Economic Risk Associated with the Potential Establishment of Zebra and Quagga Mussels in the Columbia River Basin

Independent Economic Analysis Board[1]

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[1] This report includes contributions from a number of non-IEAB persons who provided text and edits for the report. These contributors include ISRP and ISAB members (Dennis Scarnecchia, Colin Levings), Council staff (Jim Ruff), Thomas Whittier (Oregon State University), and Mark Sytsma (Portland State University). We also appreciate information provided by federal and State agency representatives. In all cases, their contribution does not imply endorsement.

Contents

LIST OF ACRONYMS

AIS	Aquatic Invasive Species
Basin	Columbia River Basin
BPA	Bonneville Power Administration
BPS	Border Protection Stations
CDFA	California Department of Food and Agriculture
CDFG	California Department of Fish and Game
CRBT	Columbia River Basin Team
ESBS	Extended Submersible Bar Screen
ESSB	Engrossed Substitute Senate Bill
FCRPS	Federal Columbia River Power System
FWP	Fish and Wildlife Program
HVAC	Heating/Ventilation and Air Cooling
IANST	Idaho Aquatic Nuisance Species Taskforce
IISF	Idaho Invasive Species Fund
ISDA	Idaho State Department of Agriculture
ICTRT	Interior Columbia Technical Recovery Team
LMNRA	Lake Mead National Recreation Area
M&I	Municipal and Industrial
mm	Millimeter
MTFWP	Montana Fish Wildlife and Parks
MW	Megawatts
NASQAN	National Stream Quality Accounting Network
NPS	National Park Service
ODFW	Oregon Department of Fish and Wildlife
OSMB	Oregon State Marine Board
pH	Acidity
QZAP	Quagga-Zebra Mussel Action Plan for Western Waters
USACE	U.S. Army Corps of Engineers
STS	Submersible Traveling Screen
VBS	Vertical Barrier Screen
WDFW	Washington Department of Fish and Wildlife
WSP	Washington State Patrol

EXECUTIVE SUMMARY

The zebra mussel *Dreissena polymorpha* and quagga mussel *Dreissena rostriformis bugensis*, two species of invasive bivalve mollusks, pose an economic risk to the Columbia River Basin (the Basin), but there is a large range in the forecasts of potential economic costs. This report documents the potential economic implications of a widespread zebra or quagga mussel (mussel) infestation in the Basin.[2] We emphasize the potential effects of a mussel infestation on facilities, resources, ecosystems and species that are closely related to the Fish and Wildlife Program (FWP) and the Federal Columbia River Power System (FCRPS). The report reviews the current state of knowledge about the risk of mussel introduction, establishment, growth and densities, and estimates some potential costs of infestation, avoidance, and control. We conclude with recommendations for research and policies that could improve the assessment of the risks and costs of mussel infestation.

Science Issues and Infestation Scenarios

The IEAB worked collaboratively with regional mussel and water quality experts to describe potential infestation scenarios for the Basin. Under suitable conditions, zebra and quagga mussels can expand in numbers and locations with astonishing speed. However, scientists believe that these mussels will not thrive in parts of the Basin because they will be limited by insufficient calcium concentrations.

Calcium concentrations in the Basin are highly variable over time and between locations. In the mainstem Columbia and Snake Rivers below the Clearwater River, calcium concentrations are seasonal and within a range believed to limit mussel populations. Within this range there remains much scientific uncertainty about the viability, growth or density of mussel populations. However, for much of the Snake River above the Clearwater River, some parts of the Salmon, John Day and Pend Oreille River basins, and other local areas, calcium conditions may be generally favorable for mussels. Establishment and reproduction in these favorable locations could produce large numbers of veligers (free-floating juveniles) that could quickly establish themselves at other suitable locations downstream.

Several uncertainties limit our ability to assess probable mussel distribution and abundance based on calcium. This analysis did not include an exhaustive compilation and analysis of calcium data. Off of the mainstem rivers, calcium data are relatively sparse. Calcium in the mussel's diet and interactions with acidity (pH) may be very important. Also, calcium concentrations in the Basin's mainstem rivers are highly seasonal; they are highest in winter through early spring and lowest in the warm water summer months when mussel spawning would occur. It is possible that mussels might not thrive in parts of the mainstems because they lack sufficient calcium concentrations at the time that water temperatures are favorable for spawning.

[2] We use the word "mussel" to refer to either of the *Dreissena* species.

Much of the research on calcium has involved zebra mussels; less is known about the ecology of quagga mussels and the differences between the two species. Due to uncertainty in environmental conditions suitable for mussel growth and reproduction, research is needed to determine how variable calcium concentrations, calcium in the diet, pH, and temperature affect mussel's chances to reproduce and grow in different areas of the Basin. Such research is important to refine the estimates of potential cost of mussel infestations should they occur.

With these uncertainties in mind, the IEAB prepared, in consultation with biologists, "infestation scenarios" that describe and qualify how calcium may affect the risk of mussel infestation, densities and growth rates at different places in the Basin. Uncertainties around these infestation scenarios indicate that they should receive further scientific review and refinement as the quality of information about calcium, calcium in the diet, other water quality factors, and mussel biology improves.

In summary, and subject to the uncertainties previously described,

> In the Snake River Basin, calcium concentrations are seasonal but often very favorable for mussels, especially in the upper headwater region and the upper Snake. One important infestation scenario, both in terms of relative likelihood and potential costs, is an established infestation in the upper Snake River.
>
> Moving downriver, calcium concentrations are much lower in tributaries to the middle Snake, but still favorable for mussels at certain times and places. The Clearwater River (a major tributary to the Snake River) is generally very low in calcium; mussels will probably not survive in most locations in that subbasin. Calcium concentrations in the lower Snake River below the Clearwater are very seasonal and often reflect upstream reservoir operations. In the lower Snake, through the four FCRPS projects, calcium concentrations tend to peak in winter at levels high enough to support mussels.
>
> Much of the upper and mid-Columbia River Basin above the Snake River confluence has lower calcium concentrations than the Snake River Basin. It is unclear whether calcium concentrations in the mainstem Columbia River would support mussel establishment. However, parts of some upstream subbasins including the Salmon, John Day, upper Columbia and Pend Oreille may have areas that could support populations that could send veligers downstream. Mussels are less likely to survive in the much of the Yakima River or the Deschutes River basin, but a few areas might support populations.
>
> Calcium concentrations in the Columbia River mainstem generally decline from the Snake-Clearwater confluence downstream to the ocean. Calcium concentrations in much of the Columbia River below the Snake River are within a range where normal growth and reproduction is questionable. Still, an infestation in favorable upstream habitat might result in establishment and growth of mussels downstream. Mussels should not survive at all in the mainstem Willamette River, or in the Columbia downstream of their confluence; calcium concentrations in those areas are too low.

Potential Costs of Infestation

If an infestation did occur the damages and costs could be substantial. A Snake River infestation is used to develop cost estimates because this scenario is believed to be relatively likely. Under this scenario, an accidental introduction in the upper Snake River basin would enable veligers to drift downriver and colonize suitable areas into the lower Snake River with some establishment in the mainstem Columbia. Table ES-1 summarizes estimates of potential costs for this scenario. Cost estimates focus on hydropower and fish passage facilities at dams, hatcheries, impacts on habitat and valuable species, and water diversion and pumping facilities (including fish screens).

Hydropower facility costs are generally costs of chemical control systems, antifouling paints, cleaning, and potentially, lost power production. We build on previous work (Phillips et al. 2007) including forecasts of the types of problems and costs expected for hydropower and passage facilities (Athearn and Darland 2007; Kovalchuk 2007; RNT 2010).

Recent studies have established that some antifouling paints should be effective and environmentally acceptable (Wells and Sytsma 2010). The Corps of Engineers has provided data on square footage of some facilities that would be underwater during the non-spill season and which we assume would be painted (USACE 2010). We assume that hydropower turbines can be protected by chemical injection systems although such systems might have environmental impacts that are unacceptable or require mitigation costs.

Antifouling paints cannot be used on fine mesh screens as used in juvenile fish bypass systems. Fouling of bypass screens, especially on the lower Snake River facilities, could be a serious problem. Fortunately, low calcium concentrations during most of the fish passage season may limit mussel growth rates. Fouling is more likely to be problematic during the late summer and fall when screens are operated for adult fish fallback. For the probable scenario, we assume additional cleaning operations will be needed. Annualized costs of control, painting and cleaning FCRPS hydropower and passage facilities with a Snake River infestation could amount to tens of millions of dollars.

Total estimated capital costs for hydropower facilities, including fish passage facilities but no power losses, are over $8,800 per MW of nameplate capacity with about $160 O&M per MW capacity. For comparison, additional capital costs at Hoover Dam in the Colorado River Basin have been forecast to be $1,780 per MW. The Ontario Power Group estimated invasive mussel capital costs of $1,020 per MW and annual O&M costs of $50 per MW of generation capacity (Willet 2010). It appears that Columbia Basin costs per MW of capacity could be substantially more than at these other locations. Most of the additional cost involves fish passage facilities.

A potential worst-case scenario assumed that mussels could colonize fish bypass (turbine intake) screens on the Snake River and grow at their maximum rate. If screens cannot be cleaned fast enough to operate within prescribed passage criteria, then survival of migrating juvenile salmon and steelhead might be reduced.

Table ES 1. Potential Costs of Invasive Mussels, Snake River Infectation Scenario[1]

Type of Cost	Information Source(s)	Million (M) $ Annualized Cost Per Year	Comments
Hydropower main cooling system, trashracks, intakes, other water supply	Phillips et al (2007) and IEAB	$16 M Snake River and downstream FCRPS plus $5 M others	Includes NaOCl [2] systems not yet permitted, IEAB assumes $1M capital per dam for other water supply
Hydropower spillway gates, piers, apron, stilling basins	USACE 2010 provided square footage for paint	$3 M to $10 M, FCRPS only	Assumed $150 per sq. meter, $3M is Snake R projects only
Hydropower other	Athearn and Darland 2007, RNT 2010	Unknown	
Fish passage facilities, bypass screens, fish ladders, gatewells	Kovalchuk 2007, USACE 2010, IEAB	$1.1M Ladders, $1.95 M Screens, $1 M gatewells	Antifouling paint on fish ladders and gatewells, bypass screens mostly cleaning labor
Potential Snake River fish passage increased mortality and reduced power generation [3.]	If cleaning screens caused power loss or screens do not operate at design criteria	Potential unknown, may be juvenile survival reductions, or costs up to hundreds of M, or new bypass facilities	Depends on ability of mussels to establish and grow during passage seasons
Fish passage other	Kovalchuk 2007	Unknown	
Hatcheries	Assume new filtration systems needed at 20 hatcheries, $1 M per system, 10 year life	$3 M for 20 facilities, plus $1 M annual monitoring and cleaning, system-wide	Production might be lost if hatcheries can not filter veligers
Impacts to recreation and other facilities, including water supply, navigation, boats and marinas	IANST (2009) and source documents; plus assume 50,000 diversions at an annual average $100	Max potential unknown, estimated $50 M annually, range could be tens to hundreds of M annually	Snake River water supply may be biggest component.
Impacts to native species primarily from food web effects and loss of habitat	Assuming a serious infestation in the Snake River Basin, costs to achieve same level of recovery	Unknown, could be tens to hundreds of M annually	More biological assessment is needed

[1] Assumes that mussels are able to colonize, reproduce and grow at near-maximum rates in the upper Snake River, growth rate is less than maximum in the lower Snake River, and veligers are able to colonize and grow in the mid-Columbia and downstream through Bonneville dam.
[2] NaOCl is the chemical formula for sodium hypochlorite, a solution that is frequently used as a disinfectant or bleaching agent.
[3] Worst-case potential occurs if mussels are able to grow at near-maximum rates in the lower Snake River.

To increase survival of migratory fish, the intake screens might need to be removed and cleaned more often. Since a turbine must be shut down for cleaning, additional forced spill could occur whenever that dam is already generating at capacity. Also, more spill might be requested as a way to compensate for reduced survival caused by fouled screens. Therefore, hydropower production would be reduced if 1) any increased spill is provided for fish passage, and/or 2) if turbines must be shut down for cleaning screens at times when more flow cannot be routed through other turbines. In either case, State of Washington water quality criteria for total dissolved gas might be exceeded by more spill. Mussel management costs might also include more control costs. In the long run, redundant screens might be required or modified juvenile bypass systems might need to be designed and built.

Therefore, in the potential worst-case scenario, potential costs include some combination of hydropower production losses, cleaning and control costs, costs of redundant screens and new bypass systems, and an additional cost that should be assigned to any reduced juvenile survival. Half of the value of hydropower production from the facilities is used to estimate an approximate upper bound ($250 to $300 million annually) on potential cost. The total potential cost of mussel fouling of juvenile passage systems is unknown, but could be in the tens to hundreds of millions of dollars annually.

Hatcheries could also be infested by mussels, and hatchery operations often include operations that pump and truck fish and water to other watersheds which could lead to further infestations. Where water supplies may be contaminated, filtration systems may cost around $1 million per hatchery (Allhands, 2009). Fortunately, many hatcheries do not rely on mainstem water for their water supply; these hatcheries might experience relatively small costs. We assume that 20 hatcheries, out of more than 100 in the basin, would require new filtration systems. We also assume an infestation would increase monitoring and cleaning costs by $1 million annually. There is potential for infestation by vectors other than water supply. Any fish transported to hatchery facilities come with water; gear such as boots, nets, hoses and tanks can be vectors, and birds and mammals enter hatcheries when they are attracted by the fish.

The FWP and other entities have invested millions of dollars in juvenile fish screens for water diversions. This investment, and the survival of species protected by screens, is threatened by invasive mussels. Many fish screens are on tributaries that seem less likely to become infested. However, on the upper Snake River, where calcium is favorable and there are numerous irrigation diversions, additional cleaning costs and loss of screen protection can be expected. Substantial costs could also be incurred to maintain water supplies where mussels interfere with diversion, pumping, conveyance and distribution of water. We build on cost estimates developed by IANST (2009) to obtain an expected annual cost of about $50 million. The possible range is tens to hundreds of millions annually.

Existing technology provides no reliable options for cleaning or protecting natural habitat from a mussel infestation. Experience in other locations suggests that, where conditions are favorable, invasive mussels can be damaging to salmonids and devastating for some native species. Damage would be primarily through food web effects; dense populations of these filter-feeders can substantially alter food chains (Higgins and Zanden, 2010). Adverse effects might also occur by displacement.

The potential costs, especially in the Snake River Basin, would likely involve habitat replacement, reduced chances for recovery of protected-status species, an increased chance of listing for other species, increased costs of compliance with endangered species laws, and reduced populations of other economically important species including game fish. We assume that existing policies would require that anadromous fish and rare species populations be returned to their without-mussel status. The cost of this compensation is unknown, but could be tens to hundreds of millions of dollars annually.

There are many other important costs of mussels outside of the FWP and the FCRPS that are not detailed by this report. An infestation would result in large control costs for commercial navigation and private waterfront facilities. An infestation in the Columbia Basin would greatly increase the chance of infestations in other water bodies in the Northwest. This possibility represents an expected cost that should be included when prevention costs are justified.

Prevention Programs and Justifiable Costs

It is likely that these invasive mussels will eventually colonize some of the large rivers of the Columbia Basin. However, there is much value in delaying this result for as long as possible. First, a delay will allow scientific information to be improved. For example, many control technologies are still being developed and evaluated. Second, the annual benefit of delays in terms of immediate cost savings is large. Third, a delay will allow for more advanced planning and permitting of potential response actions that might reduce the chance for a widespread infestation or reduce management costs. In the short run, prevention buys time that can be used to prepare.

Given the large cost potential and the unresolved science issues, it appears that existing prevention programs may be under-funded in the short run. Appendix D of the Quagga-Zebra Mussel Action Plan for Western Waters (QZAP) outlines a plan for prevention costs. This plan, which is not fully funded now, proposes costs that appear to be reasonable in comparison to potential infestation costs, with one exception.[3] Using the B.7 option for a budget of $1 million per State, annualizing initial and one-time costs for ten years at 6%, and allocating 4/19ths of the cost to the Pacific Northwest results in a potential annual QZAP cost for the region of about $28 million. Current expenditures in the four State region are about $3 million annually. The IEAB believes that the annual cost of a mussel infestation could be hundreds of millions of dollars annually, so

[3] Item B.7 includes an option for more than $1 billion of annual inspection costs for over 50,000 "high-priority waters," of which 11,500 waters would be in the four-state Northwest region. This amount seems excessive, largely because it would be difficult to mobilize and deliver so much prevention resources in a short time frame.

assuming that additional expense can delay an infestation, this appears to be a good investment, at least until science issues are resolved.

