate of the rate of infestation is established.

Mussel infestation almost always has a cost impact on capital and operating budgets. Delaying a capital expenditure until the capital outlay is needed is usually preferred. However, evaluating protection options and preparing a response plan is prudent. For example, facilities that have seasonal outages or systems that can be readily taken off line without an operational impact may choose to accept an additional cleaning burden to their operational budget. Facilities that have essential equipment that can be impaired by mussels and threaten safety or achieving performance objectives may choose to make design changes to protect equipment and performance. Deciding in advance of mussel arrival what design changes will be best suited for the facility or system and assessing the costs and timelines would be a helpful part of an overall mussel response plan.

3.3: REVIEW of THE DALLES PROJECT

3.3.1: General

The Dalles Dam is located two miles east of the city of The Dalles, Oregon. The project consists of a navigation lock, spillway, powerhouse and fish passage facilities. Various recreational facilities are provided along Lake Celilo, the 24-mile-long impoundment behind the dam.

The powerhouse has twenty-two operating generating units. Fourteen units were installed during the initial construction of the powerhouse from February 1952 to 1960; eight were added later, for a total project generating capacity of 1.8 million kilowatts.

The modern navigation lock was completed in 1957 allowing increased size of tows and shorter transfer times. Several million tons of petroleum products, grains and other miscellaneous cargo move through the lock every year.

3.3.2: Intake Structures

There are three distinct inlet structures on the face of the dam at the powerhouse. The first is the inlet at each main unit bay to the Kaplan turbines. This intake is via a large tapered concrete conduit which terminates at the turbine scroll case. The second inlet structure is at the fish turbine bays. This structure is similar to the first but has a longer concrete conduit. More than half of the conduit has parallel sides. This conduit also feeds a Kaplan turbine which is much smaller in size than the main unit turbines. The third inlet from the station service bays is a tapered concrete opening that transitions to a metal penstock. It is the longest of the three inlets and directs water to a Francis style of turbine.

The high flow rate through the conduits will discourage mussel attachment. However, in areas within the intake structures where the flow is consistently less than 6 ft/sec mussels will be able to attach and flourish. Areas such as gate slots, vent lines, branch line take-offs, drain lines and mud boxes are places where low flow zones can exist and may accumulate mussels. These are the areas that would most likely be affected by mussel infestation.

Each intake conduit has two gates, a bulk head gate and an operating gate. The gate track slots may accumulate attached mussels, particularly the bulk head gate which is likely to operate less frequently. Mussels in the gate slots will not prevent the gates from operating as the gates are large, heavy structures. However, the mussel shells may become trapped in the sealing surfaces increasing leaks past the gate seals. Cycling of the gate may be necessary to flush the gate slots.

The trash racks consist of vertical bars that extend to the bottom of the intake conduit. The grates for all powerhouse generator bays have 1-3/4" spacing between the bars. At this small spacing, the trash racks are likely to become heavily infested in the event mussels become established in the Columbia River system. The racks will need to be removed and cleaned. If the racks are fixed in place or removal is impractical, cleaning will have to be done manually possibly by divers. When divers are used, a scrape and vacuum method is highly recommended in order to minimize the shell debris coming into the service water system via the scroll cage take-off.

Should cleaning become a significant operational burden, consideration could be given to painting the trash racks with proven anti-fouling paint or foul release paint as a possible longer term solution.

It is possible that mussels could attach to the walls of the intake conduit upstream of the gates when a turbine unit is shut down and low flow or no flow is in the conduit. Once flow is re-established, some of the mussels may leave the area either voluntarily because the environment is too turbulent or by being scoured off the walls by the high flow. During an extended outage of a turbine unit, a layer of mussels may become established. The increased hydraulic friction of a thin layer of mussels on the intake wall will reduce the power output that can be achieved.

Should it become necessary to drain the intake, all air vents should be checked for proper operation in the event mussels have managed to settle in the wetted portions of the vent line. Should it be impractical to check air vents either prior to or during a draining operation, the pipe wall collapse pressure should be determined or checked. If pipe wall collapse is a possible outcome of plugged vent lines, the drain process should not proceed without the approval of the system piping engineer or safety engineer.

3.4.3: Discharge Area

Water that exits from the turbines passes through the draft tube and then into the river. The discharge area has fast and turbulent flow and is unlikely to experience any mussel settlement or problems associated with mussel shell debris.

There are grates at the discharge area of each turbine unit. These are constructed with bars on a spacing of 1'. Such a wide spacing should not result in flow blockage problems.

3.4.4: Domestic Water

Domestic water for The Dalles project is provided from 3 wells. A 155,000 gallon storage reservoir provides a backup reserve supply and static head. A 10,000 gallon pressure tank provides a pressurized operating reserve. The domestic water supply is neither filtered nor chlorinated.

Domestic water is delivered to the spillway dam, non-overflow dam and on to the navigation lock. A service air compressor room in the non-overflow dam is cooled with this domestic water.

Within the power house 6" line supplies domestic water to the power turbine glands and 3/4" line supplies domestic water to the governor air compressors.

Although the domestic water is not filtered it will remain free of mussel shells as the source water is from a ground water well. The glands and shaft sleeves will not be subjected to increased wear from mussel shell debris while domestic water is used for gland cooling.

There is a cross connection to provide river water to the glands in the event of an emergency. If river water is needed to supply the emergency gland water, some shell debris may enter the gland cooling rings. Also, mussel veligers may enter the piping and settle. Once potable water supply is restored to the glands any mussel veligers that have entered the gland or gland piping will not be killed as the domestic water is not chlorinated.

The type of back flow prevention valves at the cross connection area were not able to be checked during our visit. It is uncertain if these valves have a means to verify there is no leakage across the seal faces. Should there be the possibility of any seepage past the seal faces, mussels could enter the gland water piping. It would be advisable to chlorinate the domestic water to ensure mussels are killed from any seepage of river water into the domestic water system.

3.4.5: Station Service Water

Raw river water for station service water loads is taken from the penstocks of the station service units. The water passes through duplex strainers and is then piped to the various station uses. The strainer baskets with 3/16" mesh will keep out large adult mussels and dead shells. Small adult translocators[1] and settling age veligers will pass through the strainers and can colonize the piping and equipment.

The station service water is used for the following applications: unit cooling for the station service generator air cooler and bearing oil coolers, the heating and ventilating system, air compressor cooling, sewage pump glands, and the deck

[1] Settled adults have some ability to relocate. They are called translocators. They detach their byssal threads and either move with the flow or use a small foot to push themselves to a new location.

washing system. The deck washing system has auxiliary pumps equipped with air cooled motors and these motors will not have any problems due to mussels.

Heavy colonization could reduce the water supply to the various heat exchangers and cause performance degradation. Light colonization on the piping walls may be tolerable to the equipment performance but after a period of time mussels in the piping will begin to die, the shells will be shed from the pipe walls. These shells can plug heat exchanger tubes, the manifolds at the tube sheets, or the shell side of heat exchangers. .

Mussels that are shed from pipe walls can also cause increased abrasion in the pump glands.

As the river water progresses through the various pipe branches, the branch piping gets smaller so it is these smaller pipes that are the greatest risk of rapid plugging.

Some of the power plant transformers use river water to cool the transformer oil. The cooling water enters the building from the forebay at elevation 129.5. A dual train consisting of 2 strainers, 2 pumps and associated piping delivers water to the transformer cooler. The strainers, piping and coolers are at risk of flow problems caused by mussel settlement. The pump motors are air cooled and will not have any problems due to mussels. There is no separate gland water system provided for the pumps so the glands would be at risk of increased wear from shell debris. The plant transformers are being replaced progressively with new transformers using an air cooled design. The cooling water system will therefore become redundant and will be decommissioned at some point in the future.

3.4.6: Unit Cooling Water

Unit cooling water is taken from the scroll case of each unit via a 10" line. The water passes through a duplex strainer before being delivered to the cooling loads. The strainer baskets with 3/16" mesh will keep out large adult mussels and dead shells. Small adult translocators and settling age veligers will pass through the strainers and can colonize the piping. Typically in piping this size with high flow rates, heavy colonization does not occur or if it occurs, the build-up is slow. Light colonization may be tolerable to the equipment performance but after a period of time mussels in the piping will begin to die, the shells will shed from the pipe walls and can plug the heat exchanger tubes.

The unit cooling water services the turbine and generator bearing coolers and the generator air coolers. The most common area for mussels to accumulate is in the tube inlet and outlet manifolds of the air-to-water heat exchangers and in the shell cavity of oil coolers. These areas tend to have lower flow velocities and are more attractive settlement areas for live mussels.

The manifolds and shell side cavities are also catchment areas for any shells or shell fragments that manage to find their way along the upstream piping. Shell material can gradually accumulate in these areas ultimately blocking tubes and causing poor performance of the coolers. If poor cooler performance is detected by equipment health monitoring, the maintenance personnel should be advised that mussel shell accumulation is a possible cause so they can take appropriate investigation steps.

If cooling water temperatures rise above 85°F on the discharge side of heat exchangers, then mussels will not settle in the downstream piping. Any mussels that have settled when the cooling water discharge temperature is below 85° F will die if the temperature rises above the mussel tolerance threshold (85° F) for a period of several consecutive hours.

Cooler tubes are typically manufactured of high copper content material and have high flow velocities. Mussels do not usually settle in these areas. However, tube diameters may be small enough to be blocked by a dead mussel shell or clump of shells that have detached from upstream locations.

3.4.7: Fire Protection Water

Fire protection water is provided by the domestic water system for all the offices. There are no sprinkler heads or fire hose bibs in the power house.

There is a transformer spray system on level 6. River water enters the system through a duplex strainer and is pressurized by 2 two-stage pumps to supply water to the spray piping. The spray piping has an automatic drain valve to keep all the piping external to the building drained so the water doesn't freeze.

The portion of the piping inside the building has a recirculation loop to provide for testing of the spray pumps. This piping will be at risk of mussel settlement.

If the time between system testing is long, veligers should not be able to survive as the water will become low in dissolved oxygen during the periods between system uses or testing. The rate of decay of oxygen should drop below the survival threshold (3 mg/L) within 3 weeks. However, should mussels begin to settle in the plant, the rate of oxygen decay should be measured as the decay can be variable depending on the particular water conditions.

If oxygen decay measurements reveal levels of oxygen that could support mussels, then the fire protection system is at risk of mussel colonization. Any mussel shells that slough off from the colonized portions of the fire water piping and enter the fire water piping could be delivered to the spray nozzles causing impaired performance of the nozzles

3.4.8: HVAC

The warm discharge water from the generator air coolers on Units 3 through 8 and 11 through 14 is used as a heat source for the Heat Pump system. As the need for heating is most likely outside the normal mussel breeding season (typically May to November), the piping delivering the warm discharge water to the heat pump will be at low risk of colonization by mussels.

The cooling water for the HVAC chillers is river water. All equipment and piping in this system will be at risk of mussel settlement. Shell material that is transported along the piping will present a plugging risk for the chiller heat exchanger condenser.

We noted two Orival self-cleaning filters on the pre-cooler water lines. The filters apparently perform poorly. Our experience with this style of filter is that they need about 35 psi (80 feet) of differential pressure to permit the self-cleaning operation to function properly. The differential pressure should be checked and if necessary a discharge suction pump may be needed to provide the additional pressure differential. Small-pore, self-cleaning filters are generally an effective, environmentally benign way of keeping mussels out of water systems.

We also noted one (there may be more) local air cooler on the 6th floor. This cooler was serviced with domestic water and should not have any mussel problems.

3.4.9: Drainage and Unwatering

The large drainage operations route water through a 24" drain header. A 6" header is provided for smaller drain uses. The headers route water to an unwatering sump at elevation 20.0. The sump has two sump pumps to return water to the river. The unwatering piping will remain partially flooded without flow for long periods of time as draining is an infrequent event. The water in the drain tunnel and piping will likely have oxygen levels too low to support mussel growth and the piping will not be at risk of mussel settlement. However, should mussels become established, the oxygen levels in this system should be checked.

The unwatering pumps are shown to have screens on the suction bells. The details of the drain piping routing were not available for our review but if the drainage system is such that a small but steady stream of fresh river water flows into the sump then the screen could become coated with mussels. A heavily infested screen could cause the unwatering pumps to cavitate.

General drainage from plant equipment is directed to the plant sump. The float switches in the main sump should be monitored for mussel attachment as the mussels could weigh down the floats and cause level errors.

General drainage lines that have a more or less continuous drainage flow can support mussel growth. Plugging of general drainage lines is unlikely to affect the operability of the plant but it may be a maintenance nuisance to clean embedded drainage pipes.

The dam structure incorporates collection channels to direct dam seepage to drains in the inspection gallery. 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. A plugged or partially blocked drain tube could result in some gallery flooding. 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.

The dam monitoring program incorporates several foundation uplift pipes. Water in these pipes is generally expected to be ground water seepage and not likely to transport mussels. In addition, reservoir seepage from the dam making its way to the pipes probably passes through the base material in the dam, which will normally suffocate any mussels. Uplift is monitored frequently by dam staff and any changes from the norm need to be noted and investigated further.

3.4.10: Navigation Lock

The navigation lock water enters and leaves the lock via large concrete conduits. The large size of the conduits would allow them to tolerate significant mussel growth. The flow velocities would be expected to be large. If mussels accumulate in multiple layers, these layers will eventually slough off. The operation of the lock would not be threatened by mussel settlement even if multiple layers form.

Mussel shell accumulation in the gate tracks could allow some leakage to occur but as the lock gates are cycled frequently, flushing of the gate tracks will take place as part of the normal operation of the lock.

The motor operators of the gates are very powerful and their performance would not be jeopardized by mussel accumulation.

The lock is taken out of service annually and can be cleaned of any mussel accumulation if it is interfering with the lock operation.

3.4.11: Fish By-pass Structure

The Dalles fishway system has a ladder on the north side of the dam located between the navigation lock and the spillway.

The north shore fish ladder is 1,761' in length and has a width of 24'.

The Dalles east ladder is located at the east end of the powerhouse and consists of three channels; transportation, collection, and the east entrance, which join at the junction pool. The east fish ladder has a length of 1,801', width of 30'

The ladders are blocked and drained (as far as is practical) during the time when fish are not running. Any accumulation of mussels on the walls of the structures can be cleaned during the annual winter outage.