There are still many roads in the region where an infested boat could enter uninspected. The four Basin states are increasing their commitment to prevention and inspections. However, other western states and provinces are not progressing as quickly. Other, innovative methods for identifying possible carriers such as use of cameras might deserve attention. Concepts for more cost-effective and targeted prevention may deserve development. The region might be able to use prevention dollars more effectively by targeting destinations based on suitable calcium conditions. Also, more contaminated watercraft might be intercepted using more aggressive efforts at their origin. There is potential to improve policies at locations of origin to enable more identification of contaminated boats and better coordination with destination states.

The State of Idaho has one of the most aggressive prevention programs in the region funded, in part, by boater fees. The Idaho mandatory watercraft inspection at key border crossings costs $1.3 million annually (WRPANS 2009 p. 9). Idaho has been working to better target prevention resources by identifying likely carriers. Other ways to introduce mussels include contaminated construction equipment, small boats that are not trailered, fishing equipment, or hobby aquariums. We note that much riverine fishing effort is not boat-based. Such equipment often does not pass through inspection stations at borders or put-ins, but some experts believe that an introduction by equipment other than trailered boats or construction equipment is unlikely.

Research Recommendations

In the course of this review the IEAB identified several areas of uncertainty that deserve further research. If the range of uncertainty associated with these issues could be reduced, then more detailed economic analysis might be justified.

1. Much of the Columbia Basin affected by the FCRPS has calcium concentrations that are within the range known to limit mussel populations, but the effect of these concentration levels on establishment, growth and reproductive success, and interactions of calcium with pH, diet and temperature should be determined with more accuracy. Calcium in diet may be especially important. The implications of the strong seasonality of calcium concentrations in the Snake and Columbia River mainstems, along with seasonal temperature variations, need to be explored.
2. More information on calcium concentrations, especially at locations used by trailered boats, is needed. More analysis of existing water quality databases might be useful.
3. Better understanding of the sources and fate of calcium is needed. Existing system operations and water quality models of the upper and lower Snake River, the Clearwater River, and the mainstem Columbia River could be augmented to include a calcium modeling capacity. Small scale spatial variations, including potential contributions by concrete in dam structures, deserve attention.

4. Studies to clarify differences and similarities in the ecological needs of zebra mussels and quagga mussels may be justified.
5. More research about likely modes and locations of mussel introductions, including numbers and origins of trailered boats, and application of such information to prevention programs, might help allocate prevention resources and improve economic estimates.
6. Some likely infestation scenarios involve veligers floating downstream from an upstream population. Better understanding of veliger survival during downstream transport and establishment in relation to water travel times is needed.
7. The effects of normal flow velocities on juvenile fish bypass screens as they affects the ability of mussels to attach to the screens needs to be documented by controlled experiment. Results should be coordinated with recent initiatives to reduce screen mesh size for lamprey protection.
8. Hatcheries in the Basin that: 1) transport fish upstream or to tributaries; and 2) take their water supply downstream of a potential mussel infestation should be identified. Measures to ensure that their water supply and treatment provide highly reliable protection from mussel veligers (i.e., filtration) should be taken.
9. Research, planning and advance permitting for potentially less-intrusive controls such as Zequanox ™ could be beneficial.

INTRODUCTION

The zebra mussel *Dreissena polymorpha* and quagga mussel *Dreissena rostriformis bugensis* (mussels) are two species of invasive bivalve mollusks native to the Black-Sea-Caspian Sea-Ukraine region that were accidentally introduced into the United States in the 1980s. Zebra mussels were first identified in the Great Lakes in 1988; quagga mussels were first discovered in 1989.

The two species are superficially similar in appearance, but upon inspection are easily distinguishable. Zebras are small (15 mm) and triangular in shape whereas quaggas are slightly larger (20 mm) and rounder in shape (USGS, 2010).

Since their discovery in North America, both species have steadily expanded their continental range. Zebra mussels now occupy most of the Mississippi and some Missouri river basin states, as well as selected sites in California, Utah and Colorado. Quagga mussels occupy a more restricted range including several Great Lakes and Mississippi river states. They were found in Lake Mead in 2007 and have spread to other sites in the southwestern United States (CDFG, 2010). Both species continue to expand their range.

Unlike common native species of bivalves, adult stages of both species have a byssus, a many-threaded organ that allows them to attach effectively to hard or rocky substrates. Also unlike native mussels, the immature stages (veligers) are free-swimming, and can disperse easily and widely in open water on their own once introduced into a river basin. Native mussels, in contrast, rely on specific fish species as intermediate hosts for immature stages. Zebra and quagga mussel biology and ecology are detailed in many documents (Nalepa and Schloesser 1992; Miller et al., undated; Ram et al, 1996) Many aspects of the biology and ecology are beyond the scope of this report and only key aspects are introduced here in relation to potential economic impacts.

Because of their ability to attach to structures, both zebra and quagga mussels can present major problems for underwater facilities. They can foul pipes of hydroelectric facilities, water works, and other industrial facilities, including fish passage facilities, fish screens, fish hatcheries and aquaculture operations. These highly invasive mussels can disperse and grow quickly and reach high densities, impairing facility functions and damaging ecosystems wherever they are established.

The Columbia Basin states and the federal government are increasing efforts to prevent mussels from colonizing the Columbia Basin. The Western Governors' Association Policy Resolution 10-4 states that "Control programs should be economically practical in relationship to the long-term impacts an invasive species will cause" (WGA, 2010). Economic criteria could help guide decisions about expenditures for mussel prevention programs. For example, to meet a positive benefit-cost criterion, the expected value of damage cost and control cost savings from a program that reduces the chance of infestation should exceed the cost of the program. In this criterion, the expected value of damage and control cost savings must include the reduced probability or delay of an introduction. Damages depend on mussel population characteristics, and populations depend on habitat characteristics that vary around the Basin. Generally, a prevention and control program that results in the lowest expected value of all costs (prevention, response, damages and control) is economically preferred.

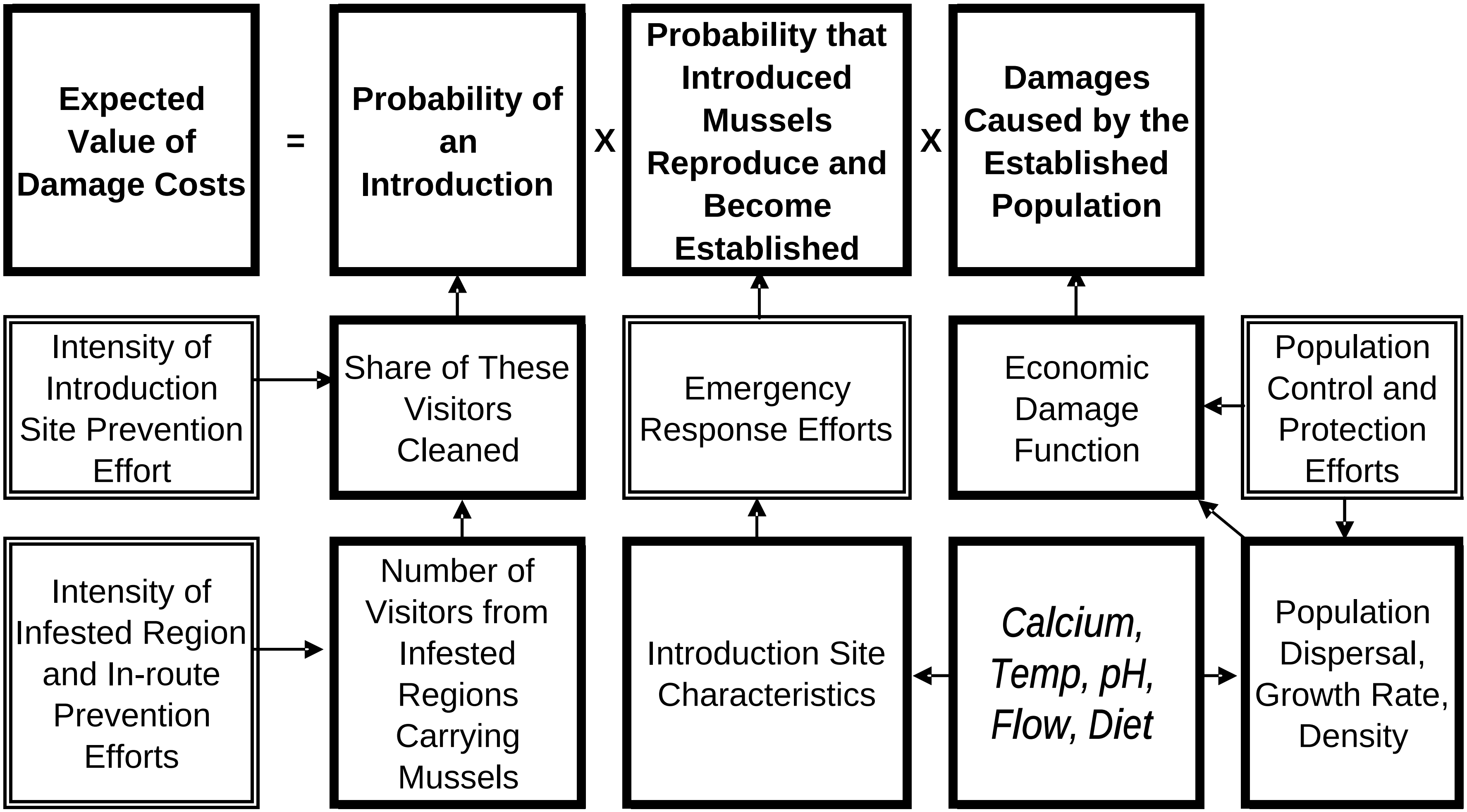
Figure 1 displays some of the key factors involved in such an economic analysis. The expected value of damage costs is the probability of an introduction, times the probability that that introduction will become established, times the damage cost of the established population. Each of the three components of "expected value of damage costs" is subject to man-made and water quality factors. The probability of an introduction is influenced by prevention programs, the probability of establishment is affected by emergency response programs, and damages are determined by a damage function and population characteristics which are themselves affected by control and protection programs. Key population variables are dispersion, the geographic extent of the infestation; density, and growth rates. Key water quality variables that affect these population characteristics are calcium concentrations, water velocity, acidity, and temperature.

Application of an economic model like Figure 1 is complicated by the quality of data and uncertain forecasts. Most importantly, the probability distributions required to calculate the expected values are often unknown. Rather, there are many uncertainties that defy quantification. A variety of risks and ecological scientific uncertainties make it difficult to know exactly how easy it will be for mussels to become established in the Basin, how widely they will disperse, and how abundant they will become.

There is a large range in the forecast of potential economic costs. Warziniack (2006) estimates "the expected loss to households in the Columbia Basin will be about $1.94 million annually." The Idaho Aquatic Nuisance Species Taskforce (IANST, 2009) estimates costs of $94.5 million for Idaho alone. This wide range of estimates leaves much doubt about actual costs, and how much may be justified for prevention.

This report first presents a summary of literature about the damage costs of zebra and quagga mussels. Secondly, we discuss key factors expected to affect potential establishment, distribution and abundance of mussels should they enter the Basin.This discussion leads to "infestation scenarios" which are general descriptions of the potential for introduced mussels to become established by region, and information about their potential density and rate of growth. Then, we summarize estimates of physical and economic damages from a potential infestation. Finally, we discuss the potential costs of prevention programs, compare their costs to potential damages, and provide recommendations about science that we believe should help compare benefits and costs.

Figure 1. Flow Diagram for Expected Value of Damages from an Introduction Site



LITERATURE REVIEW

The selective literature review focused on sources that provide quantitative estimates from other localities that might be transferable to the Columbia River Basin. Quantitative estimates of potential costs are dependent on 1) dollar estimates of economic costs, and 2) factors that affect mussel populations.

The literature reviewed is included as the references, and results are summarized in Table 1. There is a large amount of cost information that is useful for estimation in the Columbia Basin. This information is summarized by each economic cost type below.

Potential Economic Costs

Most estimates of economic costs associated with mussel infestations come from the eastern United States. Surveys conducted over many years documented costs reported by electric power generation, water treatment facilities, industry and others (O'Neill 1997). The eastern experience has resulted in a history of control and costs, and these costs have sometimes formed the basis for cost estimates for the Columbia Basin (IANST, 2009) even though conditions in the east and west are different. In the west, experience in the Colorado River basin is providing new data, but here also, conditions are very different from the Columbia Basin.

The impacts of mussels in the Basin will be different from existing infestations because 1) the population characteristics of the mussels will be different, and 2) the structure of industries and resources affected will be different. In particular, there is little experience elsewhere in the U.S. with the types of fisheries and fish passage facilities found in the Columbia Basin.

Factors Affecting Mussel Populations

Several key factors can potentially affect establishment, distribution and abundance of mussels should they enter the Basin. A review of literature indicated that three key factors potentially limiting to mussel establishment, distribution, and abundance are calcium content of the water, water velocity, and water temperature.

Mussels require calcium to build their shells. Calcium is known to constrain mussel growth rates, densities and reproductive success. Cohen and Weinstein (2001, p. 33) summarize numerous studies and find that "zebra mussels can not become established (i.e., persistently complete their full life cycle) at ambient calcium concentrations below about 20 mg/l." Whittier et al. (2008) provide an initial basis for infestation scenarios based on calcium.

Table 1. Summary of Published Quantitative Estimates of Quagga and Zebra Mussel Costs

Source	Service affected	$ Cost	Unit of cost	For what	Type of Cost	How cost estimated	Area of Resource	Notes
Phillips 2005	Hydro-power							Results have been updated in Phillips 2007
Phillips et al 2008	Hydro-power	$62,599	Per generator	NaOCl injection System	Capital	Updated Ontario and Nashville COE costs	FCRPS	Based on OPG and Nashville COE experience. 169 generators, total $10.58 million FCRPS every 5 years
	Hydro-power	$100,000	Per facility (dam)	NaOCl system O&M	Annual O&M		FCRPS	13 facilities, $1.3 million per year FCRPS
	Hydro-power	$81,000	Per generator	Anti-fouling paint trash racks	Capital, every 5 years	$12.50 per sq ft	FCRPS	169 generators, total $13.04 million FCRPS every 5 years
	Hydro-power	$85,714	Per generator	Remove, sandblast, repaint and install	Labor, every 5 years	Based on Bonneville I and II trashracks	FCRPS	169 generators, total $14.48 million FCRPS every 5 years
	Hydro-power	$7,800	Per generator	Service generator coolers	Service every year instead of every 5	Bonneville Power-house	FCRPS	Increase per year, 169 generators, total $1.32 million per year FCRPS
	Hydro-power	$1,783	Per generator	Clean water intakes	Annual	Bonneville Power-house	FCRPS	Annual cost of cleaning 21 instead of 3 annually, 169 generators, total $0.30 million per year FCRPS
CRBT (2008)	Other CRB	Notes that:” The costs of zebra mussel control cited in (Phillips 2008) will increase significantly, potentially 2-3 fold or more, when mitigation costs for juvenile and adult fish passage facilities, and maintenance and cleaning down time for systems and equipment including (but not limited to) generators, fire suppression/deluge, heating, ventilation, and air conditioning equipment,						

Source	Service affected	$ Cost	Unit of cost	For what	Type of Cost	How cost estimated	Area of Resource	Notes
		drain galleries, sumps, oil water separator and forebay/tailwater sensors are factored in."						
	Various other						Bonneville	Includes Athearn and Darland paper on Bonneville response plan
	Fish passage facilities						Bonneville	Includes Kovalchuk paper on CRB fish facilities
Connelly et al. 2005	Drinking water systems	$110,282	Per system, < or = 1 mgd	Planning, treatment, removal, inspection	Annual	Survey data, 322 respondents	Area where zebra mussels known to be present	Respondents had difficulties in assigning costs to different pests
		$146,735	Per system, 2-10 mgd					
		$505,461	Per system, > or = 11 mgd					
Phillips, 2001 (also source)	Drinking water system	$3.66 million	Per system	Potassium Permanganate system	Capital only			1994 costs, served 1.6 million people
(also U WI Sea Grant Zebra Mussel Update #28)	Industrial water system	$400,000		Chlorinization and sodium bisulfite	Annual		Bethlehem Steel, Portage Indiana	1996 costs
	Industrial water system	Less than $100,000		Chlorination when water > 55	Annual		Inland Steel, East Chicago Ind.	1996 costs
Lovell and Stone (2005) Zebras starting p. 44	Hydro-electric	$84,000			Annual			1999 costs
	Fossil fuel	$145,000			Annual			

Source	Service affected	$ Cost	Unit of cost	For what	Type of Cost	How cost estimated	Area of Resource	Notes
	Nuclear	$822,000			Annual			
Park and Husak, from Lovell and Stone	Drinking water system	$87,000	Per system, 1-10 mgd	Generally chorination or potassium permanganate	Annual	Survey		1993 costs
		$159,000	Per system, 11-300 mgd		Annual			
	Utilities and Industry	$10,000	Small <11 mgd		Annual			
		$92,000	Medium 11 to 300		Annual			
		$439,000	Large 300 mgd or more		Annual			
Idaho Aquatic Nuisance Species Task Force 2009	Relies on unit costs from Phillips et al (2005), O'Neill (1997), Vilaplana and Hushak (1994) along with numbers of facilities (hydropower dams, other dams, drinking water intakes, golf courses, boat facilities, fish hatcheries, boater costs, fishing use) to estimate total potential costs in Idaho of about $95 million. Irrigation discussed, no dollar estimates							
O'Neill 1997	Navigation locks	$1,730 plus $683.2	Per facility	Expenses plus monitoring	Annual		$484800/56/5 $3416/5	1995 costs
	Navigation company	About $112,000	Per company		Annual			
	Drinking Water	$42,870	Per facility		Annual			
	Golf Courses	$150	Per facility		Annual			
	Boat Facilities	$750	Per marina, dock or launch		Annual			
	Hatcheries/Aquaculture	$5,860	Per facility		Annual			
Vilaplana	Boat Maintenance	$265	Per boat		Annual			Probably 1993

Source	Service affected	$ Cost	Unit of cost	For what	Type of Cost	How cost estimated	Area of Resource	Notes
et al (1994)								costs
Yost 2010	Inspection and wash station	$125,000	Per station	Station and maintenance	Capital, part of annual	Duck Valley Indian reservation, Nevada		

This study provides "ecoregional risk classifications" of very low, low, high and highly variable using distributions of calcium concentrations at sites within the region. A map of the United States is provided that displays relative risk, with some differentiation within the Columbia Basin. These characterizations are extremely general and were not intended to assess the ability of mussels to survive at specific locations, on a finer scale, e.g., within particular river basins. Other information (Chandra et al. 2009; Cohen and Weinstein 2001) and cases in the intermountain west suggest that mussels might survive in lower-calcium waters. Acidity (pH), calcium in the diet, and variations caused by local calcium sources such as concrete might be important in affecting the suitability of particular sites for colonization by adult mussels.

One expert (Whittier, 2010) provided this summary about the importance of calcium:

> If all other conditions (e.g., nutrient supply, turbidity, flow, temperature, substrate) are optimal for *Dreissena* growth and reproduction, then calcium begins to become a limiting factor around 20 mg/l. If 20 mg/l calcium is maintained (in otherwise optimal conditions) over time, then one would expect that the mussels will be able to establish and maintain colonies. At 14 mg/l, calcium concentrations are approaching levels that can seriously stress the mussels, for both maintenance of physiological processes, and reproduction. At that concentration, mussels may be able to invade, but are not likely to thrive. That is, colonies are not likely to be dense, and may come and go, assuming an ongoing supply of veligers.

Another report (RNT, 2010) reported that, at 8 to 10 mg/l, "adults do not survive long-term." At less than 15 mg/l there is "uncertainty of veliger survival." Calcium concentrations of 16 to 14 mg/l support a "moderate infestation level" and a concentration greater than 24 mg/l supports a "high infestation level."

The IEAB and cooperating scientists compiled some data on calcium concentrations from mainstem river sampling sites. These data show that calcium concentrations in mainstem rivers are highly seasonal (See figures following text). Claudi (2010) notes that "calcium oscillations are introducing a big unknown in terms of mussel survival." In particular, calcium concentrations are generally low in early summer when water temperatures are first favorable for spawning.

Biologists are currently conducting several studies and summaries related to calcium concentrations and mussel growth; in particular, a summary of water quality data in the Basin, studies of Colorado River-origin mussel growth rates in Columbia River water, and vulnerability assessments involving mainstem dams. While results are preliminary, these studies appear to generally confirm earlier studies that found calcium should limit mussel establishment and growth in many areas. However, calcium concentrations within tributary river basins and even at river sampling sites are quite variable, and within or close to the narrow range in which calcium is known to affect density and growth rates.

Therefore, there is still much uncertainty about how well mussels will do in much of the Basin. Additional research and review should help to reduce this critical uncertainty.

Water velocity is a second key factor potentially limiting to mussel establishment and abundance. Veligers may be unable to remain attached to substrates where velocities are high (perhaps 6 feet per second or more). Infrequent high velocities may strip mussels from structures, preventing infestations from occurring. Zebra mussels can tolerate higher velocities than quaggas (Peyer et al. 2009).

A third key, potentially limiting factor is water temperature. Temperature is important to zebra mussel reproduction. Water temperatures of about 10° C are required for spawning, and peak spawning can occur at around 18° C. This information could help to establish when veligers are likely to be present. In the Columbia River near Bonneville, zebra mussel spawning could occur from late March through November with peak spawning from mid-July to mid-September (CRBT, p. A-1).

While less is known about ecological factors controlling the quagga mussel life cycle, water temperature may be less of a limiting factor. This may be inferred from their occurrence in deep waters of the Great Lakes which stay cold (<10º C) year-round. In the Colorado River basin, relatively warmer water temperatures allow quagga mussels to spawn year-round, complicating mussel management.

The normal timing and duration of dewatering and existing maintenance schedules for many facilities will limit the potential severity of mussel infestation. Mussels can survive out of water for hours, days or possibly weeks depending on air temperature (too hot or freezing), humidity, and their exposure as affected by the micro-scale characteristics of their location. This factor is discussed with respect to economic cost types below.

In summary, calcium, water velocity and water temperature appear to be potential limiting factors. Calcium may limit potential growth rates and densities, water velocity may limit the micro-locations of infestations, and temperature may limit spawning location and timing. In addition, normal (pre-mussel) timing and duration of de-watering will be a critical consideration for estimating costs at most facilities.

MUSSEL INFESTATION SCENARIOS

Useful economic analysis requires mussel infestation scenarios that describe, given an upstream introduction, the likely growth rate and ultimate density of mussels at different downstream locations. The IEAB reviewed published literature and held discussions with shellfish biologists regarding the potential severity of mussel infestations in different locations around the Basin. In particular, what density and growth rate of mussels might be expected?

In preparing the infestation scenarios, we assume that no survival of introduced mussels will occur at calcium concentrations of 7 mg/l or less. Little survival or growth can be expected as concentrations between 7 and 12 mg/l. At 12 mg/l colonization is possible, but unlikely. 15 mg/l is required for mussels to grow to adult size. At 20 mg/l there is a good chance that mussels can establish and maintain colonies with reproduction. At higher calcium concentrations reproduction is even more likely.

Growth rates are economically important because they influence how often some facilities, especially fish bypass screens, fish screens and other facilities must be cleaned. At 12 mg/l to 20 mg/l, we assume that mussels would exhibit below-normal growth rates. Normal growth rates might occur at 25 mg/l. At 30 mg/l there is a good chance that normal growth rates, about 0.12 mm per day for small adult zebra mussels, and about 0.05 mm per day for 15 mm adults, could occur. At much higher concentrations, 35 mg/l or more, normal growth rates are even more likely to occur.

Data on Calcium Concentrations

The IEAB has compiled existing and available calcium data from mainstem locations and from summer grab samples summarized at the HUC 6 level. Results are described in the text below and in the figures following the text. Data were obtained from the USACE (1999), The USEPA EMAP data (Whittier, 2010), Whittier (2010a) and the USGS NASQAN database (2010). Our analysis of the available data was not exhaustive. Also, within any region, sub-basin or tributary, even one characterized by low calcium concentrations, localized higher calcium concentrations may occur. These sites may have the potential to develop localized damaging infestations, and these infestations might allow veligers to seed susceptible downstream areas within the Basin.

In the upper Snake River Basin, calcium concentrations are often among the highest in the Basin (Table 2). Median concentrations of 48 and 27 mg/l were sampled in the headwaters and upper Snake region, respectively. In the headwaters region, 25 percent of grab samples had concentrations greater than 62 mg/l, and 25 percent were less than 19 mg/l. Concentrations are lower in tributaries of the middle Snake, but still favorable for mussels at times and places. Variability in calcium is related to seasons and flow levels; drier years will generally have higher calcium levels and will therefore be more favorable for mussel growth.

In Hells Canyon of the Snake River, median concentration just above the Clearwater confluence was 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.

The Clearwater River, in contrast, is generally very low in calcium. The USACE data and grab samples suggest calcium concentrations of about 5 mg/l or less. The median from the grab samples was only 4 mg/l, 75 percent of samples were less than 5 mg/l and the maximum observation was only 26 mg/l.

Moving downstream, calcium concentrations generally decline from the Snake-Clearwater confluence downstream to the ocean. In the lower Snake, through the FCRPS projects, calcium concentrations are highly seasonal and tend to peak in winter. In the USACE study, median summer-fall calcium concentrations in the Snake below the Clearwater River (16.4 mg/l) were about half those in the Hells Canyon reach. At Burbank[4], calcium concentrations ranged from 7 mg/l in May through July to over 25 mg/l in the fall and winter (Figure 2, remaining figures follow text). The Clearwater River accounts for a smaller share of Snake River flow after September, which probably contributes to increasing calcium concentrations in the fall and winter.

The upper and mid-Columbia River mainstem upstream of the Snake River generally has less calcium and less variable conditions. In Canada, at Birchbank, concentrations ranged from 15 to 22 mg/l. At Revelstoke Dam, concentrations ranged from 12 to 21 mg/l (Figure 3, following text).

For the Columbia River at Northport WA, near the Canadian border, calcium concentrations ranged from 16 to 18 mg/l in the warm-water season, but were higher, up to 20 mg/l, during the winter (Figure 4). In one of five years, concentrations reached about 22 mg/l. At Priest Rapids WA, calcium concentrations in the growing season were slightly lower than Northport, generally between 14 to 18 mg/l, and up to 20 mg/l during the winter (Figure 5).

The upper and mid-Columbia River subbasins, including the Wenatchee Basin, have much lower calcium concentrations than the Snake River. The median level for upper Columbia grab samples was only 6 mg/l. The Pend Oreille subbasin had much higher calcium concentrations, however; a median of 18 mg/l with 25 percent of samples more than 28 mg/l.

In the Salmon River and John Day basins, median calcium concentrations from grab samples were 14 and 15 mg/l, respectively. A quarter of samples were more than 25 and 31 mg/l, respectively. In the Yakima Basin, the median of grab samples was only 8 mg/l and the maximum only 25 mg/l.

Calcium levels in the mainstem Columbia River below the Snake River confluence reflect the influence of both rivers. At Warrendale below Bonneville Dam, summer calcium concentrations are generally 12 to 18 mg/l (Figure 6). Concentrations can exceed 20 mg/l, but not by much, from about February to April.

Calcium concentrations in the mainstem Willamette River and in the lower Columbia downstream of its confluence are low. The mainstem Willamette River has calcium

[4] Refers to NASQAN calcium measurement site name on the Snake River near Ice Harbor Dam.

concentrations of 5 to 8 mg/l. Calcium levels are higher but far less than ideal in the lower Columbia River below the confluence of the Willamette River. At the Beaver Army Terminal near Quincy, calcium concentrations were generally 10 to 17 mg/l (Figure 7). Acidity at this location is shown in Figure 8.

It is useful to compare these calcium concentrations to the Colorado River where mussels are thriving. Recent calcium concentrations at Lake Mead and Laughlin were 77 and 76 mg/l, respectively (Willet, 2010a). These levels are far above most readings found within the Columbia basin.

Table 2. USEPA EMAP West Calcium Data by Columbia Basin sub-basins, from summer grab samples, mostly on creeks and small rivers

			Calcium mg/l		
HUC6 number [1]	**Subbasin**	**Number of Sites**	**Median**	**Interquartile**	**Min/Max**
170102	Pend Oreille	23	18	8 to 28	1 to 53
170200	Upper Columbia	71	6	3 to 18	1 to 56
170300	Yakima	10	8	6 to 12	4 to 25
170401	Snake headwaters	7	48	19 to 62	15 to 90
170402	Upper Snake	22	27	16 to 52	3 to 69
170501	Middle Snake to Boise	23	8	4 to 13	1 to 79
170601	Lower Snake	8	7	6 to 9	4 to 10
170602	Salmon	21	14	2 to 25	2 to 47
170603	Clearwater	13	4	2 to 5	2 to 26
170702	John Day	95	15	7 to 31	3 to 93
170703	Deschutes	19	6	4 to 8	2 to 28
170800	Lower Columbia	8	5	3 to 6	<1 to 8
170900	Willamette	20	5	4 to 9	2 to11

[1] HUC6 = USGS 6-digit Hydrologic Unit Code
Source: USEPA EMAP data, Whittier 2010

Figure 9 is a map showing median calcium concentrations from the Table 2 grab samples at tributaries around the Basin. Figure 10 provides the Table 2 data in graphical form.

Mussel Infestation Scenarios by Location

For all locations below, localized damaging infestations could occur in tributaries or in slack water where calcium is provided from natural or man-made sources

The Snake River basin in southeastern Idaho generally has favorable calcium conditions for invasive mussels, especially in the headwater region and the upper Snake. One important infestation scenario, both in terms of relative likelihood and potential costs, is an infestation in the upper Snake River, which then produces veligers (free-floating juveniles) that establish themselves downstream. Calcium concentrations are less in the middle Snake, but still favorable for mussels.

The Hells Canyon reach of the Snake River has variable calcium levels but conditions for mussels are often favorable in late summer, fall and winter. Water velocities might limit establishment locations.

The Clearwater River is generally very low in calcium; mussels should not survive in almost all locations.

The lower Snake River has quite variable calcium concentrations. In some summers mussels might be unable to establish colonies. In late summer to early fall, veligers from an upstream infestation might become established and take advantage of higher calcium concentrations. Conditions in some years might allow for mussels to reproduce.
In the Salmon River and the John Day basins, calcium concentrations might support populations at some times and places. Mussels are unlikely to survive in the much of the Yakima River or the Deschutes River basins, but a few areas might support populations.

Areas in the upper and mid-Columbia River, including the Wenatchee Basin, have much lower calcium concentrations than the Snake River. However, parts of some upstream basins, such as the Pend Oreille, have areas that could support populations that could send veligers downstream.

The upper and mid-Columbia River upstream of the Snake generally have less calcium and less variable conditions. It is not clear that calcium concentrations in the mainstem would support establishment. Calcium concentrations are in a range where mussel's ability to grow and reproduce should be limited. Conditions are similar at Priest Rapids. The ability of mussels to thrive in this range of calcium is unclear.

Calcium concentrations in much of the Columbia River below the Snake River are within a range where normal growth and reproduction is questionable. Still, an infestation in favorable upstream habitat might result in establishment and growth of mussels downstream.

Mussels should not survive at all in the mainstem Willamette River, calcium concentrations are too low. Calcium levels are far less than ideal in the lower Columbia

River below the confluence of the Willamette River. It is unlikely that fast-growing, self-reproducing or dense populations could become established.

POTENTIAL ECONOMIC COSTS

This information suggests that the most potential for an extensive and self-reproducing infestation is in the Snake River Basin. Such an infestation could provide large numbers of juveniles to points downstream of the Clearwater River, but the ability of these veligers to grow and reproduce in most downstream waters is unclear.

Our analysis of economic costs assumes that invasive mussels will not grow and reproduce at their known maximum potential, especially during the late spring and summer. If the science later suggests that calcium will not generally constrain growth rates and reproduction, or that calcium will constrain growth and reproduction even more, then a change to the economic outlook would be justified.

Hydropower

The available information about costs of a mussel infestation on FCRPS and other basin hydropower facilities is primarily from Phillips (2005) as updated by Phillips, Darland and Sytsma (2008), with information from Athearn and Darland (2007), Sytsma et al. 2010 and USACE (2010). Vulnerability assessments for The Dalles and John Day dams are expected to eventually provide more detailed information.

Table 3 of the Athearn and Darland study provides a summary of expected facilities, level of risk, reason for risk and expected preventative actions for hydropower and other FCRPS facilities. Phillips et al. (2007) estimated costs at FCRPS hydropower facilities to install and operate NaOCl chemical drip systems, to remove, paint and re-install trash racks, to service generator coolers, and to clean water intakes (See Table A1 and Table A2 following text). The IEAB estimates that the annualized cost of these actions would be $12.85 million for the eight FCRPS hydropower projects. Costs at other Columbia Basin hydropower facilities, primarily in the Snake River Basin, extrapolated based on nameplate MW of hydropower capacity, could be another $4.31 million. Phillips et al. also suggest that a redundant header pipe costing $4 million might be required for each dam. The redundant pipe would allow for continued hydropower production while one pipe is cleaned. The annualized cost of this investment at eight FCRPS facilities would be $4.57 million and $1.53 million at other facilities.