The diffuser grating will be at risk of mussel attachment. This grating is likely to be the most problematic portion of the fish passage system if mussels become established at the dam. A single season of mussel attachment and growth is unlikely to affect the performance of the diffusers. However, the cleaning of the grates is likely to be a time and labor intensive task. Once drained, the mussels in the ladder will either desiccate or freeze. Pressure washers are the typical means to clean walls and floors but the grates have an underside and may need to be removed to clean them thoroughly, increasing the time and labor cost.

There is some grating that is not exposed by drainage. This grating would be at risk of progressive accumulation each season. A manual technique of cleaning such as grate removal or cleaning in place by divers may be necessary every few years. If cleaning becomes an operational burden, then antifouling or foul release coatings could be considered for the grates.

The collection structure and transportation channels are controlled by adjustable weir gates. The walls of the channels and surfaces of the gates may accumulate mussels but flow impairment seems unlikely as the flow area is large. The walls of the collection structure may accumulate some dead mussel shells that could pose a risk of fish injury.

The passage channels have orifices that can be opened and closed. The seals on the orifices may have shells that become trapped in the seal surface permitting leakage. The diffuser sluice gates have tracks that can attract mussel settlement and may have trapped shells that could cause leakage at the gate seals.

3.4.12: Level and Flow Instruments

Dispersed throughout The Dalles Project there are instruments used to track the water levels at various locations such as a channel manometer, intake manometer, or differential transducer in the fish by pass structure

Level stations commonly include tap lines, a stilling well and/or floats. The inlet to the tap line pipe could become colonized with mussels and could impair the accuracy of the level station where there are frequent or sudden changes in flow and levels. For locations where flow rates and water levels change very slowly, there may not be a reduction in accuracy as a plugged pipe would still allow water to percolate to a stilling well or manometer tube.

Floats such as those used to activate sump pumps could have sufficient mussels attached such that the level readings become unreliable and may activate or stop the pump at an undesirable point.

Tap lines are usually small diameter and could therefore become plugged quickly. When plugged, tap lines will need to be cleaned using a lance or snake.

Cleaning of floats is usually done manually.

Should the mussels become established and the cleaning of the level gauging equipment becomes an onerous task, the use of non-contact instrumentation such as ultra-sonic or infra-red level probes can be considered.

3.4.13: The Dalles Summary

Summary Table for The Dalles Dam

Component/Structure	Vulnerability/Comment	Mitigation
Trash racks, grates, diffuser panels (areas that are dewatered annually)	Partial plugging	Annual dewatering will limit build up Manual cleaning required, Likely need to use divers on continuously wetted areas.
Trash racks, grates, diffuser panels (Areas that are continuously wetted)	Plugged openings	Remove components for cleaning or use divers. Anti-fouling coatings will help extend time between cleaning.
Gates, stop logs, adjustable weirs	Leakage from trapped shells. Increased wear on seals	Cycle gates to flush gate tracks.
Penstock, intake tunnels	Increased hydraulic friction losses.	Manual cleaning when friction creates unacceptable losses of power or flow.
Small pipes and tubes for pressure or level sensing	Can plug quickly resulting in inaccurate readings	Manual cleaning or hot water flush
Air vents in penstock , long pipes and tanks	Pipe wall collapse. Slow draining or pressure balancing	Check if pipe wall collapse is possible. Check operation when vents are needed and clean as necessary
Service Water and Unit Cooling Water Systems	Impaired performance of equipment	Keep mussels out of system or deal with individual equipment as described below.
System piping	Flow reduction, source of shells to plug other equipment	Periodic kill and flush when accumulation is reducing performance or shell sloughing is unacceptable
Strainers (Wye, duplex), Filters	Increased plugging	Manual cleaning or install strainers with backwash capability
Valves	Increased leakage esp. air vent valves.	Manual cleaning.
Cooler manifolds	Plugged with shells	Manual cleaning
Cooler tubes	Plugged with shells	Isolate cooler and lance tubes or dissolve shells with organic acid
Turbine shaft seal	Reduced cooling water flow: increased sleeve wear.	Chlorinate gland water
Fire Water System	Plugged fire nozzles	Keep mussels out of system or treat system (kill and flush) annually.
Sumps, pump intake screens	Floats measure incorrect level. Plugged screens cause cavitation.	Manual cleaning
Fish by-pass, screens and conduit	Plugged screens, mussel shells on walls of conduit may injure fish	Screens removed during winter, End of season cleaning of conduit as necessary

3.4: REVIEW of the JOHN DAY PROJECT

3.4.1: General

The John Day Dam project consists of a navigation lock, spillway, powerhouse and fish passage facilities on both shores. The powerhouse has 16 main generators, the first of which began operating in 1968 and the last in 1971. At peak production, the powerhouse is capable of producing 2.2 million kilowatts.

3.4.2: Intake Structures

The inlet to each turbine is via a concrete conduit from each generator bay. The high flow rate through the conduit will discourage mussel attachment. In areas where the flow is consistently less than 6 ft/sec mussels are able to attach and flourish. Areas such as gate slots, vent lines, branch line take-offs, drain lines and mud boxes are places where low flow zones can exist and these areas may accumulate mussels.

The intake conduit has two gates, a bulk head gate and an operating gate. The gate track slots may accumulate attached mussels particularly the bulk head gate which is likely to operate less frequently. Mussels in the gate slots will not prevent the gates from operating as the gates are large heavy structures. The mussel shells may become trapped in the sealing surfaces increasing leaks past the gate seals. Cycling of the gate may be necessary to flush the gate slots.

The trash racks consist of vertical bars that extend to the bottom of the intake conduit. Drawing A1652 shows grates for all powerhouse generator bays with 1-3/4" spacing between the bars. At this small spacing, the trash racks are likely to become heavily infested in the event of mussel establishment in the system. The racks will need to be removed and cleaned. If the racks are fixed in place or removal is impractical, cleaning will have to be done manually, possibly by divers. A scrape and vacuum method is highly recommended in order to minimize the shell debris coming into the service water system via the scroll cage take-off. The existing trash removal system will help to remove some of the mussels.

Should cleaning become a significant operational burden, consideration could be given to painting the trash racks with proven anti-fouling paint or foul release paint as a possible longer term solution.

It is possible that mussels could attach to the walls of the intake conduit upstream of the gates when a turbine unit is shut down and low flow or no flow is in the conduit. Once flow is re-established some of the mussels may leave the area. During an extended outage of a turbine unit, a layer of mussels may become established. The increased hydraulic friction of a thin layer of mussels on the intake wall will reduce the power output that can be achieved.

Should it become necessary to drain the intake, all air vents should be checked for proper operation in the event mussels have managed to settle in the wetted portions of the vent line. Should it be impractical to check air vents either prior to or during a draining operation, the pipe wall collapse pressure should be determined or checked. If pipe wall collapse is a possible outcome of plugged vent lines, the drain process should not proceed without the approval of the system piping engineer or safety engineer.

3.4.3: Discharge Area

Water that exits from the turbines passes through the draft tube and then into the river. The discharge area has fast and turbulent flow and is unlikely to experience any mussel settlement or problems associated with mussel shell debris.

There are grates at the discharge area of each turbine unit. These are constructed with bars on a spacing of 1'. Such a wide spacing should not result in flow blockage problems.

3.4.4: Potable Water

Potable water for the John Day project is provided from 3 wells on the north shore of the river. A 250,000 gallon storage reservoir provides a reserve supply and static head. The potable water supply is chlorinated.

The water from the wells should be mussel free and the use of chlorine in the water will kill any mussels in the unlikely event mussels should find their way into the potable water piping.

Potable water flows through an 8" pipe to the Navigation Lock and then on to the Power House. From the Power House a 6" line proceeds to the south shore.

Within the Power House, a 4" line supplies potable water to the power turbine glands and a 2" line supplies potable gland water to the fish turbine pumps.

Although the potable water is not filtered, it will remain free of mussel shells as the source water is from a ground water well. The glands and shaft sleeves will not be subjected to increased wear from mussel shell debris while potable water is used for gland cooling. In the event river water is needed to supply the emergency gland water, some shell debris may enter the gland cooling rings. Once potable water supply is restored to the glands any mussel veligers that have entered the gland or gland piping will be killed by the chlorinated water.

3.4.5: Industrial Water

Cooling water for heat exchangers TO-1 and TO-2 is river water taken at elevation 208.5. The water passes through a 4" duplex strainer and is then piped to the heat exchangers. The strainer baskets with 3/16" mesh will keep out large adult mussels and dead shells. Small adult translocators and settling age veligers will pass through the strainers and can colonize the piping. Heavy colonization of the strainer basket and piping could reduce the water supply to the heat exchangers and cause performance degradation. Light colonization on the piping walls may be tolerable to the equipment performance but after a period of time mussels in the piping will begin to die, the shells will shed from the pipe walls and can plug the heat exchanger tubes.

Cooling water for the septic tank pump gland is also river water taken at elevation 229.5 that passes through a duplex strainer. Mussels that pass through the strainer and colonize the strainer and the piping will reduce the cooling water flow and eventually dead mussel shells will be shed from the pipe walls and cause increased abrasion in the pump gland or perhaps gland overheating.

As the piping for both the heat exchangers and septic tank pump are only 1-1/2 " diameter, heavy colonization could reduce the flow in the pipes rapidly, possibly within one season.

The gate repair pit wash water is river water which passes through a strainer to a pump and then is piped to the pit wash station connections. This piping should be purged with air or hot water after use to kill any mussel veligers that have entered the piping during the gate repair process.

Large fan rooms with water to air radiators cool the generator hall. The radiators use river water which passes through a strainer. The radiators have header plates which give access to the cooler tubes and these are cleaned periodically. If the normal cleaning cycle is insufficient to remove mussels before they cause a performance problem with the radiators, then during the winter the radiator piping should be drained and dried or flushed with hot water to kill any mussels that have attached during that season.

3.4.6: Unit Cooling Water

Unit cooling water is taken from the scroll case of each unit via a 10" line. The water passes through a duplex strainer before being delivered to the cooling loads. The strainer baskets with 3/16" mesh will keep out large adult mussels and dead shells. Strainer baskets can be both filled with dead shells and colonized on both sides by settling mussels. Mussel settlement on the downstream side of strainer baskets will eventually impair the operation even if the strainers are self cleaning. Small adult translocators and settling age veligers will pass through the strainers and can colonize the piping. Typically in piping of this size with high flow rates, heavy colonization does not occur or if it occurs, the build-up is slow. Light colonization may be tolerable to the equipment performance but after a period of time mussels in the piping will begin to die, the shells will shed from the pipe walls and can plug the heat exchanger tubes.

The unit cooling water services the turbine and generator bearing coolers and the generator air coolers. The most common area for mussels to accumulate is in the tube inlet and outlet manifolds of the air-to-water heat exchangers and in the shell cavity of oil coolers. These areas tend to have lower flow velocities and are more attractive settlement areas for live mussels.

The manifolds and shell side cavities are also catchment areas for any shells or shell fragments that manage to find their way along the upstream piping. Shell material can gradually accumulate in these areas ultimately blocking tubes and causing poor performance of the coolers. If poor cooler performance is detected by equipment health monitoring, the maintenance personnel should be advised that mussel shell accumulation is a possible cause so they can investigate and take appropriate steps.

If cooling water temperatures rise above 85°F on the discharge side of heat exchangers, then mussels will not settle in the downstream piping. Any mussels that have settled when the cooling water discharge temperature is below 85° F will die if the temperature rises above the mussel tolerance threshold (85° F) for several consecutive hours.

Cooler tubes are typically manufactured of high copper content material and have high flow velocities. Mussels do not usually settle in these areas. However, tube diameters may be small enough to be blocked by a dead mussel shell or clump of shells that have detached from upstream locations.

3.4.7: Fire Protection Water

Fire protection water is taken from the unit cooling headers of units 1 and 3 via a 6" line. The line provides water to the fire pump which then provides fire water to the service building. The power house does not have a river water fire suppression system.

The fire protection system water passes through the unit cooling raw water strainer prior to entering the fire water system piping. The strainer should keep out any shell material or adult mussel translocators during fire system testing. However, veligers will be able to enter the fire protection piping during system testing or during use of the fire water system and could colonize the piping.

In the portions of the fire water piping that are normally stagnant for extended periods, veligers should not be able to survive as the water will become low in dissolved oxygen during the periods between system uses or testing. The dissolved oxygen level should drop below the survival threshold (3 mg/L) within 3 weeks. However, should mussels begin to settle in the plant, the rate of oxygen decay should be measured to verify the above assumption. Variables such as organic content of the water, the frequency of fire system testing and the possible use of fire hoses for other uses such as washing surfaces will all affect the rate of oxygen decay..

If oxygen decay measurements reveal levels of oxygen that could support mussels, then the fire protection system is at risk of mussel colonization. Any mussel shells that slough off from the colonized portions of the fire water piping and enter the fire water piping could be delivered to the hose nozzles and room sprinkler nozzles, causing impaired performance of the nozzles.

Therefore depending on how the fire protection system is used and tested, the fire protection system may be at risk of blockage or impaired fire nozzle performance from shell material.

Other methods to keep fire protection systems free of mussel veliger entry especially during testing or use of the fire water for other than fires include:

- A chemical injection system at the fire water take-off that activates only when flow is detected in the fire water piping.

- Addition of small-pore self-cleaning filters at the fire water take-off. A filter design change should include a by-pass line to allow flow should the filters become inoperable during an actual emergency event.

- Periodic (yearly) thermal flush or a chemical soak. The chemical is transported away after use for disposal.

- Connect to municipal fire water or well water where these are available

We noted that there are branch lines that take off from the fire protection system piping also provide emergency cooling water to the air compressors and diesel generator. These piping segments would also be at risk of mussel colonization unless the time period between uses is sufficiently long to kill mussels by oxygen deprivation.

3.4.8: HVAC

The discharge water from the generator air coolers on Units 1 through 6 is used as a heat source for the Heat Pump system. As the need for heating is most likely outside of the normal mussel breeding season (typically May to November), the piping delivering the warm discharge water to the heat pump will be at low risk of colonization by mussels.