The environmental impacts and potential mitigation costs for chemical water treatment such as NaOCl systems are important issues. Some currently available chemical treatments would not be suitable for the Columbia River because of their adverse effects on aquatic life, or because they can not be permitted. Control options used for facilities in the Midwest include physical cleaning, chlorine, potassium permanganate, bromine and biocides (Hushak and Deng 1997). For drinking water, unwanted disinfection by-products may limit use of chlorine and bromine in the future. Alternative treatments such as UV radiation may become the standard. Research, planning and advance permitting for potentially less-intrusive controls such as Zequanox ™ could be beneficial.

Athearn and Darland (2007) provide a detailed list of Bonneville Dam hydropower components that may be affected. This study and discussions with Phillips (2010) and Darland (2010) suggest that a number of costs were not counted by the Phillips (2008) study. At Bonneville Dam, water supply for generator air coolers, thrust bearing coolers, and Heating/Ventilation and Air Cooling (HVAC) systems would all be covered by the NaOCl system. Water supply for the fire suppression system is provided separately, so additional costs for checking, testing and mussel removal might be required. The IEAB assumes an additional filtration system costing $1 million is required at each FCRPS facility on the lower Snake River or downstream.

Mussel buildup on some spillway components could affect flow, increase debris build-up, and be a hazard for migrating juveniles. We assume that the following spillway components, all underwater during the non-spill season, would be painted; spillway gates on the upstream side, spillway gate piers, the spillway apron on the upstream side, and stilling basins below the spillway, up to the normal operating line. Most of the surface area involves the stilling basin. Most of the spillways would not require antifouling paint because they are seasonally dewatered or exposed to water velocities that are too fast for mussels to hold on.

A recent study (Wells and Sytsma 2009) provides information about costs of antifouling paints.

> The cost of silicone-based coatings over a five-year period (installation, materials, labor, maintenance, and disposal) were estimated in 1999 to range between $108/m^2 and $127/m^2 (Gross 1997; Jones-Meehan et al. 1999). EPRI (1992) estimated the application costs, including material and labor, for one commercially available silicone-based foul-release coating to be $44/m^2 for concrete, and $55/ m^2 for steel. Recoating was generally half the initial application costs.

These costs are significantly less than the costs used by Phillips et al. (2007), which work out to about $284/m^2. This cost difference might be due to inflation, or it might be due to unusual labor costs in painting trash racks. The IEAB assumes a cost of $150/m^2, including labor, for painting these facilities.

The IEAB has not estimated a cost associated with most potential impacts identified by Athearn and Darland (2007) and displayed in Table A1. Similar types of impacts are identified by RNT Consulting Inc. (2010). Additional monitoring and cleaning of drain galleries, sump chambers and piping, and oil/water separators would require more cost, and forebay/tailwater sensors and dissolved gas monitors contact raw water so that additional monitoring and cleaning costs should be counted. The risk of infestation at

FCRPS navigation facilities is described as “moderate” due to exposure to raw water. Fire suppression systems are a concern. Costs of antifouling paints needed for mooring bits and other navigation components are not likely to be large.

Fish Passage

Phillips (2008) did not count additional costs involving fish passage facilities. Athearn and Darland (2007) describe impacts to passage facilities generally. Water velocity conditions near some juvenile passage facilities are nearly ideal for mussels, fish guidance efficiency could be reduced, and juvenile passage criteria might not allow for turbine operation; i.e., generation could be reduced. Passage issues for adults might include fouling of fish ladders and fish counting facilities.

The IEAB has focused on juvenile passage systems because of potential management issues, survival impacts and hydropower costs. Some parts of bypass systems, including gatewell slots, a portion of submersible traveling screens and vertical barrier screens, are currently submerged all year. Bypass screens have a small mesh size so mussels might accumulate quickly, but anti-fouling paints are probably not an option. Some bypass systems might have to be re-engineered to ensure that they can be dewatered and cleaned more often.

Kovalchuk (2008) describes potential costs in more detail; in particular, for John Day and Bonneville Dam. The IEAB has augmented information from Kovalchuk to develop cost estimates (Table A2, following text).

> In many cases, equipment vulnerability and associated risk may require the modification of maintenance schedules, increased inspection and maintenance, improved cleaning techniques, installation of higher capacity pipes and redundant supply lines, and purchase of spare parts or backup equipment (p. F2-5).

Kovalchuk notes that bypass screens are a particular concern, because they are “submerged and in use during the most active period of the year for dreissenid reproduction, veliger dispersal, and colonization” (p. F2-7) and because their small mesh size (2 mm) means that even small mussels could inhibit flow. At normal growth rates of 0.12 mm per day, mussels on screens could influence operating criteria in a matter of days.

From USDC (2005):

> Two submersible fish-screen designs are used to guide fish away from turbine intakes and into juvenile bypass systems: a submersible traveling screen (STS) or an extended submersible bar screen (ESBS). The STSs utilize a monofilament mesh screen that rotates around large rollers at the top and bottom of the screen. The screen is rotated periodically to allow flow passing through the screen to flush the mesh

> surface clean of debris. STSs are currently installed at Lower Monumental, Ice Harbor, John Day, and Bonneville Dams. ESBSs are made of a fixed wedgewire screen material and have a brush sweep that is activated periodically to remove debris from the face of the screen. ESBSs are currently installed at Lower Granite, Little Goose, and McNary Dams. The Dalles Dam does not have a mechanical screen juvenile bypass system.
>
> The mechanical screen bypass systems consist of a submersible fish screen within each turbine intake (for each turbine, there are three intakes and associated gatewells) that diverts migrants upward into a gatewell. Once in the gatewell, a vertical barrier screen (VBS) concentrates and further guides the fish into the upper gatewell area where they pass through a submerged orifice and into a collection channel that travels the length of the powerhouse. The channel conveys fish and orifice flow from all gatewells directly to the river, or to dewatering facilities that reduce flow to approximately 30 cfs. This reduced flow can then be routed directly to the river or to secondary dewatering/separation facilities for subsequent separation, sampling, holding (for delayed truck- or barge-loading), or direct loading onto barges.

Figure 11 is a diagram of a typical fish collection system. STS, ESBS and VBS screens all have a 2 mm mesh size. VBS screens are left underwater all year. Some agencies are suggesting smaller screen size on extended bar screens to help prevent impingement of downstream lamprey migrants. Smaller mesh screen could probably be fouled by mussels faster.

Kovalchuk (below, page F2-7) says "Although flows through and around these screens are generally fast (3-5 fps) several irregular angles and crevices would provide suitable attachment conditions, particularly on the backside of ESBS screens." Three to five feet per second is slower than the 2 meters/second velocity, below which mussels might colonize, mentioned earlier in Athearn and Darland (2007, p. F1-3). The potential for mussels to foul screens at normal operating velocities is not clear; a controlled experiment might be useful.

It is likely that there will be a strong seasonal aspect to the mussel problem, especially on the Snake River. Calcium levels are far less than ideal for mussels during the early part of the migration season from about April 1 (4/1) through early August. However, the juvenile fish passage season extends to 9/30 at Lower Monumental, 10/31 at Little Goose and Lower Granite, and 12/15 at Ice Harbor (Kovalchuk 2009). At Lower Monumental, juvenile passage facilities are operated for adult fallback from 10/1 to 12/15. At Lower Granite and Little Goose, juvenile passage is operated for adult fallback from 10/31 to 12/15.

Most salmon and steelhead outmigrants have passed before the late-summer to fall out-migration period. Possibly, mussel buildup would not be much of a problem during most of the juvenile out-migration period. Build-up that might require cleaning would be more likely to occur during the fall. These cleanings would be in addition to maintenance that now occurs during the winter. VBSs are currently submerged all year. Any cleaning of VBSs requires that gatewells be dewatered and turbines shut down.

Discussion with USACE staff and Kovalchuk (2010) was used to develop one possible scenario for dealing with mussels on bypass screens. When mussels have grown enough to affect flow conditions, the turbine unit would be shut down. The STS or ESBS in each of three gatewells would be removed for each turbine unit. It is assumed that a new gantry crane would be purchased for each dam for this operation. Fish recovery operations are required. Then, the STS or ESBS would be cleaned, and at the same time, the gatewell would be dewatered and the VBS would be cleaned. The gatewell would then be flooded, the STSs or ESBSs re-inserted, and the turbine restarted. This process might take 8 persons five days to complete for each unit, so cleaning each unit would take 320 person-hours. Labor cost is based on $85,000 for a full-time equivalent of 250 days. Cost for a gantry is assumed to be $50,000.

There are 70 generator units in John Day, McNary, The Dalles and Bonneville dams, and 24 more on the four lower Snake dams. We assume that the Columbia turbine units would be cleaned this way once per year, and the Snake River units three times per year. Therefore, a total of 142 cleanings per year would be required at a labor cost of $1,931,200 annually.[5] Capital costs for new gantries at eight dams would be $400,000. Total annualized costs are about $1.95 million annually. Lost generation is not counted. As discussed below, there could be additional lost revenues for BPA. It is implicitly assumed that the generation lost when each unit is shut down could be replaced by generation elsewhere in the system although this may not be possible.

We also assume that fish screen gatewells must be painted with anti-fouling paint. Square footage of gatewells for FCRPS projects was provided by the USACE (2010). Initial cost is about $4 million; annualized cost is about $1 million.

A worst-case scenario involving Snake River bypass systems was evaluated. It is assumed that mussels colonize screens continuously during the outmigration period and grow at their maximum rate of about 0.12 mm per day. At this growth rate, bypass systems could not be operated at their design criteria unless they were cleaned frequently, perhaps every few days, perhaps weekly. Since cleanings could take up to five days, and turbines must be shut down during cleaning, generation might be lost by additional forced spill. Forced spill occurs when a dam’s turbines are operating at capacity. During forced spill, a turbine shut-down increases spill even more. This could cause dissolved gas supersaturation standards to be exceeded. If bypass screens could not be operated at their design criteria, then more spill might be used to achieve survival targets. The potential for spill to compensate for reduced survival may be limited by dissolved gas supersaturation standards. In either case, the increased spill is associated with reduced hydropower production. The amount of lost revenue due to spill could vary significantly from year to

[5] (70+24x3)*(40/250)*$85000/2000

year due to fluctuations in power market prices and water supply conditions, among other factors.

One possible partial solution to mussel fouling would be to have redundant screens so that turbines could continue to operate while screens are cleaned. Some re-design as the VBS screens might also reduce cleaning time; VBS screens are currently fixed in the gatewells. New juvenile passage systems might need to be designed and constructed. Possibly, these systems might not provide the same level of protection as existing systems. In the potential worst-case scenario, costs include some combination of hydropower losses, cleaning and control costs, costs of new bypass systems, and an additional cost that can be assigned to any reduced juvenile survival.

We are not able to assess the potential costs of new bypass systems or the cost of reduced juvenile survival. However, costs of changes in hydropower production can be estimated. Council staff estimated that the annual gross value of power from the four Snake River dams is about $500 million annually increasing to $650 million by 2030 (Morlan, 2010). Presumably hydropower systems could still be operated during the winter when juvenile bypass systems are not needed. The worst-case scenario assumes that costs could be similar to half of the value of annual hydropower production.. In summary, actual costs might include hydropower losses, reduced juvenile survival, cleaning and control costs, costs of redundant screens, and/or the costs of modified bypass system designs and implementation.

The information base available for adult fish passage facilities is similar to that for juvenile passage. In general, potential impacts are believed to be not as severe as for juvenile facilities (Kovalchuk, Table 1 p. F2-25 to F2-27). However, the seasonality of calcium concentrations may allow for more growth and establishment during parts of the adult passage season. Athearn and Darland (2007) note that, at Bonneville Dam, if one fish ladder were shut down temporarily for maintenance, then the associated powerhouse would also be shut down to avoid attracting adults to the tailrace.

We assume that fish ladders would receive antifouling paint. The cost of treating fish ladders with antifouling paint can be roughly estimated from the square footage of treated area and the assumed cost per square meter ($150). The annual average cost of painting a fish ladder of 23,000 square feet is about $64,000.[6] The IEAB assumes that 15 fish ladders of this size or 345,000 square feet would be painted every 5 years

Kovalchuk (2008) describes the potentially affected systems and potential management response in more detail. Table A2 (following text) reproduces a summary of expected management actions augmented by information developed by the IEAB. The IEAB has not estimated a cost associated with most potential impacts identified by Kovalchuk.

[6] $13.93 per sq foot, 23,000 square feet per ladder, every 5 years.

Hatcheries

Hatcheries could become infected from veligers provided by several different sources, including their water supply, fish shipments such as brood stock, fish transport truck and boats, and other hatchery equipment (Waller et al. 1996). Also, fish hatcheries have been identified as a potentially significant vector for transmission of zebra and quagga mussels into previously uninfested hatcheries or watersheds.

The source of the water supply is an important determinant of hatchery infestation risk. Hatcheries that divert their water supply from the mainstem Columbia or Snake River or from major tributaries have a relatively large risk. Table 3 shows water sources for some Columbia River hatcheries. Many hatcheries use groundwater where the risk of contamination by veligers is negligible. Other hatcheries use surface water from small tributaries where the risk of upstream infestation is low.

Table 3. Water Sources for Some Columbia River Hatcheries

Hatchery	River Name	Water Source
Carson NFH	Wind River	Tyee Springs
Dworshak NFH	Middle Fork Clearwater R.	N. F. Clearwater River; Dworshak Res. gravity fed
Hagerman NFH	Salmon River (ID)	Springs, Eastern Snake Plain Aquifer
Irrigon Hatchery	Grande Ronde River	5 remote wells, maybe 2 now [1.]
Kooskia NFH	Clearwater River M F	Clear Creek
Lookingglass Hatchery	Imnaha River	Lookingglass Creek and 2 wells
Magic Valley Hatchery	Salmon River (ID)	Crystal Springs
Spring Creek NFH	L Col R (D/s McN Dam)	Several springs located at adjacent basalt cliffs
Bonneville Hatchery	Columbia R	Tanner Creek and wells
Wallowa		Wallowa River and Spring Cr [1.]
Hatcheries of Special Interest to the FWP		
Klickitat Hatchery	Klickitat River	Large groundwater spring [2.]
Lyons Ferry Hatchery	Snake River	Well water
McCall Hatchery	Salmon River (ID)	Payette Lake
Nez Perce Tribal Hatchery	Clearwater	Clearwater River and wells
Hood R: Parkdale, Oak Spring and Round Butte/Pelton Ladder		Unknown
Sawtooth Hatchery	Salmon River (ID)	Salmon River and 3 production wells
Tucannon Hatchery	Tucannon River	Tucannon River, well water and a spring
Umatilla Hatchery [3.]		Umatilla Hatchery uses a Ranney well water supply
Mid-Columbia Coho Related		
Entiat Hatchery	Okanogan River	Packwood Spring and 6 wells

Hatchery	River Name	Water Source
Leavenworth NFH	Wenatchee River	7 wells, Icicle Creek and Snow and Nada lakes
Willard [4.]		Groundwater or springs
Winthrop NFH	Methow River	Methow River, two wells and one spring
Yakama Related:		
Cle Elum, Prosser, Yakama		Unknown
Eagle Creek NFH	Eagle Creek	Eagle Creek
Little White Salmon NFH	Little White Salmon River	Little White Salmon River

Source: Primarily USFWS federal hatchery reviews.
http://www.fws.gov/pacific/fisheries/hatcheryreview/reports.html
[1.] Source BPA 2002
[2.] Klikitat Master Plan p. 113
[3.] Source: APRE Summary. Program name:Summer Steelhead- Integrated. Subbasin: Umatilla. ESA status:Threatened
[4.] Willard produced fish for Yakama and Mid-Columbia Coho Restoration projects

Members of the Council's science boards have provided information about the potential for hatchery introductions by vectors other than water supply. Veligers might be introduced along with any fish that enter the hatchery, with contaminated equipment, by birds or animals that enter the hatchery, or by a flood event.

The U.S. Fish and Wildlife Service has compiled a list of preventative measures for preventing infection and spread of zebra mussels in Midwestern tribal hatchery programs (USFWS 2010). The Missouri Department of Conservation has prepared a series of procedures and protocols for its hatchery programs (MDC 2010). Several research studies have been conducted on ways to treat tank and other hatchery water to prevent transport and dispersal of zebra mussels while providing a suitable environment for transport of the fish in for rearing and out for stocking (Edwards and Culver, 2000, 2002).

Hatchery personnel normally disinfect sampling gear (boots, nets), trucks (hoses & tanks but not tires), so that infectious diseases (bacteria and viruses) are not transported back to the hatchery. It is unclear whether existing disinfection techniques for hatcheries would control transfer of mussels to hatcheries via contaminated equipment.

Birds or small mammals such as mink or weasels might transfer mussels (including veligers) when they enter a hatchery raceway or ponds to steal fish. This seems unlikely but is clearly possible.