The cooling water for the air conditioning comes from the forebay near the gate slot, passes through the cooler and is discharged back to the forebay. One a/c system serves 2 units. All the piping in this system will be at risk of mussel settlement. During the winter period when the units require heating instead of cooling the piping in this system should be drained and dried or flushed with hot water to kill any mussels that have attached during that summer season.

3.4.9: Drainage and Unwatering

The unit incorporates an un-watering system to allow each intake, scroll cage and draft tube to be drained. The drain tunnel will remain flooded without flow for long periods of time since draining is an infrequent event. The water in the drain tunnel and piping should have oxygen levels too low to support mussel growth and the piping will not be at risk of mussel settlement. If mussels become established in the Columbia River, the oxygen levels in this system should be checked.

General drainage from plant equipment is directed to the plant sump. The float switches in the main sump should be monitored for mussel attachment as the mussels could weigh down the floats and cause level errors.

General drainage lines that have a more or less continuous drainage flow can support mussel growth. Plugging of general drainage lines is unlikely to affect the operability of the plant but it may be a maintenance nuisance to clean embedded drainage pipes.

The dam incorporates collection channels to direct dam seepage to drains in the inspection gallery. 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. A plugged or partially blocked drain tube could result in some gallery flooding. 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.

The dam monitoring program incorporates several foundation uplift pipes. Water in these pipes is generally expected to be ground water seepage and not likely to transport mussels. In addition, reservoir seepage from the dam making its way to the pipes probably passes through the base material in the dam, which will normally suffocate any mussels. Uplift is monitored frequently by dam staff and any changes from the norm need to be noted and investigated further.

3.4.10: Navigation Lock

The navigation lock water enters and leaves the lock via large concrete conduits. The large size of the conduits would allow them to tolerate significant mussel growth. The flow velocities would be expected to be large. Multiple layers of mussels would eventually slough off so that operation of the lock would not be threatened by mussel settlement even if multiple layers form.

Mussel shell accumulation in the gate tracks could allow some leakage to occur but as the lock gates are cycled frequently, flushing of the gate tracks will take place.

The motor operators of the gates are very powerful and gate performance would not be jeopardized by mussel accumulation.

The lock is taken out of service annually and can be cleaned of any mussel accumulation if it is interfering with the lock operation.

3.4.11: Fish By-pass Structure

John Day Dam includes a full adult passage system on each side of the project. The south fish ladder is located on the Oregon shore next to the powerhouse. The north fish ladder is located between the spillway and the navigation lock on the north side.

The ladders are blocked and drained (as far as is practical) during the time when fish are not running.

The diffuser grating will be at risk of mussel attachment. The accumulation will not be large as only one season of mussels is possible before the ladders are drained. The exposed mussels will desiccate or freeze. There is some grating that is not able to be exposed by drainage. This grating would be at risk of progressive accumulation each season. A manual technique of cleaning such as grate removal or cleaning in place by divers will be necessary every few years. If cleaning becomes an operation burden, then antifouling or foul release coatings could be considered for the grates.

The diffuser sluice gates have tracks that can attract mussel settlement and may have trapped shells that could cause leakage at the gate seals.

The fish ladder exit grates have spacing of 1 foot. Blockage of these grates will take several years. There may be some risk of fish injury from bumping into dead mussel shells on the mussel build up as fractured dead shells can have sharp edges.

A surface collection structure guides downstream travelling fish into a channel that directs fish over the spillway. The entrance to the collection channels is controlled by adjustable weir gates. The walls of the structure may accumulate mussels but flow impairment seems unlikely as the flow area is large. The walls of the collection structure may have some dead mussel shells that could pose a risk of fish injury.

A juvenile bypass system has a collection channel that runs the length of the powerhouse and routes fish to a bypass conduit. This conduit may need to be drained to desiccate or freeze any mussel accumulation to keep the accumulation to an acceptable level.

The vertical barrier screens have main bars on 2' centers and are covered with a polyester screen. The screens will be at risk of mussel settlement.

Rotating screens at the entrance to each turbine unit direct fish into a collection channel that routes the fish through a bypass conduit which discharges downstream of the dam. These screens will also be at risk of mussel attachment.

The vertical barrier screens and the rotating screens are all removed annually when the fish are not travelling. During this period the screens can be cleaned. At most, one season of mussel attachment will occur.

3.4.12: Fish Water Turbine

The forebay water powers three turbine pumps providing attraction water pulled from the tailrace for the collection channel on the south ladder.

The oil in the gear box and bearings is cooled by river water. The raw water piping and the cooler will be at risk of mussel settlement. The pump stuffing box is cooled with potable water and will not experience any problems from mussels.

Six electric motor driven pumps provide for auxiliary water supply from the tailrace on the north ladder. The motors are air cooled and not exposed to problems from mussels. The pump stuffing boxes (glands) are cooled with potable water that is free of any mussel problems.

3.4.13: Level and Flow Instruments

Dispersed throughout the John Day Project there are instruments used to track the water levels at various locations such as a channel manometer, intake manometer and differential transducer, all in the fish by pass structure.

Level stations commonly include tap lines, stilling wells and/or floats. The inlet to the tap line pipe could become colonized with mussels and could impair the accuracy of the level station if there are frequent or sudden changes in flow and levels. For locations where flow rates and water levels change very slowly, there may not be a reduction in accuracy as a plugged pipe would still allow water to percolate to a stilling well or manometer tube.

Floats such as those used to activate sump pumps could have sufficient mussels attached such that the level readings become unreliable and may activate or stop the pump at an undesirable point.

Tap lines are usually small diameter and could therefore become plugged quickly. When plugged, tap lines will need to be cleaned using a lance or snake.

Cleaning of floats is usually done manually.

Should the mussels become established and the cleaning of the level gauging equipment becomes an onerous task, the use of non-contact instrumentation such as ultra-sonic or infra-red level probes can be considered.

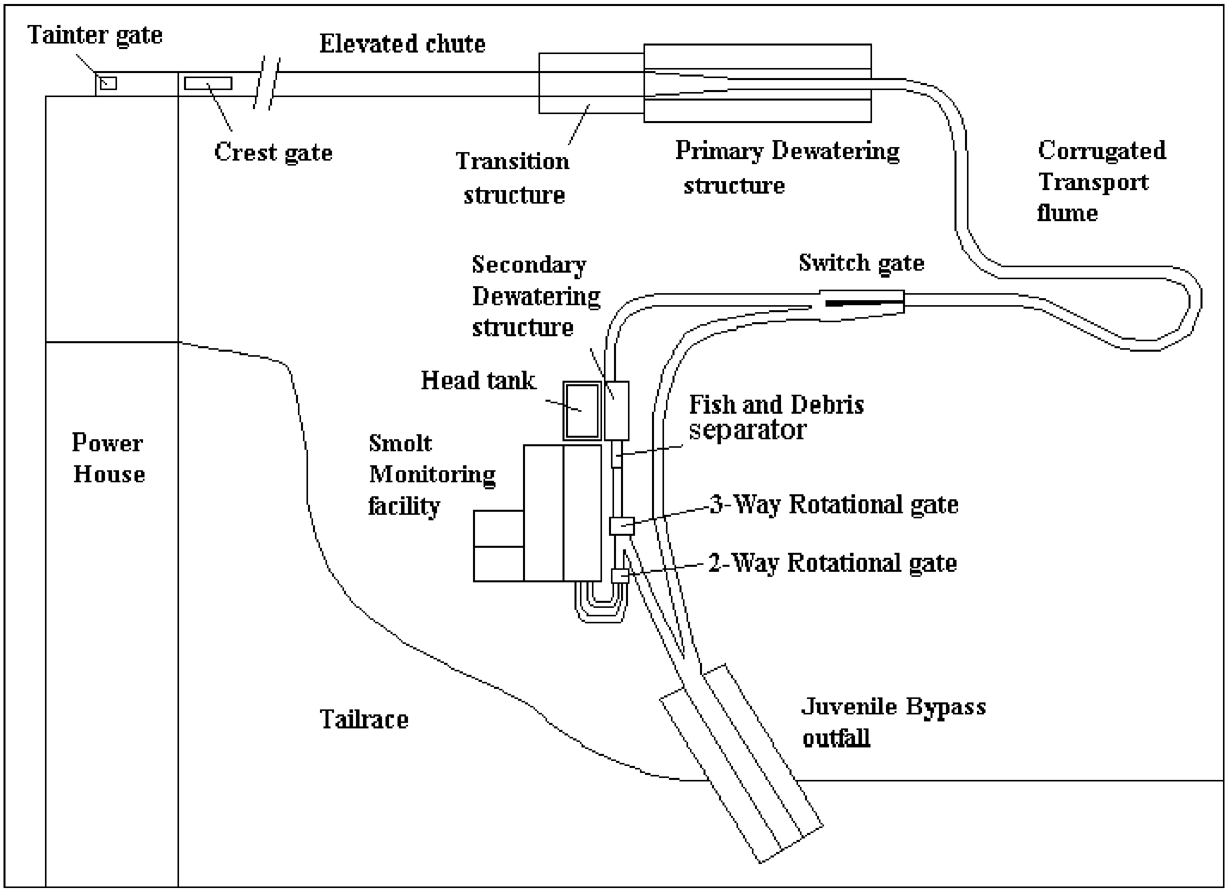
3.4.14: John Day Summary

Summary Table for John Day Dam

Component/Structure	Vulnerability/Comment	Mitigation
Trash racks, grates, diffuser panels (areas that are dewatered annually)	Partial plugging	Annual dewatering will limit build up Manual cleaning required, Likely need to use divers on continuously wetted areas.
Trash racks, grates, diffuser panels (Areas that are continuously wetted)	Plugged openings	Remove components for cleaning or use divers. Anti-fouling coatings will help extend time between cleaning.
Gates, stop logs, adjustable weirs, fish passage orifice gates	Trapped mussel shells could. Increased wear on seals	Cycle gates to flush gate tracks.
Penstock, intake tunnels	Increased hydraulic friction losses.	Manual cleaning when friction creates unacceptable losses of power or flow.
Small pipes and tubes for pressure or level sensing	Can plug quickly resulting in inaccurate readings	Manual cleaning g or hot water flush
Air vents in penstock , long pipes and tanks	Pipe wall collapse. Slow draining or pressure balancing	Check if pipe wall collapse is possible. Check operation when vents are needed and clean as necessary
Service Water and Unit Cooling Water Systems	Impaired performance of equipment	Keep mussels out of system or deal with individual equipment as described below.
System piping	Flow reduction, source of shells to plug other equipment	Periodic kill and flush when accumulation is reducing performance or shell sloughing is unacceptable. Drain and dry gate repair pit water piping between uses.
Strainers (Wye, duplex), Filters	Increased plugging	Manual cleaning or install strainers with backwash capability
Valves	Increased leakage esp. air vent valves.	Manual cleaning.
Cooler manifolds	Plugged with shells	Manual cleaning
Cooler tubes	Plugged with shells	Isolate cooler and lance tubes or dissolve shells with organic acid
Turbine shaft seals (glands)	Reduced cooling water flow: increased sleeve wear.	Chlorinate gland water
Large air coolers	Accumulation of live adults or dead shells in the cooler manifolds.	Air coolers are seasonal. Clean them during the winter.
Fire Water System	Plugged fire nozzles	Keep mussels out of system or treat system (kill and flush) annually.
Sumps, pump intake screens	Floats measure incorrect level. Plugged screens cause cavitation.	Manual cleaning
Fish by-pass, screens and conduit	Plugged screens, mussel shells on walls of conduit may injure fish	Screens removed during winter, End of season cleaning of conduit as necessary

3.5: REVIEW of the JOHN DAY SMOLT MONITORING FACILITY

3.5.1: General Layout of Smolt Monitoring Facility



3.5.2: Tainter Gate, Crest Gate and Elevated Chute

The tainter gate regulates the amount of water flowing out of the fish bypass system and over the crest gate into the elevated chute. In general, flow through the chute is very fast and is typically greater than 6 ft/sec. At the end of the fish monitoring season, the crest gate is raised and the elevated chute is subsequently dewatered.

The tainter gate is unlikely to be affected by mussels. The water flow is fast and the gate moves frequently so that any mussel attachment in the seal area would be rubbed away.

The level instrumentation that controls the position of the gate may be at risk of inaccurate readings due to mussel attachment and growth in level sensing lines. Non-contact instrumentation may be needed as a backup if accurate level control is an operational requirement.

When the chute is drained at the end of the fish passage season, any mussels that have attached will desiccate or freeze. If attached mussel shells are possibly injurious to fish, then manual cleaning may be necessary.

3.5.3: Primary Dewatering Structure

The Primary Dewatering Structure (PDS) separates the fish from most of the water routed down the elevated chute. The separation is done by dewatering screens. The removed water returns to the river via a 6 ft diameter underground conduit. Water in the conduit is fast flowing and minimal mussel settlement would be expected. The conduit is large so that some mussel accumulation should not reduce the flow capacity by a sufficient amount to cause a performance problem.

The dewatering screens are panels of wedge wire design with a 2 mm gap and supported by perforated backing plates. The screen frames are lowered into vertical guide slots of the bypass channel. The screens are fitted with screen cleaning brushes. The brushes will remove any mussels that attach to the screens. The surfaces not directly in contact with the screen brushes may have some mussel attachment occurring during the fish passage season.

The PDS is dewatered from approximately October through March. During the dewatered period any attached mussels will die and can be cleaned manually as required.

3.5.4: Corrugated Transport Flume

The corrugated transport flume moves the remaining water and fish from the PDS to the secondary dewatering structure (SDS). The flume is a corrugated metal channel with an open top. The top is covered with panels that can be removed for cleaning of the flume channel. The top covers are in small sections so removal for cleaning would be a tedious process. The flume is drained annually; any mussels that have attached will likely be small and will die from desiccation or freezing. Several seasons may pass before the accumulation of dead mussels is large enough to require cleaning. As the flume is over 1000 feet long, the cleaning process may onerous and costly if done manually. An ROV cleaning tool may be considered.

The switch gate is unlikely to be adversely affected by mussels. The blade seals will sweep attached mussels during each cycling of the gate.