Potential management costs at fish hatcheries involve existing and potential water treatment, sanitation practices, and the normal timing and duration of dewatering of facilities. A few hatcheries have filters and UV treatment systems that may be adequate for mussel veligers (see discussion of Nez Perce hatchery below). Hatchery components that are currently dewatered during part of the year, especially in winter, should not experience much mussel build-up, but additional cleaning costs may be expected. For hatcheries that divert from infested surface water, some part of diversion facilities is normally underwater all year. More cleaning of diversion facilities may be required. Antifouling paint may be economical for some components.

The Nez Perce tribal hatchery obtains water from wells and from the Clearwater River. Due to low calcium levels the Clearwater is not likely to become infested with mussels, but the Nez Perce hatchery experience helps to understand some of the types of management that might be required at other hatcheries.

Well production at the Nez Perce tribal hatchery has declined over time. The Clearwater River water source is necessary for fish production. Surface water is diverted through Zero Gravity ™ filters, then it can be UV treated, then the water is sent through a heat exchanger and is chilled (Penney, 2010). The filters can remove veligers down to about 30 microns. (The smallest veligers are on the order of 40 microns.) Turbidity of the source water sometimes renders the UV treatment ineffective.

Many hatchery operations involve movement of fish between watersheds. Fish are usually pumped from the hatchery into tanks on the back of trucks using hatchery water. These operations should not be allowed if mussel veligers might be in the hatchery water and the water cannot be disinfected. Presumably, fish could not be moved to upstream satellite facilities without proof that water in the hatchery system and trucks is not contaminated.

With the large potential costs and management issues associated with mussels it seems likely that any facilities threatened by infestation would have filters installed. Some hatcheries might be able to substitute groundwater or some other reliable source for the potentially threatened water.

Two types of filters known to be used in hatchery applications are Zero Gravity™ and Amiad EBS Filters™. In one case in Vermont, Amiad filters added to prevent mussel infestation cost about $1,000,000 (Allhands, 2009). In addition, annual costs are required for routine cleaning cycles and maintenance. After nearly seven years of operation, repairs on the nine filters and ancillary equipment have been minimal. UV treatment might also be used where source water supplies are infested.

Another cost element is the treatment of facilities exposed to infested water. For example, fish weirs can be used to separate natural from hatchery returning spawners. The Council recently approved a plan that includes a weir system at Hood River, the expected installation cost is about $750,000. Treatment of existing or new weirs with antifouling paints would be an additional cost. Engineering and cost studies of such treatment have not been undertaken.

For cost analysis, the IEAB assumes that 20 hatcheries in the Basin would require filtration systems at a cost of $1 million each, or $20 million total. In addition, $1 million of new annual costs for monitoring and cleaning is included. More detailed analysis would be required to determine the extent to which hatcheries in the basin may be susceptible to mussel infestations. In general, direct costs to hatcheries are not expected to be large. It might be prudent to ensure that all hatcheries using mainstem surface water and routinely moving fish to other watersheds are equipped with highly reliable filters.

Other Fish-Related Facilities

There are a variety of water quality, flow and fish monitoring facilities throughout the basin. For example, there are about 42 total dissolved gas and temperature monitors installed at various locations throughout the Columbia River Basin, 15 of which are year-round monitors. The potential for damage or lost use of such facilities from mussels is currently unknown, but could be significant, especially in the Snake River Basin. Additional work to identify cleaning and redundancy costs for these facilities would help to quantify expected costs. Most fish monitoring facilities are included within the fish passage and hatchery cost categories. Some water quality monitoring facilities are included in hydropower facilities. Fish screens are included in the water supply facilities.

Fish transport barges are potentially impacted. Potential costs involve reduced fuel efficiencies, lost service times and cleaning. Water in fish barges could also be a vector for moving veligers to other areas of the Basin.

Salmonid Habitat

Mussels could infest important spawning and rearing habitat in many locations throughout the basin. The establishment of a dense population of filter feeders could dramatically change the food web; mussels could interfere with food supply during rearing. Food webs for resident salmonids and other desirable species could also be affected. This potential was addressed in the ISAB report on non-native species (ISAB 2008-4) and will be further addressed in a forthcoming ISAB report. Damage could also occur if mussels can cover or otherwise modify spawning gravels.

Higgins and Zanden (2010) provide a meta-analysis of the effects of dreissenids on freshwater ecosystems. Results for river habitats include “significant declines in phytoplankton biomass, large and significant declines in zooplankton biomass” and “increases in abundance” of most benthic invertebrates. The latter effect may occur because mussels increase water clarity and channel energy to the benthos. The effects on fish depend on their “ability to utilize pelagic or benthic resources” but effects on planktivores and their predators were negative across a number of studies. In the Great Lakes, recovery of the salmon fishery “is severely inhibited by the dreissenid-induced declines in zooplankton and the collapse of Diporeia.”

Recent work in Great Lakes tributaries suggests the types of impacts that might be expected in rivers (Leonard, 2010). Two studies have considered how zebra mussels changed food availability for steelhead parr (the juvenile freshwater life stage). Parr densities declined following mussel colonization, and densities decreased the most where mussels were most abundant. Steelhead parr diet declined in quality and parr growth rates and condition had declined by 60% and 38%, respectively, four years after colonization. A decline in Chinook salmon parr densities near areas of high mussel infestation was also noted.

In the Basin, it is believed that the risk of infestation in headwater, sub-alpine stream types is relatively low due to the smaller number of human visitors, and water quality characteristics in small tributaries are highly variable. A mainstem infestation is more likely and has more potential to interact with salmonids. Two major areas of concern are 1) the Hanford Reach, and 2) the Snake River below Hells Canyon.

The goal for upriver bright Chinook spawners in the Hanford Reach above McNary Dam is 45,000 fish. This run is important to both Native Americans and recreational fishers. The potential for mussel establishment in this reach is unclear. Reproduction seems unlikely as calcium may be limiting, but veligers from an upstream infestation might establish and grow. Average water velocities may be unfavorable in parts, but velocities are variable and slower near cobblestone bottoms. Recent research suggests that zebra mussels may do better than quaggas in fast water (Peyer et. al 2009).

The potential for a mussel infestation in the Hells Canyon reach of the Snake River is probably greater than in the Hanford Reach because of the greater chance of colonization upstream, but also due to substantially higher calcium levels. Snake River steelhead, spring-summer Chinook, fall Chinook, coho, sockeye and bull trout use the Snake River for rearing, migration, and/or overwintering.

From the Hells Canyon subbasin plan, p. 85-86:

> Three species listed as endangered, eight listed as threatened, and four designated as candidate species under consideration for listing occur or potentially occur within the Snake Hells Canyon subbasin.
>
> Bull trout were listed under the ESA on July 10, 1998. Four species occurring within the subbasin are currently under the jurisdiction of NOAA Fisheries because of their listing under the ESA. These species include Snake River fall Chinook salmon and spring/summer Chinook salmon, listed as threatened on May 22, 1992, Snake River sockeye salmon, listed as endangered on November 20, 1991, and Snake River summer steelhead, listed as threatened on October 17, 1997. Pacific lamprey is a candidate for federal listing but is listed as endangered by the state of Idaho. (NPCC 2004).

Most of the Snake River runs are hatchery stock. Most of the fall Chinook run is comprised of hatchery fish from the Lyons Ferry Hatchery, fall Chinook acclimation ponds program, Nez Perce Tribal Hatchery, and the Oxbow Hatchery fall-run Chinook hatchery programs.[7] Many spawners use the Tucannon River, Grande Ronde River, Imnaha River, Salmon River, and Clearwater River where the chance of an infestation is probably less. Still, any fish that use the Snake River for rearing could be damaged by a Hells Canyon infestation. Also, a mainstem infestation would certainly increase the risk of infestation in nearby tributaries.

The threatened Snake River fall Chinook spawns and rears in the mainstem Snake River below Hells Canyon Dam. This species may have more potential to be affected by a mussel infestation because it depends on the mainstem for spawning, incubation, and rearing. For 1994 to 2004, the average abundance of natural-spawning fish (1,273) was below the natural abundance threshold (3,000) that the Interior Columbia Technical Recovery Team (ICTRT) identified as a minimum for low risk of extinction. Run size was less than 3,000 and declined every year from 2004 to 2009 (Schriever, 2010). The ICTRT also recommended that no fewer than 2,500 of the 3,000 natural-origin fish be mainstem Snake River spawners. Roughly 80 percent of the Snake River fall Chinook spawning has occurred in the mainstem of the Snake River in recent years, and the share of juveniles rearing in these areas should be proportional. The NMFS Biological Review Team characterized a risk factor for diversity as "moderately high" due to, among other factors, “the significant hatchery influence on the extant population” (NOAA NMFS 2008). From this information we infer that naturally spawning Snake River fall Chinook stocks in the Hell’s Canyon reach should be regarded as very important to the ESU’s recovery.

There are a number of economic methods that might be used to value the benefits of preventing a mussel infestation in anadromous fish habitat. All methods would require some estimate of the incremental physical quantity of loss to be expected. This could be fish population or, perhaps, percent survival. In this case, no such estimates are possible.

We focus on the Hells Canyon Reach because conditions there seem more likely to result in a severe infestation which could have a substantial effect on populations. Two approaches to valuing an increment of lost population are: Method 1) to value the benefits lost if the increment is lost; or Method 2) to estimate the cost that would be required to restore the population to its original level. Method 1) involves “use values” such as harvest and recreation, and “non-use values.” Non-use values are benefits that people place on the population even though they do not plan on using it. Method 1) is appropriate if people will accept the loss of the increment and its benefits. Method 2) is the avoided cost method. Method 2) is most appropriate if, in fact, people will try to restore the population back to its original level.

The Endangered Species Act mandates that endangered species be recovered. The Northwest Power Act and other guidance suggest that populations of fish and wildlife should be increased, at least to their present levels, but for most species, even more. This policy environment suggests that the avoided cost approach should be pursued.

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[7] NOAA http://www.nwr.noaa.gov/ESA-Salmon-Listings/Salmon-Populations/Chinook/CKSRF.cfm

The cost of fish population losses caused by mussels is the cost of actions needed to restore populations back to their without-mussel condition. These actions cannot currently be foreseen. However, the types and costs of actions currently used to support fish populations provide an indicator of what may be expected.

Two types of costs that benefit just the Snake River runs can be easily identified. Total cost of BPA's contribution for lower Snake River hatcheries is about $25 million (BPA, 2010). The annual average cost of lower Snake River spill to benefit these runs under the current NOAA Fisheries Biological Opinion is about $39 million (Fazio 2010).

There are many other costs that help Snake River runs, but the share to attribute to the Snake River runs is not immediately available. The total cost of BPA's Fish and Wildlife Program is currently about $230 million (BPA 2010). The cost of spill at the four dams downstream of the Snake River (i.e. the 4 lower Columbia River federal dams) is estimated to average about $175 million annually (Fazio, 2010). In addition, court-ordered spill, which has been implemented in recent years, may be worth about $45 million annually system-wide. (It is uncertain whether this additional court-ordered spill will become a permanent part of future hydroelectric operations.) Additional system-wide annual costs for operations, maintenance, depreciation on fish and wildlife investments, amount to $186 million.[8] In total, BPA estimates that it expends about $750 million annually for Fish and Wildlife purposes. With $64 ($25 + $39) million of this total just for Snake River runs (not even counting the cost of additional court-ordered spill), the total amount of expense attributable to Snake River runs could easily amount to $100 to $200 million annually.

Given the amount of expenditure in recent years to recover the Snake River runs, and the likelihood that a Snake River infestation could be severe, we conclude that the value of avoiding an infestation there could be large. The potential damage cost of a Snake River infestation is unknown but could be tens to hundreds of millions of dollars annually. These costs could include costs of additional spill, habitat acquisition and management, modified hatchery operations, and a variety of actions to control mussel populations or their adverse effects. Since fish populations might not actually be restored to their without-mussel levels, costs might include lost use and non-use values.

One argument against the avoided cost approach is that, although the region may be paying hundreds of millions annually now to preserve the runs, they may not be willing to pay even more to preserve them. That is, the costs of existing actions plus costs of actions to compensate for mussels may be beyond the benefits people place on preserving the populations. This may be true, but the ESA and other policy guidance do not suggest such comparisons.

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[8] From BPA 2010, 41+8+137

With so much uncertainty about potential mussel populations and their effects, more economic work is probably not justified at this time. More work, primarily biological analysis, is advised before costs can be quantified in more detail.

Other Native and Game Species

Many other native species and valuable game fish species could be adversely affected by mussels. The subbasin plan for the upper Snake River provides information about some of the other native species that might be affected by a Snake River infestation.

From the Upper Snake Subbasin Plan, page 1-27:

> Over 40 native mollusc species reside in the mainstem Snake River and adjacent springs. Five snails are listed under the Endangered Species Act (ESA), and three others are classified as species of concern. The listed snails are primarily limited to the Snake River basin below American Falls Dam.
>
> A relatively small number of coldwater fish species, primarily Catostomidae (suckers), Cottidae (sculpins), and *Rhinichthys* (dace), are native to the Upper Snake River above Shoshone Falls. Other native non-anadromous species include Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), finespotted cutthroat trout (*O. clarki spp.*), mountain whitefish (*Prosopium williamsoni*), Utah chub (*Gila atraria*), and leatherside chub (*G. copei*).

In the Hells Canyon, white sturgeon use the river for spawning and rearing. Idaho springsnail, Snake River physa and Pacific lamprey also occur in the Hells Canyon subbasin (Hells Canyon subbasin plan, p. 25). A number of non-native valuable game species, primarily bass and trout, could be negatively affected.

Invasive mussels might have some positive attributes. Some species such as sturgeon, some ducks, otter and mink may eat mussels. Effects on some species through food web effects could be positive. On the other hand, accumulation of contaminants by the mussels could be a problem for predators as contaminants are concentrated near the top of the food web.

Potential costs are similar to those identified for anadromous fish. Potential costs include additional habitat costs, increased costs of restoration and preservation, lost use of resources such as water supply and hydropower, and lost use and “non-use” values.

We believe that economic costs associated with native and game species from a widespread mussel infestation could be large, but ultimately, economic estimates must depend on the biology of mussels as well as the impacted species. We conclude that costs are unknown, but should be included within the range of tens to hundreds of millions identified in the previous section.

Water Supply Facilities and Fish Screens

Water supply facilities include irrigation, municipal and industrial (M&I) diversions, and industrial direct diversions. The Council has an interest in irrigation and M&I water systems primarily because many of these systems have fish screens, many of them financed by the FWP. Fritsch (2004) lists about 900 fish screens on gravity diversions on tributaries above Bonneville dam. Large numbers of screens were employed on the Grande Ronde (130), John Day (293), Yakima (83), Lemhi (104) and most other large tributaries used by salmon in the Basin.

If these screens are fouled by mussels, this is not only a problem for the water users, it also increases the likelihood that fouled screens will be removed as an emergency measure to protect water supplies. Fortunately, most fish screens are on tributaries that may be less likely to become infested.

We have found very little work on the potential economic impacts of mussel infestation on water diversion facilities. The Midwest and East regions, where the mussels are common, have had experience with mussel infestations in M&I water systems. The Metropolitan Water District of Southern California recently estimated that expenses for quagga mussel control in the Colorado River Aqueduct would be $10 to $15 million annually (Associated Press, 2009). To date, most western irrigation systems are mostly mussel-free, and the Midwest and East have little irrigation using surface water, so estimates of infestation costs can only be speculative.

Costs to water supply facilities may include increased cleaning costs and loss of use. Most irrigation facilities in the region are dewatered in the winter, which should kill mussels and provide an opportunity for seasonal cleaning. Irrigation system components that are not dewatered and cleaned in winter, screens, trash racks and pumps, for example, might experience accumulated fouling by mussels. Other costs may include antifouling paint and lost use from blockage of drip and micro-irrigation systems. Filtration to prevent blockage of drip and micro-irrigation systems might become cost-effective. In addition to dewatering, possibilities for controlling a mussel infestation in irrigation systems include flushing the system with hot water (above about 95° F), and introducing fertilizer into the water in concentrations that inhibit the mussels.

We have not found a tally of the number of M&I and irrigation diversions in the Columbia Basin, but the number is very large. Idaho Aquatic Nuisance Species Taskforce (2009) estimated that there are over 56,000 diversions in the State of Idaho alone. The 1995 System Operation Review (SOR, USACE 1995) counted 32.6 million acre-feet of diversions in the basin, of which 22.7 million were in the Snake River. The number of pumps found by the SOR diverting from the mainstem lower Snake and Columbia Rivers appears in Table 4. As calcium conditions for mussels are more favorable in the Snake River, and most irrigation occurs there, it is safe to conclude that most of the irrigation costs of invasive mussels can be expected there.

The 17,700 cfs Columbia Basin Project pumps at Grand Coulee could be subject to infestation if mussels become established in Lake Roosevelt. Such an infestation could well spread into Banks Lake and to control structures in the Columbia Basin Project. The other large and medium size projects in the mainstem Columbia, the Yakima, and the Snake River in southern Idaho (many of them private) are similarly at risk.