3.5.5: Secondary Dewatering System (SDS):

This system has several components which serve to remove most of the remaining transport water, separate adult and juvenile fish, and separate debris. The continual flow of reduced water volume together with passage and rubbing contact of fish and debris will likely inhibit mussel attachment and growth during the monitoring season. This area also has regular manual attention to clear larger debris. At those times any mussel attachment or accumulation of dead shells can be removed to keep mussels from affecting operation during the monitoring season. When the system is dewatered inspection and cleaning can take place.

3.5.6: SMF Lab

The components located inside the lab are used regularly by lab staff. Any problems from mussel attachment or shell accumulation will be identified quickly. The lab equipment is routinely cleaned using water and brushes during the fish monitoring season. The lab equipment is dewatered and dry during the winter. The risk of problems inside the lab due to mussels is negligible.

3.5.7: Outfall

The outfall piping carries all the fish, water, and debris from the juvenile collection channel to the tailrace outfall flume when the crest gate is in bypass mode. The flow velocity is usually greater than 6 fps and unlikely to experience significant mussel attachment. Mussel shell material will be flushed through the conduit and into the river.

3.6: REVIEW of the Wasco County PUD PROJECT

3.6.1: Intake Structures and Discharge Area

The flow into the facility can be blocked by a radial gate. Mussels have little impact on radial gates. The side seals may trap shells which may cause some abrasion on the seal. The bottom seal may get shells trapped that let in minor amounts of leakage water. When the gate is opened, the bottom seal is flushed clean. If trapped shells cause an unacceptable leakage, the gate may need to be cycled to flush the seat.

The power house intake is a concrete channel that receives water from the fish by-pass screens and directs that water into a steel penstock.

The high flow rate through the penstock, draft tube and discharge area will discourage mussel attachment. In areas where the flow is consistently less than 6 ft/sec mussels will be able to attach and flourish. Areas such as gate slots, vent lines, branch line take-offs, drain lines and mud boxes are places where low flow zones can exist and may accumulate mussels.

Mussels may also attach during periods when the turbine is not operating with the penstock watered. Mussels that attached during this period may establish sufficient attachment strength that they can remain attached when normal flow is restored.

The exit of the draft tube can be blocked with a gate. The gate track slots may accumulate attached mussels particularly if the gate operates infrequently. Mussels in the gate slots will not prevent the gate from operating as it is a large, heavy structure. The mussel shells may become trapped in the sealing surfaces increasing leaks past the gate seals. Cycling of the gate may be necessary to flush the gate slots.

Water that exits from the turbines passes through the draft tube and then into the fish ladder. The discharge area has fast and turbulent flow and is unlikely to experience any mussel settlement or problems associated with mussel shell debris.

Mussel accumulation on the walls of the penstock and draft tube is likely to be very limited and unlikely to cause a forced outage of the turbine. Routine planned inspections of the penstock should provide sufficient opportunity to clean any minor accumulation of mussels. However, if a single layer of mussels is allowed to accumulate, the increased friction will reduce the power output of the turbine and that may be an unacceptable economic penalty.

3.6.2: Fish By-pass Structure

The fish bypass structure serves to separate fish from the water stream that enters the power house. A concrete entrance directs fish and water into a tapered deep channel. One side of the channel has a wall of screens that allows water to pass through into the power house intake channel. The fish are directed along the narrowing channel to its terminus where the fish enter a 24" diameter conduit that routes the fish into the fish ladder entrance area on the downstream side of the dam.

The fish barrier screen panels are 1/8" vertical profile wires with a 1/8" gap between wires. A brush system is provided to sweep the surface of the screens. The brush moves horizontally along the length of the tapered channel. The bristles move across the screen wires perpendicular to the wires. The brushes will keep mussels from the surface of the wires. It is not clear from the design if the bristles will penetrate the gap between wires and remove any attached mussels from the wire surface facing the gap. There may be some risk that the gap could be bridged by mussels attaching within the gap. The screens are removed at the end of the fish passage season. If mussel accumulation during the fish passage season causes operational problems then an anti-fouling or foul release coatings could be considered for the screens.

The bypass conduit is dewatered after the fish passage season and any mussels attached to the walls of the conduit will desiccate or freeze. Mussel accumulation should be low as the flow is large with high velocity, limiting the opportunity for attachment and mussels will only experience one season of growth before being killed during the conduit drained period. Should cleaning of the conduit become necessary to remove dead shells, an ROV cleaning tool will be required as the conduit is long (1500 ft) and too small for workmen to enter.

3.6.3: Service Water

We observed extensive use of copper piping for service water and cooling water applications throughout the plant. Copper is toxic to mussels and they will not settle on copper unless a bio-film has formed on the copper.   The risk of mussels blocking piping in the plant is greatly reduced due to the use of copper piping materials.

There are two non-potable pumps in the spiral case gallery that provide pressurized service water. The water enters the system via a small duplex strainer.

As most of the piping is copper, there is little risk of problems from mussel settlement in this system. The greatest risk is from shell material coming in from upstream sources. The duplex strainer should have a basket with as small a screen size as practical, preferably 1/8" or less to avoid mussel shell accumulation problems. Primary settlement may still be a problem

3.6.4: Cooling Water

Cooling water is taken off the penstock pipe via an 8" connection. The opening for the connection has vertical bars across the opening on 1" spacing. These bars could become attachment sites for mussels and the openings could close quickly due to the narrow bar spacing. Cleaning the grate may require the penstock to be drained in order to open the 8" line and clean the grate. The cost in lost power production could be significant. If there are planned outages where the penstock is to be drained then the opportunity should be taken to coat the grate bars with anti-fouling paint. These paints can have life spans of up to 10 years depending on the operating environment and for this application could reduce or eliminate the need for an unplanned outage.

The cooling water passes through a duplex strainer before being delivered to the cooling loads. The strainer baskets with 3/16" mesh will keep out large adult mussels and dead shells. Small adult translocators and settling age veligers will pass through the strainers and can colonize the piping.

Light colonization of the piping may be tolerable to the equipment performance but after a period of time mussels in the piping will begin to die, the shells will shed from the pipe walls and can plug the heat exchanger tubes.

The cooling water services the turbine and generator bearing coolers, the generator air coolers, the air compressor after cooler and the hydraulic power unit oil cooler.

The most common area for mussels to accumulate is in the tube inlet and outlet manifolds of the air-to-water heat exchangers and in the shell cavity of oil coolers. These areas tend to have lower flow velocities and are more attractive settlement areas for live mussels.

The manifolds and shell side cavities are also natural sedimentation areas or catchment area for dead shells or shell fragments that manage to find their way along the upstream piping. Shell material can gradually accumulate in these areas ultimately blocking tubes and causing poor performance of the coolers. If poor cooler performance is detected by equipment health monitoring, the maintenance personnel should be advised that mussel shell accumulation is a possible cause and take appropriate investigation steps.

If cooling water temperatures rise above 85°F on the discharge side of heat exchangers, then mussels will not settle in the downstream piping. Any mussels that have settled when the cooling water discharge temperature is below 85° F will die if the temperature rises above the mussel tolerance threshold (85° F) for several hours.

Cooler tubes are typically manufactured of high copper content material and have high flow velocities. Mussels do not usually settle in these areas. However, tube diameters may be small enough to be blocked by a dead mussel shell or clump of shells that have detached from upstream locations.

3.6.5: Fire Protection

Water is not used for fire protection in the plant.

3.6.6: Drainage and Unwatering

Drain lines on the penstock, scroll case and draft tube will have their inlet areas wetted by normal flow but at low velocity. These areas are the most likely places for mussels to attach and settle. The flow is low and oxygen and food supply will be continually refreshed from the normal turbine flow.

General drainage from plant equipment is directed to the plant sump. The float switches in the main sump should be monitored for mussel attachment as the mussels could weigh down the floats and cause level errors.

General drainage lines that have a more or less continuous drainage flow can support mussel growth. Plugging of general drainage lines is unlikely to affect the operability of the plant but it may be a maintenance nuisance to clean embedded drainage pipes.

Should it become necessary to drain the intake, any air vents should be checked for proper operation in the event mussels have managed to settle in the wetted portions of the vent line. Should it be impractical to check air vents either prior to or during a draining operation, the pipe wall collapse pressure should be determined or checked. If pipe wall collapse is a possible outcome of plugged vent lines, the drain process should not proceed without the approval of the system piping engineer or safety engineer.

Should it become necessary to drain the intake, any air vents or vents lines necessary for draining, filling or balancing should be checked for proper operation in the event mussels have managed to settle in the wetted portions of the vent line. Should it be impractical to check air vents either prior to or during a draining operation, the pipe wall collapse pressure should be determined or checked. If pipe wall collapse is a possible outcome of plugged vent lines, the drain process should not proceed without the approval of the system piping engineer or safety engineer

3.6.7: Level or Pressure Sensing Equipment

Level sensing equipment usually includes a tap line, stilling well and float. The inlet pipe could become colonized with mussels and could impair the accuracy of the gauging station if there are frequent or sudden changes in flow and levels. For locations where flow rates and water levels change very slowly, there may not be a reduction in accuracy as a plugged pipe would still allow water to percolate to the stilling well.

Only one level sensing line was noted in the plant. This line was of copper material. Mussels will not settle on copper that is clean. Copper with a heavy bio-film cover may experience some mussel attachment but this is usually weak attachment as the mussels are attaching to the bio-film not the copper. They are therefore easy to clean from copper surfaces.

The floats could have sufficient mussels attached such that the level readings become unreliable.

Should the mussels become established and the cleaning of the gauging stations becomes an onerous task, the use of non-contact instrumentation such as ultra-sonic or infra-red level probes can be considered.

Summary Table for PUD

Component/Structure	Vulnerability/Comment	Mitigation
Trash racks, grates, fish by-pass screens	Partial plugging	Annual dewatering will limit build up Manual cleaning required. Existing trash brush system will likely keep most mussels from attaching except on downstream side of screen.
Radial gate weirs	Trapped shells may increase wear on seals	Cycle gates to flush gate seats.
Penstock, intake tunnels	Increased hydraulic friction losses.	Manual cleaning when friction creates unacceptable losses of power or flow.
Small pipes and tubes for pressure or level sensing	Can plug quickly resulting in inaccurate readings	Manual cleaning g or hot water flush
Air vents in penstock, long pipes and tanks	Pipe wall collapse. Slow draining or pressure balancing	Check if pipe wall collapse is possible. Check operation when vents are needed and clean as necessary
Service Water and Unit Cooling Water Systems	Impaired performance of equipment	Keep mussels out of system or deal with individual equipment as described below.
System piping	Flow reduction, source of shells to plug other equipment	Periodic kill and flush when accumulation reduces performance or shell sloughing is unacceptable. Use of copper piping will limit settlement.
Strainers (Wye, duplex), Filters	Increased plugging	Manual cleaning or install strainers with backwash capability
Valves	Increased leakage esp. air vent valves.	Manual cleaning.
Cooler manifolds	Plugged with shells	Manual cleaning
Cooler tubes	Plugged with shells	Isolate cooler and lance tubes or dissolve shells with organic acid
Turbine shaft seals (glands)	Reduced cooling water flow, increased sleeve wear.	Chlorinate or filter gland water
Sumps	Floats measure incorrect level.	Manual cleaning
Fish by-pass, conduit	mussel shells on walls of conduit may injure fish	End of season cleaning of conduit as necessary

RECOMMENDATIONS

Due to the uncertainties in timing of mussel introduction and the uncertainty of them thriving in the Columbia River, we suggest a stepwise, graduated approach to asset protection. The suggested steps and associated actions are outlined in the Executive Summary. Additional detail is provided here in the following recommendations:

1. Current dreissenid mussel monitoring effort should continue in the Columbia River system to verify that there is no developing dreissenid population.
2. Additional collection of all environmental parameters throughout the Columbia River Drainage Basin is recommended. Calcium levels and pH profiles are a priority but collection of seasonal temperature and dissolved oxygen profiles is recommended particularly in the reservoirs. Additional environmental data will allow for better quantification of the risk of dreissenid establishment.
3. The review of facilities and structures in this report identifies which areas are vulnerable if a dreissenid population became established. Having this assessment means that management is capable of a swift response should protection of facilities and structures become necessary. In particular, the following monitoring activities are proposed for areas that should be watched closely:
    a) Check level and flow measuring gauges in direct contact with raw water. These gauges if infested with mussels would not operate properly. Non-contact instrumentation is advisable.
    b) Integrate monitoring for mussels into normal dam, plant, and component inspection cycles and routine walk around 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.
    c) Provide staff training on mussel identification and likely locations inside the dams such as drain gutters and the sumps.

4. Monitor the progress of commercial introduction of Zequanox - a biological control specific only to dreissenids providing an environmentally acceptable chemical solution.

5. Initiate permitting process with the regulator so you can begin mitigation when required (discuss Zequanox, pH adjustment, oxidizing chemicals)

6. Develop an action plan for each system which requires protection, including:

    a) Evaluate which systems could be switched from river water to domestic water.
    b) Install injection points at the start of each raw water system
    c) Initiate introduction of self-cleaning strainers and filters in areas which currently experience fouling with Asian clam shells and silt.

7. Chlorination of domestic water on continuous basis would be valuable.

8. Initiate a non-toxic, foul release coating study on the fish grates of the fish handling system to gather first hand performance data.

9. If a vigorous mussel population is confirmed 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 the 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, time and resources may be targeted more appropriately by waiting until mussels are established in the reservoir.

10. 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).

11. Prepare and test operational procedures to clean critical areas of the dam such as the seepage collection pipes and vent pipes. Where possible, vent lines should be inspected prior to draining pipe lines.

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

13. Replacement of fixed trashracks at the end of their useful life could also consider retrofitting the replacement design with removable trashracks to facilitate cleaning and reduce or eliminate the need for costly diver support

14. 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.

15. For water uses that are occasional such as fire water systems or systems that have low water usage but vulnerable to mussels settlement, consider connecting to municipal water systems or wells in the future.

Literature Reviewed

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.

Mackie G.L and R.Claudi 2009 Monitoring and Control of Macrofouling Mollusks in Fresh Water Systems, Second Edition, CRC Press

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.