The Idaho Aquatic Nuisance Species Task Force (2009, p. 1) prepared estimates of the costs of mussel introduction in Idaho:

> The drinking water facilities included in this analysis are facilities that draw surface water for municipal or public drinking water use. Mussels foul intake piping and water processing infrastructure, increasing maintenance costs and degrading water flavor due to mussel waste and decomposition in water lines. Private single family home water intakes for drinking and irrigation are not included in this estimate. Estimates based on O'Neill (1997) figures from water treatment facilities ($42,000 per facility) applied to 100 facilities in Idaho.
>
> Golf courses are at risk for additional maintenance costs for irrigation systems. Fouling of pipes and pumps and clogged sprinklers are projected to increase operating expenses. Estimates based on O'Neill (1997) costs from golf courses ($150 per facility) applied to 114 Idaho courses.

Over 56,000 points of diversion were identified in Idaho by the Idaho Department of Water Resources. Most, but not all of the points of diversion in the Idaho report are in the Columbia drainage basin. Multiple points of use may be associated with each point of diversion. Each point of diversion and point of use could be affected by the introduction of zebra or quagga mussels. Because of the way irrigation developed in Idaho, much of it years before the Bureau of Reclamation was established, many Idaho diversions are small, and may be owned by canal companies, irrigation districts, or private individuals.

Mussels can grow up to 0.12 mm per day under ideal conditions and could impact even those water conveyances that are seasonally dry. Fouling from mussel establishment is cumulative and increased fouling and flow reduction would occur in ditches, pipes, pumps, fish screens and diversion structures over time.

Published research on mussel-related flow reduction in irrigation systems is minimal, but mussel establishment in pipes and pumps is well documented. The ultimate impacts of zebra and quagga mussel introduction on irrigated agriculture are highly uncertain, but there is a high likelihood that mussels would increase maintenance costs for operations that rely on surface water for irrigation.

Some water supply systems do not shut down in winter because they need to provide water for livestock or M&I use, or they deliver winter water for aquifer recharge. Such systems may face additional costs including lost use.

The potential for mussel build-up at municipal and industrial diversions may be greater because water is typically diverted all year. Anti-fouling paints, flushing critical piping with hot water, and introducing chlorine earlier into the treatment facilities are possible treatment options. Any treatment program will be complicated by the need to follow public health and environmental standards. Some typical costs were shown in Table 1. In general, the upper Snake River, where calcium is favorable and where there are numerous diversions, is most likely to experience additional costs and loss of protection by fish screens.

Table 4. Diversion Pumps Identified by System Operations Review at Selected Pools

Pool	Irrigation	Other
John Day	25 irrigation pumping plants (many of them large)serving 139,500 acres	M&I and small irrigation uses include 2 fish hatcheries, city of Boardman water supply, city of Umatilla sewage Treatment plant, an aluminum plant, and a school.
Ice Harbor	13 irrigation pumpers irrigate 39,489 acres from the reservoir.	Three pumps are used by the Corps to irrigate wildlife habitat.
Lower Granite, Little Goose, Lower Monumental	No large irrigation pumpers.	Uses include Corps wildlife pumps, a sand and gravel operation, Whitman County parks, Clarkston golf course, Washington and Idaho state parks. There are 9 pumps in Lower Granite pool, 2 in Little Goose, and 2 in Lower Monumental.
Grand Coulee	A 17,700 cfs 12-unit pumping plant located just above the dam lifts water 300 feet to irrigate 560,000 acres in the Columbia Basin Irrigation Project	Several small M&I and small irrigation pumps are located along the shore of Lake Roosevelt.
Source: US Army Corps of Engineers, "Columbia River System Operation Review, Final Environmental Impact Statement, Appendix F, Irrigation, Municipal and Industrial Water Supply", November 1995.		

Other Columbia Basin Facilities

Costs of dealing with mussel infestation on public and private navigation facilities could be significant. Mussels can colonize the inside of motors causing catastrophic failure. The number of towboats currently operating within the FCRPS navigation facilities is unknown. Mussels on barges increase drag. Antifouling paints and/or more cleaning would be required. The 1999 juvenile migration feasibility study counted 198 dry cargo and tanker barges (USACE 1999). Navigation facilities may face increasing painting and cleaning costs. The 1995 SOR Appendix H counted 54 port facilities in eight FCRPS reservoirs (USACE 1995a). Some navigation-related costs from other regions are shown in Table 1.

Invasive mussels could have profound impacts on the value of living and recreating on the Columbia River. For boats, waterfront properties and marinas, costs may include additional cleaning and antifouling paints.

The SOR estimates that, from 1987 to 1993, there were an annual average of 18 million recreation days taken on Columbia Basin lakes and rivers (USACE 1995b). These days generate economic value for users and for the businesses that benefit from their expenditures. Both the number of days and the average value of days could be reduced by a mussel infestation that resulted in reduced quality of the recreation experience, additional time and expense for dealing with mussel regulations, and costs of cleaning boats.

Mussels can foul and damage engines. Some recreational boat costs from other regions are shown in Table 1. One study estimated a cost of $250 per infested boat (Vilaplana et al. 1994). There were recently over 600,000 boat registrations in the four states. This number does not count many very small boats or boats from outside of the region. The number of boats using the Columbia Basin each year, or the number requiring cleaning, is unknown. Still, costs of cleaning boats infested or potentially infested with mussels could amount to tens of millions of dollars annually.

The amount of potential cost for facilities in the Basin is highly uncertain. Numbers from IANST (2009) are representative for the categories included. Table 5 provides a very rough cost estimate for facilities for a Snake River infestation based on this source. We allow 50% more for other States in the basin or a total of about $50 million annually.

Table 5. Potential Facilities Cost Estimate Based on IANST (2009)

Type of Facility	Number	Annual Cost per Unit	Total
Boats	100,000	$250	$25,000,000
Boat Facilities	380	$750	$285,000
Golf Courses	100	$150	$15,000
Drinking and Industry Intakes	100	$42,000	$4,200,000
Other Diversions	50,000	$100	$5,000,000
Total			$34,500,000
Remainder of basin (50% more)			$17,250,000
Total Basin			$51,750,000

Increased Chance of Infestation Outside of Columbia Basin

An infestation in the Columbia Basin would substantially increase the chance of infestations in other waterways in the Pacific Northwest by boats. Recreational boats commonly move from the Columbia Basin by land and by sea. Freshwater ballast taken up by deep sea ships in the lower river might contain larvae and they could be moved elsewhere if mid ocean exchange is not conducted. Costs of coastal shipping could be affected by a Columbia infestation.

Impacts to Tribal Harvest Locations

Mussels could interfere with tribal harvest at the usual and accustomed places. Ceremonial uses could be adversely affected above and beyond the direct effects of mussels on fish and other important resources.

Response and Control Costs

If an infestation of mussels were found, there might be an attempt to eradicate them before they spread. Heimowitz (2010) provides a cost estimate for one rapid response control effort. Costs for sampling and surveys, control of spread, treatment, and logistical costs are estimated to b $7.5 million. These costs could vary by orders of magnitude, and the control effort might ultimately prove futile. The potential for success is closely related to the speed of the response. This speed will be related to the ability to apply available control measures as soon as possible which will depend on having the necessary permits in hand.

PREVENTION COSTS

This section provides a brief overview of how dreissenid mussels (including zebra and quagga mussels) are spread by people, the level of effort in various states to prevent their invasion, and what the guidance there is from existing studies as to the best allocation of effort between prevention and control.

Background

The establishment of an invasive species proceeds from the species being present in some vector (e.g. recreational boat traffic), to being transported and released alive, to colonization, and finally to growth in area and numbers. As the species spreads, the management options available to contain or control them generally become fewer and more expensive.

Invasive mussels first became established in North America from ocean-going ships' ballast water. They spread quickly by downstream dispersal and overland by human transport. After the initial invasion of the Great Lakes about 1986, the species are now in several locations in the west, including Lake Mead and the lower Colorado River as of January 2007.

The most likely way for mussels to become established in the Columbia Basin is by boats trailered from infested waters, so most prevention efforts are targeted to boat trailers. Initially, prevention by education, boat inspection, and boat cleaning is an option. After the initial invasion, early detection and rapid response and eradication may be feasible in some settings (isolated lakes) but not in large rivers or reservoirs. Little can be done to stop the spread of dreissenid mussels in most cases. Then, the only option is human adaptation through investments or maintenance to minimize the costs. The Introduction and Figure 1 provided a general economic model that could be applied to mussel prevention economics.

For the Columbia Basin, recreational trailered boats are the primary concern. Therefore, data and models that predict the probability of an introduction by trailered boat for combinations or origins and destinations can help allocate prevention resources.

The best data set on boater traffic in the western U.S. has been developed by the U.S. Fish and Wildlife Service's 100th Meridian Initiative. Since the year 2000, this program has collected interviews of more than 20,000 boaters. The tabulation for Idaho shows that surveys have been conducted at American Falls Reservoir, Brownlee Reservoir, Lake Coeur d'Alene, Palisades Lake, Lucky Peak Reservoir and a number of other waters (USFWS, 2010).

There have been a number of analyses using these data to develop estimates of the relative probability of dreissenid mussel invasion at different waters (Bossenbroek et al. 2007). Jerde and Bossenbroek (2009) estimated a national gravity model to predict the number of boats entering a destination with zebra mussels. The model was applied to 13 non-invaded lakes and predictions evaluated for 15 recently invaded lakes. For example, the model was used to compare the probability of Lake Mead being invaded before Lake Roosevelt (estimated to be 0.797). Work is underway to develop a risk assessment of recreational boating traffic and aquatic nuisance species (specifically dreissenid mussels) to lakes, rivers, and reservoirs in the Western U.S., funded by the Western Regional Panel on Aquatic Nuisance Species (Phillips 2010). This analysis will also utilize the 100th Meridian data set.

Prevention Programs in the Northwest and Western States

As recently as two years ago, little was spent for mussel prevention in the Columbia Basin. Limited funding was provided for education, outreach and some monitoring. In the last several years, expenditures have increased with states legislating boating and recreation user fees to fund inspection stations and bolster enforcement activities.

State governments have taken the lead on prevention of aquatic nuisance species in the Western U.S., with most western states initiating active operational programs since the discovery of quagga mussels in Lake Mead on the Colorado River in early 2007. Activities by state are summarized here, first for states with waters in the basin and then for other western states.

Basin states

Idaho — Idaho's mandatory inspection program, funded by boat fees, is currently the largest in the region. The Idaho Invasive Species Law, enacted by the Legislature in 2008, provides policy direction, planning and authority to prevent and combat invasive species and established the Idaho Invasive Species Fund (IISF). The Invasive Species Prevention Sticker Law was passed in 2009. All boats are required to have an Invasive Species Sticker to launch and operate in Idaho. The sticker program is administered by the Idaho Department of Parks and Recreation. Revenue generated by this program is deposited in the IISF and administered by the Idaho State Department of Agriculture (ISDA. 2010).

The program is currently spending about $1.3 million per year (Ferriter 2010). The program includes mandatory inspections at border crossing and boat launches, public education, and coordination with other state, local and tribal agencies who assist with administration and enforcement.

In 2009, 18,300 boats were intercepted and three were found to be infested with dreissenid mussels. One infested boat was from the Great Lakes, one was from Nevada, and one was from the Southwest. In 2010, 21 mandatory inspection stations were operating statewide. As of June 10, 2010, six boats fouled with mussels had been intercepted and decontaminated.

Oregon — Oregon legislation established the Oregon Aquatic Invasive Species Prevention Program, including a boat permit program, in 2009 to fund aquatic species inspections. It is supported through boat registration fees. Through the first six months of 2010, income from the boat permit program was about $500,000; expectations were for about $1 million per year in boat permit fees per year.

Oregon's program is administered by two state agencies. The Oregon State Marine Board (OSMB) is an agency unique to Oregon that deals with all things having to do with both marine and freshwater boats, including licensing. The OSMB handles the collection of aquatic nuisance species license fees and boater education, while the Oregon Department of Fish and Wildlife (ODFW) is charged with doing all the field work involved with roving boat inspections, including purchasing trailers and boat-cleaning equipment and hiring about 10 field staff.

The Oregon prevention program differs from those in Washington and Idaho in that mandatory vehicle inspection stations will not be set up on either a roving (like Washington) or port of entry basis (like Idaho) for boats trailered by the public, because state courts have interpreted Oregon's constitution as making it "illegal to impose a mandatory check on the general public."[9] However, Oregon does have a Clean Launch Law, which makes it illegal to launch a boat with any aquatic species on the exterior (including native species). This provides inspectors the authority at launch points to inform boat owners when a simple arms-length visual inspection indicates it is illegal to launch their craft, and if they do they will be cited, and to recommend that they allow the boat to be fully inspected and cleaned (Dolphin, 2010).

To date, Oregon's boat inspection program, which started in spring 2010 with five teams of inspectors stationed at various locations around the state, is not nearly enough to cover all points of entry. For 2010, the ODFW budget for the field operations part of the boat inspection program was $413,000 (Boatner, 2010). As of June 2010, there were no reported cases of boats contaminated with either zebra or quagga mussels. However, there have been cases of boats having New Zealand mud snails, as well as a case of a boat from San Francisco Bay, headed for Portland, that was badly encrusted with invasive salt water shellfish. The State of Oregon does have authority at Ports of Entry to inspect commercial vehicles.

Washington — In 2002, the Washington State Legislature began addressing the issue of interstate travelof AIS contaminated watercraft by passing Engrossed Substitute Senate Bill (ESSB) 6553. The legislation in ESSB 6553 required the Washington Department of Fish and Wildlife (WDFW) and the Washington State Patrol (WSP) to develop a cooperative plan to inspect watercraft entering the state in an effort to interdict AIS. This resulted in the development of a "Cooperative Boat Inspection Plan," which provided a framework for efforts to interdict AIS entering Washington State (WDFW 2008).

In 2005, the Washington Legislature recognized that AIS are a major threat to the economy, environment and public health of the citizens and aquatic resources of Washington by passing ESSB 5699. The main intention of ESSB 5699 was "to prevent the introduction or spread of highly destructive species currently not found in Washington's waters." The legislation accurately concluded that prevention was and is significantly less expensive and causes far less ecological and economical damage than attempting to control new infestations. The legislation in ESSB 5699 created a funding source for this purpose by implementing a fee to be added to every watercraft registration in the State of Washington (WDFW 2008).

In 2007, with support from WDFW, the Washington Legislature passed ESSB 5923. The new bill allowed WDFW to have joint access to funds in the AIS enforcement account which had been previously managed solely by the WSP. The legislation also identified

WDFW as the primary enforcement agency regarding Washington State AIS laws. ESSB 5923 also granted check station authority to WDFW to operate mandatory watercraft inspections in an effort to interdict AIS (WDFW 2008).

Washington now has a coordinated aquatic nuisance species prevention, control, eradication and enforcement program. The state's enforcement program provides training to other enforcement officers including the WSP, which is the agency leading the integrated inspection and mandatory boat inspection station efforts.

Washington has a goal of 36 mandatory check stations statewide over the summer. Check stations in Washington are shifted around by region and operated for one to two day periods so that the public does not know when and where the next check station will be operating. Many other boats are inspected along with safe boat inspections. Since 2006, the WSP have intercepted over 20 boats at port of entry inspection stations having either zebra or quagga mussels attached. In 2010, officials seized a 24-foot boat in Spokane contaminated with quagga mussels from Lake Mead, Nevada.

Since 2007, the State of Washington has spent approximately $500,000 to 600,000 annually on *Dreissena* mussel prevention and enforcement efforts. Prior to that, the average amount spent was about $50,000 per year. Pending successful legislation next year to establish a boat permit system, the Washington's prevention and enforcement efforts could ramp up to roughly $2.5 million annually. The total amount spent within Washington since 1998 on these efforts has been about $1.4 million (Pleus, 2010). Legislation may establish a boat permit system to help fund inspections in Washington as early as 2011.

Montana — Montana's program, funded by general revenues, funds 4 field crews rotating between 15 points in the state. The state program includes Department of Agriculture inspection stations at the state border, but boat inspection is not mandatory, as it is in Idaho and Washington. The 14 border check stations operate on weekends only and three management area inspection stations operate 7 days per week — all operate for 12 hours each day.

Montana Department of Fish, Wildlife and Parks (MTFWP) also inspects boats at boat ramps and access points in a roving operation, and much of the budget goes to that effort. About 1,000 boats were inspected in 2009. One contaminated boat was self-reported and decontaminated, which was a case of a boat inherited by a state resident from family in the Chicago area. With current funding levels it is anticipated that the number of boats inspected in 2010 will be substantially increased, perhaps doubling or more. In general, Montana's approach is more focused on transportation within the state, interception at the most susceptible waters based on environmental factors and boat transport patterns, and on education of the public to take ownership and responsibility for this potential problem.

In 2009 the Montana Legislature provided one-time funding of $660,000 to cover two fiscal years of 2010 and 2011 (e.g., July 1, 2009 through June 30, 2011) for aquatic nuisance species prevention efforts. In addition, MTFWP provides about $140,000 per year for funding ANS efforts from general funds off fishing and hunting license sales. Thus the state's total funding per year for all ANS purposes is $470,000, a share of which is focused on dreissenid mussel prevention efforts. (Ryce, 2010)

Wyoming — Wyoming recently allocated approximately $1.5 million to start a boat permit and inspection system.

Utah — The prevention expenditure by the State of Utah in 2009 was $1.4 million in general funds plus $407,861 in partner funding (Utah Division of Wildlife Resources 2010). As an indication of the effort undertaken in Utah, 299,151 boats were interdicted (including 106,000 by the National Park Service at Lake Powell), 2,511 boats that had been on zebra or quagga mussel infested waters in the last 30 days were decontaminated, and 15 boats were found encrusted with mussels (including 11 at Lake Powell).

Other western states

California — The discovery of invasive mussels in the lower Colorado River and at 20 other locations in California in 2007 and 2008 prompted legislative action, and Assembly Bill (AB) 1683 was signed by Governor Arnold Schwarzenegger on October 10, 2007. AB 1683 became California Department of Fish and Game (CDFG) Code Section 2301, which authorizes CDFG to conduct inspections, order quarantines, work with water managers in the development of mandated response plans for infested waterbodies, and to take other actions to prevent the spread of invasive quagga/zebra mussels. CDFG Code Section 2301 includes civil penalties up to $1,000. On September 30, 2008, the Governor signed AB 2065. Implemented as CDFG Code Section 2302, this legislation requires that uninfested public reservoirs implement a program to prevent the introduction of mussels, which includes public education, monitoring, and management of recreational activities (CDFG 2009).

The goal of the CDFG is to prevent further introduction of dreissenid mussels into the state, contain mussels within currently infested waters, and eradicate mussels from infested waters if feasible. Six main objectives are defined in CDFG's Quagga/Zebra Mussel Management Strategy, which include coordination, prevention, detection (monitoring), response, control and eradication, and information dissemination. In recent years CDFG spent $2.55 million to implement its Q/Z Mussel Management Strategy in FY 2007-08, and $2.2 million in each of FY 2008-09 and FY 2009-10 (California Quagga/Zebra Mussel Project 2008, 2009).

The California Department of Food and Agriculture (CDFA) operates 16 Border Protection Stations (BPS) located on the major highways entering the state. The CDFA BPS operates 24 hours a day, 7 days a week. Vessels entering the state through a CDFA BPS undergo an inspection for standing water, presence of adult quagga/zebra mussels, and/or aquatic weeds.

From January 29, 2007 to April 30, 2010, CDFA BPS inspected 371,954 vessels of which 28,177 vessels needed to be drained, and 578 vessels were quarantined with confirmed quagga/zebra mussel finds. CDFA has spent $2.5 million for its boat inspection program in FY 2007-08, and $2.2 million in each of FY 2008-09 and FY 2009-10 (Norton, 2010).

Local governments with authority over individual water bodies within California may also require a boat inspection prior to launch. All local boat inspection efforts conducted by local governments are fully funded by local governments.

Arizona — In recent years the State of Arizona has been spending approximately $220,000 to $230,000 annually on public education and outreach programs, including funding for the state's invasive species coordinator. In 2009 the State of Arizona passed the Aquatic Invasive Species Interdiction Act, which provides the state with the authority to interdict, inspect and decontaminate boats containing invasive species. This new state regulation, which went into effect in March 2010, is intended to help prevent the spread of quagga and zebra mussels. Arizona currently does not have a boat inspection and decontamination program. However, in 2011, Arizona expects to purchase several mobile boat decontamination units to implement the Aquatic Invasive Species Interdiction Act using $150,000 in funding from the state watercraft fund and/or a QZAP grant. (McMahon, 2010)

Lake Mead National Recreation Area (LMNRA), administered by the National Park Service, requires marina concessionaires to include contract language for boaters mooring their boats in Lake Mead longer than five days requiring them to be inspected and decontaminated when they leave the LMNRA. However, inspections are not available at night, boaters have access to their boats at all times, and some boaters may have left without being inspected. Many boats are trailered from the infested Lake Mead to the Northwest. Moreover, the National Park Service has been unwilling to provide information such as descriptions and boat registration numbers for departing vessels destined for other states. "Due to Privacy Act regulations, personal information collected from boaters who are in compliance with our decontamination requirements cannot be distributed" (USDI NPS 2010).

Colorado — Expenditures in Colorado for FY 2009-2010 were expected to be about $3.2 million annually (Colorado Division of Wildlife and Colorado State Parks 2010). Prevention efforts in Colorado include inspections of over 400,000 boats and 3,300 decontaminations. In 2009, a total of 19 boats were identified with attached zebra or quagga mussels that were intending to launch in Colorado waters. As of July 2010, 12 boats with zebra or quagga mussels had been intercepted.. Most of the contaminated boats were from Arizona, Illinois, Louisiana, Minnesota, New York and Ohio. The majority of intercepted vessels were from the Great Lakes, the Mississippi River and Arizona.

The recent Colorado report also notes that for a third consecutive year, juvenile mussel veligers were found in Pueblo Reservoir. This indicates a reproducing population of adult mussels in this waterbody, which was the only water with a positive detection for zebra or quagga mussels in 2009 in Colorado. However, Granby Reservoir, Grand Lake, Shadow Mountain Reservoir, Willow Creek Reservoir, Tarryall Reservoir and Jumbo Reservoir are all considered “positive for zebra and/or quagga mussels.” Blue Mesa is considered “suspect” for quagga.

Summary — The presence of the ever-expanding mussel invasion in Lake Mead and downstream reservoirs on the Colorado River, and the infestation in State of Colorado waters indicates the increasing vulnerability of the Columbia Basin in the face of national and, especially, western U.S. boat traffic. Ricciardi et al. (1994) found that 25 percent of all boats leaving infested Michigan lakes were contaminated with live mussels. The more lakes or other waters that become infested, and the closer these waters are to the Columbia Basin, the higher the probability of a dreissenid mussel invasion in the Columbia Basin.

Levels of expenditure and associated authorities are variable across states. Idaho is currently spending about $1.3 million annually. Montana is spending $470,000 per year (Ryce, 2010), and Washington and Oregon are both spending about a half million dollars annually. Nevada and New Mexico apparently do not have similar programs and Arizona’s program includes no inspection stations. The lack of inspections in these states means that the costs of inspections must be borne by those States and federal agencies who do sponsor inspections. The Invasive Species Emergency Response Fund Act (S. 3063), sponsored by Senator Harry Reid, would provide $80 million for each of the fiscal years 2011 through 2015 for States west of the 100th Meridian for cost-sharing for prevention, protection and response efforts. States would generally be required to provide 25% of funds (Cantlon, 2010).

Existing prevention efforts use information about the origins of boats, especially those coming to Idaho, to help target prevention resources. Also, some types of events are national and attract boaters from regions known to have mussels. For example, bass fishing competitions attract a larger share of anglers from more distant and infested regions. The Idaho Invasive Species program is proactive in identifying bass tournaments and working with promoters and fishermen to minimize the chance of an introduction (Ferriter, 2010).

Coordination among states will be critical to the prevention effort. The Idaho program has demonstrated how information and coordination can combine to prevent introductions. Contaminated boats have left Lake Mead marinas because owners ignored their contracts or they were unaware of their contractual requirements. In one case, notification by California Fish and Game allowed an infested boat to be intercepted en route to the Pacific Northwest.

Economic Analysis of Prevention Efforts

An important question is whether current levels of prevention expenditure are adequate or whether much higher levels are justified. Communication with a number of individuals indicated that there is not much guidance on this question from the standpoint of case studies and formal benefit-cost evaluations.

A recent book-length analysis, (Keller et al. 2009) concluded that no guidance currently exists about how best to allocate limited funding to alternative methods of prevention versus control. A case study of the ecology and economics of a potential dreissenid mussel introduction in the Basin is provided (Bossenbroek et al. 2009). The study asks what it is worth to keep these mussels from becoming established in the Western watersheds. The study estimates that the annual welfare loss is roughly $3.3 million annual, based on impacts to hydropower (state, federal and municipal), irrigated agriculture and municipal water supplies (excluding fish hatcheries). Additionally no non-market effects are included, for example on recreational boating. This estimate of net annual welfare costs is more sophisticated than simply adding up direct costs; for example cost-minimizing behavior such as substitution and linkages within the economy are taken into account. The study concludes that the answer to “what is it worth” is still uncertain and depends, among other things, on ecological predictions of establishment and abundance, as well as the behavior of decision makers. Work continues on this general issue, with analysis showing more definitive results now under review and potentially forthcoming (Bossenbroek 2010).

Another economic study, Leung et al. (2004) found that it was cost effective to spend up to $324,000 annually to prevent colonization of a single lake in the Midwest with a large hydropower unit on it. In other words, Leung felt that the costs of infestation at a single hydropower plant justified annual prevention costs of $324,000.

While formal economic analysis of the appropriate level of prevention costs are limited, a general impression offered by many individuals contacted for this review is that the experience in the Midwest is that states with aggressive education and outreach programs (Minnesota, Michigan, and Wisconsin) seem to have fewer infested lakes and that their expenditures on prevention are worthwhile. For example, one view is that Minnesota is the best example: the state has had 20 years of living with mussels in the land of 10,000 lakes with 900,000 registered boaters and it has experienced very little spread of mussels (Billerback 2010). Jenson (2010) provided an overview of the Minnesota program as follows:

> Many states point to Minnesota as a model in addressing the pathways. In the early 1990s, Minnesota responded to the threats of AIS by emphasizing public education, watercraft inspection, monitoring, regulations and enforcement. Authorized by the Legislature, the Minnesota DNR established a program to prevent establishment of new harmful AIS, control the spread of existing AIS, and reduce their impacts. Today,

> the successes of the these efforts continue to rely on collaborations with many partners including the University of Minnesota Sea Grant Program, University of Minnesota Extension, U.S. Fish and Wildlife Service, and Minnesota Waters.
>
> For nearly two decades, Minnesota has worked with recreational boaters and anglers, encouraging them to act in ways that will prevent aquatic "hitchhikers" from spreading. We understand how boaters and anglers get their information. We also have insights into their risks for spreading AIS, their attitudes, motivation and behavior. We know boaters and anglers are willing to take action because they truly value our lakes and rivers. Based on these efforts, 99% of Minnesota boaters (866,000+ registered) report based on our surveys (up from 90% in 2000 and 70% in 1994) that they are taking actions to prevent the spread. (97% in Wisconsin and Iowa). I mention this because it emphasizes the successes and importance of focusing on prevention rather than reactively.
>
> According to the Minnesota DNR (2008), expenditures on AIS activities was \$2,532,000. In 2009, the Legislature authorized an increase of AIS activities to \$4.7 million. In 2008, 40% of the budget was on prevention (10% was education/public awareness + 30% inspections and enforcement) and 34% on management and control. Depending upon level of effort, current budget, extramural funds, Minnesota Sea Grant contributes probably around another \$150k based in public outreach and research. So, DNR and Sea Grant would bring the total up to \$4.850 million annually.

The Minnesota 2010 annual report (Invasive Species Program 2010) noted that in 2009 the number of inland lakes with mussels increased from 8 to 16. As in previous years, infested waters include the Mississippi, St. Croix and Zumbo Rivers.

In addition to the Minnesota experience, there have also been several cases where estimated costs of an invasion have been shown to be relatively high, justifying a substantive prevention program. This includes an analysis for Florida and another for Lake Tahoe. Lee, Adams, and Rossi (2007) estimated the costs of a zebra mussel invasion in the 448,000 acre Lake Okeechobee. As in the Columbia Basin, Florida has states nearby with zebra mussel infestations, and also like the Columbia Basin, some parts of Florida have the right water quality for infestations. One vulnerable water is Lake Okeechobee, an important water supply source for irrigation and for support of recreational angling. The authors estimate the costs of “doing nothing” and getting a major zebra mussel infestation at a present value (cost) of \$244 million over a 20 year time horizon. They compare the benefit-costs of three programs: prevention alone, late eradication, and a combination of prevention and early eradication. The costs of these programs are, respectively \$2.5 million, \$185.9 million, and \$55.4 million for the combined program. Prevention alone would reduce costs from an infestation by about 72% and save \$177 million, late eradication is feasible, but costly and would save only \$33 million, the combined program is cheaper than late eradication and would reduce the infestation costs to zero. The benefit-cost ratios are estimated to be, respectively, 70:1, 1.2:1, and 4.4:1. The basic finding of this study is that it is rational to invest in prevention.

An analysis of the potential economic costs of a mussel invasion in Lake Tahoe (USACE 2009) concluded that over a 50 year time horizon, the present value of infestation impacts would be $417.5 million, or $22.4 million annual equivalent value. The primary costs were due to impacts on property values and tourism, but also included boat and pier maintenance and recreation. The study concluded that “Spending on prevention and early eradication produces a higher benefit to cost ratio than post-infestation control programs such that maximum benefits are reached through early and preemptive action.” The plan was motivated by the increased threat to Lake Tahoe associated with the discovery of mussels in Lake Havasu and Lake Mead and because of the high incidence of traffic from these areas to Tahoe. The total available budget for ANS related spending on prevention at Lake Tahoe was $5.2 million for 2007 through 2008.

Comparing Prevention and Damage Costs in the Columbia Basin

It is likely that invasive mussels will eventually live in most of the large rivers of the Columbia Basin. There is much value to delaying this outcome for as long as possible. The annual benefit of delays in terms of immediate cost savings is large and a delay will allow the science to improve. A more refined understanding of how mussels are transported and established may allow for more effective prevention programs. Improved information about mussel reproduction and growth might allow for better management plans. Many control technologies are still being developed. Further, a delay will allow for more advance permitting that might reduce the chance for a widespread infestation and reduce management costs.

We have reviewed potential costs for mussel programs as outlined in Appendix D of the Quagga-Zebra Mussel Action Plan (QZAP) for Western Waters (WRPANS, 2009). Recent initiatives to increase funding for actions described in the QZAP seem appropriate. The QZAP costs do not appear to be unreasonable, with one possible exception. Item B.7 includes an option for inspection costs of over a billion dollars annually for 19 western states, for tens of thousands of potential inspection locations. This seems excessive, if only because it may be difficult to train and mobilize such resources in a short time frame, but also because there should be more cost-effective means, such as border inspections, to find and inspect potentially infested trailered boats.

Without this inspection cost, recommended QZAP costs for the Basin region, estimated as 4/19ths of costs for all western states, are about $20 million of initial and one-time costs plus $25 million of annual costs. In addition to these costs, USFWS personnel has estimated preparedness costs of about $1 million of one-time costs plus $1 million annually (Heimowitz, 2010).

Given the current scientific uncertainty and large cost potential (tens to hundreds of millions annually), and given that many points of entry are not being monitored and that infested boats are being found where they are being monitored, we conclude that existing prevention programs (about $3 million in four States) may be insufficiently thorough and under-funded.

Most prevention effort has been focused on trailered boats. It is clear that not all possible entry points for boats are being monitored; more inspections will be in place in the next two years or so. It appears that additional prevention efforts in some western states and provinces, especially Nevada, Arizona, New Mexico, Alberta and British Columbia may be justified. Boat inspection technology is advancing. There may be potential for use of cameras and detection devices to help route limited boat inspection resources.

Other possibilities for mussel introductions include contaminated construction equipment, small boats that are not trailered, fishing equipment, or hobby aquariums. We note that much riverine fishing effort is not boat-based, and the potential for introduction by other fishing equipment may deserve more attention. Upriver salmon fisheries include a relatively large share of fishermen using tubes, waders and small boats that could carry veligers and do not go through checkpoints at put-ins. Some mussel experts believe that an introduction by veligers directly is unlikely (Ferriter, 2010).

Better targeting of prevention dollars to the more likely persons, points and methods of introduction based on better science seems advisable. A review of State laws and authorities may be in order; federal agencies apparently have limited jurisdiction over recreational boat launches and rapid response, even at federal facilities.

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TABLES AND FIGURES

Table A 1. Management Actions and Costs at Hydropower Facilities exclusive of Fish Passage Costs. Table 3 from Athearn and Darland (2007), but with IEAB Assumed Preventative Actions and Costs

Facility, Level of Risk and Reason for Risk from Athearn and Darland			**Assumed Preventative Actions**	**Costs with 6% interest**	**Total Annualized Costs, Million $**	
Facility	**Level of Risk**	**Reason for Risk**	**IEAB Costs Based on Phillips, Darland, Sytsma (2008)**		**FCRPS**	**Other Hydropower Facilities**
Turbine cooling systems	High	Use raw water with no domestic water backup	NaOCl Injection System	Capital, 20 yr life and annual O&M	$2.30	$0.77
HVAC systems	High	Use raw water with no domestic water backup	Same NaOCl Injection System	Included		
Turbine intake trashracks	High	Exposure to raw water	Paint trashracks with Antifouling Paint	Capital and labor every 5 years	$6.53	$2.19
Service main generator coolers		Identified by Phillips et al (2008)	Serviced every year instead of every 5	Annual cost plus 1 yr interest	$1.40	$0.47
Raw water screens		Identified by Phillips et al (2008)	All screens cleaned annually	Same	$0.32	$0.11
Redundant header pipe		Identified by Phillips et al (2008)	Additional 24" equalizing header	Capital, 50 yr life	$4.57	$1.53
IEAB Estimates from Other Sources						
Fire suppression systems	High	Use raw water with no domestic water backup	IEAB: Water filtration system	$1 million capital per dam	$1.09	

Facility, Level of Risk and Reason for Risk from Athearn and Darland			**Assumed Preventative Actions**	**Costs with 6% interest**	**Total Annualized Costs, Million $**	
Facility	**Level of Risk**	**Reason for Risk**	**IEAB Costs Based on Phillips, Darland, Sytsma (2008)**		**FCRPS**	**Other Hydropower Facilities**
Spillway gates Spillway piers Spillway aprons Stilling basins	Medium	Exposure to raw water but should remain operable	Antifouling paint applied because of threat to salmonids; most cost (57%) is stilling basins	$3.17 to $10.03 million	$3.17 to $10.03 million	
Navigation lock – floating mooring bits	Medium	Exposure to raw water but should remain operable	Paint with protective antifouling coating	minimal	minimal	
Drains and sumps	High	Exposure to raw water	- Provide redundancy in drain lines			
			- Repair/replace leaking valves			
			- Provide backup pumps			
Forebay/tailwater sensors	High	Exposure to raw water	Additional sensors at each facility			
Dissolved gas monitors	High	Exposure to raw water	Additional dissolved gas monitors at each facility			
Oil/water separators	High	Exposure to raw water	- Provide redundancy in supply lines			
			- Provide additional water supply capacity			
			- Repair/replace leaking valves			
Boats	High	Exposure to raw water	- Provide site for storing boat out of water when not in use			

Facility, Level of Risk and Reason for Risk from Athearn and Darland			Assumed Preventative Actions	Costs with 6% interest	Total Annualized Costs, Million $	
Facility	**Level of Risk**	**Reason for Risk**	**IEAB Costs Based on Phillips, Darland, Sytsma (2008)**		**FCRPS**	**Other Hydropower Facilities**
Air compressors	Medium	Use domestic water with raw water backup	- Repair/replace leaking valves in raw water system			
Gland water for cooling/lubricating	Medium	Use domestic water with raw water backup	- Provide redundancy in supply lines			
			- Provide additional water supply capacity			
			- Repair/replace leaking valves			
Irrigation systems	Medium	Seasonal use raw water with no domestic water backup	- Repair/replace leaking valves			
			- Provide domestic water backup			
			- Provide capability to drain systems when not in use			
Ice and trash sluiceways	Low	Exposure to raw water (at High velocity)				
Visitor centers	Low	No exposure to raw water				

Table A 2. Management and Costs at Fish Passage Facilities. Table 3 from Kovalchuk (2007), but with IEAB Assumed Preventative Actions and Costs

					Total Annualized Costs, Million $	
Fish Facility Component	**Potential Risk**	**Reason for Risk Level**	**Assumed Preventative Actions**	**IEAB Costs with 6% interest**	**FCRPS**	**Other Hydropower Facilities**
Powerhouse and Auxiliary Water Supply Trashracks	High	Submerged all year, difficult to access and clean, excess debris accumulation can cause fish injury	IEAB: Included in hydropower costs	See Table A1		
Bypass Screens: -STS –ESBS –VBS	High	Submerged during veliger season or all year (VBS), difficult access; mesh and wedge wire screens are susceptible to fouling, units must be shut down for cleaning/maintenance, storage slots in water	IEAB: Additional cleaning; purchase 1 gantry per dam, clean three times per year for lower Snake projects; once per year downstream	$1.95	$1.95	
Gatewells, Orifices, and Juvenile Collection Channel	Moderate	Submerged almost all year, generally high flows, but slow flow areas may produce druses, difficult to access and clean	IEAB: Paint gatewells with antifouling paint	$1.03	$1.03	
Tainter Gate, Elevated Chute, and Crest gate	Low	Generally high flows, dewatered after fish passage season, easy access, crest gate seal may experience excess wear, sensor fouling potential	Check and clean expansion joints and crest gate seal, remove water accumulation in winter if needed			
Ogee Ramp and Tailrace Outfall Flume	Low to Moderate	Leakage from crest gate during fish passage season may promote mussel growth in ogee and flume	Inspect and maintain effective seal on crest gate, re-route leakage			

					Total Annualized Costs, Million $	
Fish Facility Component	**Potential Risk**	**Reason for Risk Level**	**Assumed Preventative Actions**	**IEAB Costs with 6% interest**	**FCRPS**	**Other Hydropower Facilities**
Primary Dewatering Structure, Modulating Weirs, and Adult Drain	Low to Moderate	Submerged during fish passage season, slight risk of mussel growth on dewatering screens, adult drain leakage may promote mussel growth	Remove mussels during winter maintenance, inspect and clean adult drain, design plug for this area			
Corrugated Transport Flume and Conveyance Pipe	Low to Moderate	Submerged during fish passage season, normal high flows, very difficult to access conveyance pipe	Seasonal inspection and cleaning after dewatering			
Switch Gates and Flushing Valves	Low	Normal high flows, leakage may allow mussel growth in bypass flumes, flushing water increase	Inspect and clean in winter, purge flushing water in-season, blockage drain diameter, inspect seal for wear			
Fish and Debris Separator – Secondary Dewatering System, Porosity Unit, Wetted Separator Bars, Juvenile Collection Hopper, and Distribution Flumes	Moderate	Submerged during fish passage season, normal high flows, dewatering screen, perf plate, and separator bar fouling, difficult access to parts of distribution flumes	Frequent inspection and cleaning, periodically purge supply valves and separator bars, provide improved access to flumes			
Tertiary Dewatering Units, PIT Tag Detectors and Rotating Sample Gates	Low to Moderate	Submerged during fish passage season, smooth surfaces, high flow areas, access possible but limited, flushing water supply valves vulnerable to fouling	Clean units as needed, purge flushing water supply lines and valves, provide improved access to flumes, devise scouring method for cleaning inaccessible areas			
SMF Laboratory: Holding Tank, Butterfly Valves, and Crowder Panels	Low	Submerged during fish passage season with periodic cleaning, discharge water perf plate fouling, inflow valve clogging potential	Increased cleaning, periodic purging of butterfly valves, inspect and replace crowder seal as needed			

					Total Annualized Costs, Million $	
Fish Facility Component	**Potential Risk**	**Reason for Risk Level**	**Assumed Preventative Actions**	**IEAB Costs with 6% interest**	**FCRPS**	**Other Hydropower Facilities**
Pre-anesthetizing Chambers, Fish Lifts, Drainage Lines, and Flushing Water	Low to Moderate	Submerged during fish passage season, difficult to access, even small accumulations can cause problems for fish and smolt monitoring personnel	Increase cleaning, improve water supply line isolation capabilities, install access portals to drain lines, devise scouring method for cleaning inaccessible areas			
Sorting Trough, Return Pipe, and Recovery Tanks	Low	Daily dewatering and cleaning, mostly easy access, water supply and valve clogging potential	Provide backup return pipe or devise scouring method for cleaning inaccessible areas			
Release Pipes and Exit to River Flume	Moderate	Submerged during fish passage season, difficult to access, problems would be difficult to Detect	Improve access for inspections, implement cleaning as needed			
Recirculation Pump, Water Chiller, and MS-222 Filters	Low	Submerged during fish passage season, difficult to access, many small diameter supply lines, increased pump wear and charcoal filter replacement	Remove seasonal accumulation of debris from storage tank, purge or clean lines to filters, maintain pump			
Research Activities – Temporary Holding Tanks, Degassing Columns, and Transportation Tanks	Low to Moderate	Submerged during fish passage season, inflow supply lines, valves, and degassing column clogging potential	Maintain tank cleaning protocols, purge supply valves daily, inspect and clean degassing columns as needed			
Avian Hydro-cannons	Low	Uses raw water, supply line mostly buried and susceptible to clogging and wear, no backup	Purge water supply line after use, inspect nozzles for wear			
Adult Collection Channel	Low to Moderate					

					Total Annualized Costs, Million $	
Fish Facility Component	**Potential Risk**	**Reason for Risk Level**	**Assumed Preventative Actions**	**IEAB Costs with 6% interest**	**FCRPS**	**Other Hydropower Facilities**
South Fishway Entrance	Low					
Fish Pump Intake Basin	Low					
Francis Wheel Fish Turbines	Low					
Fish Ladder Weirs, Submerged Orifices, Overflow Weirs, and Serpentine Weirs	Low					

Figure 2. Calcium and Temperature, Snake River at Burbank, near Columbia River Confluence, 1995 to 2000, from NASQAN (Whittier 2010a)

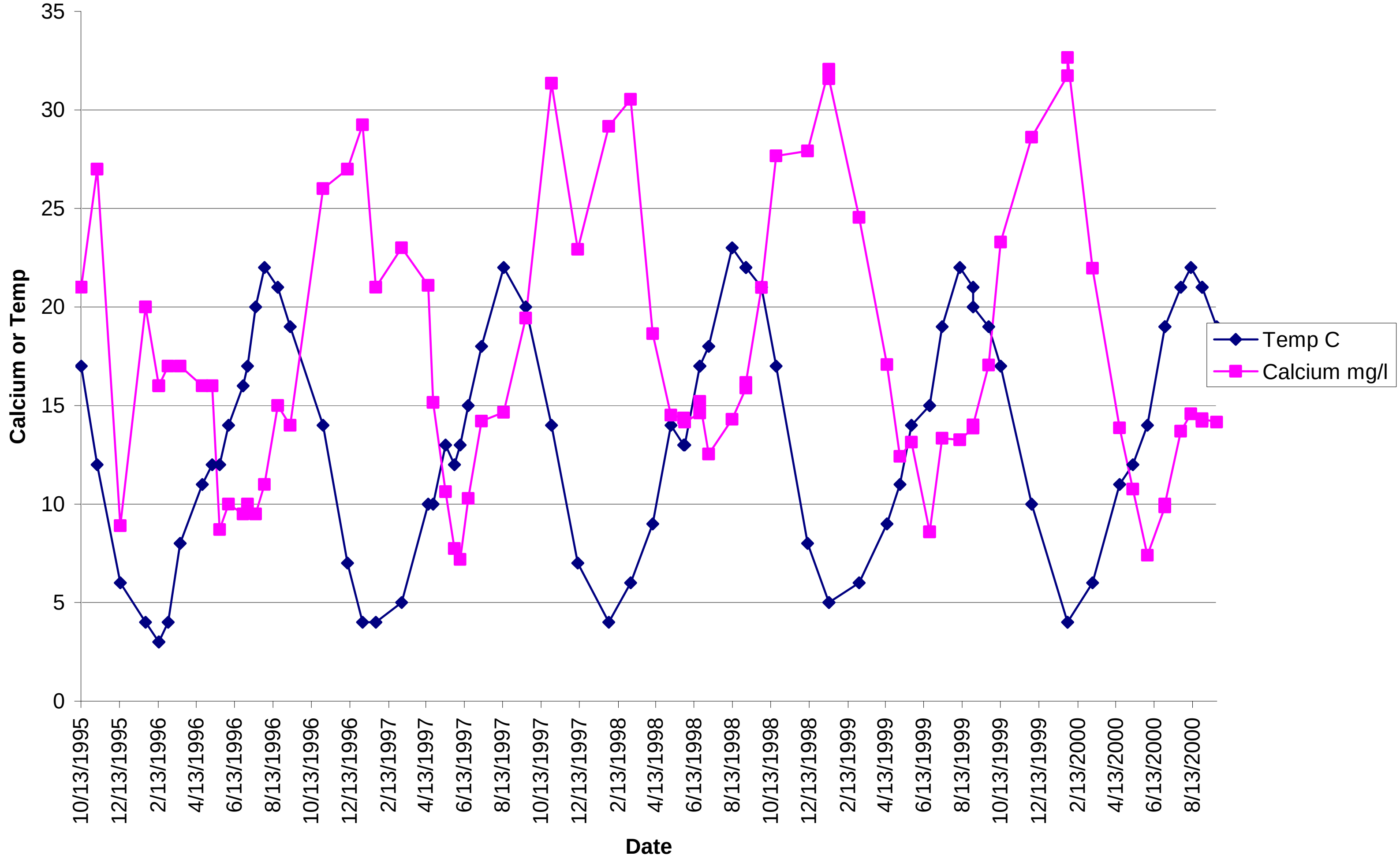
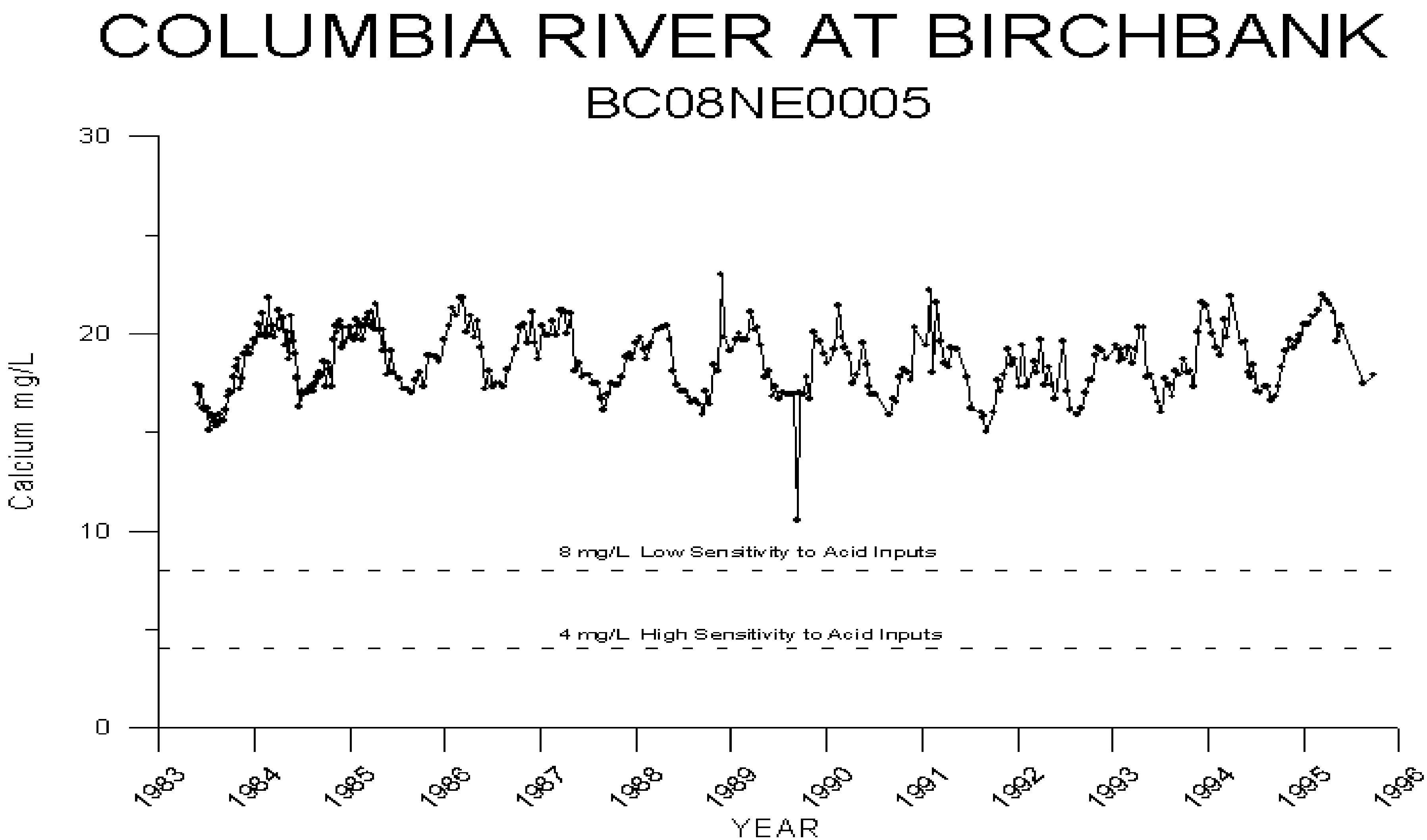
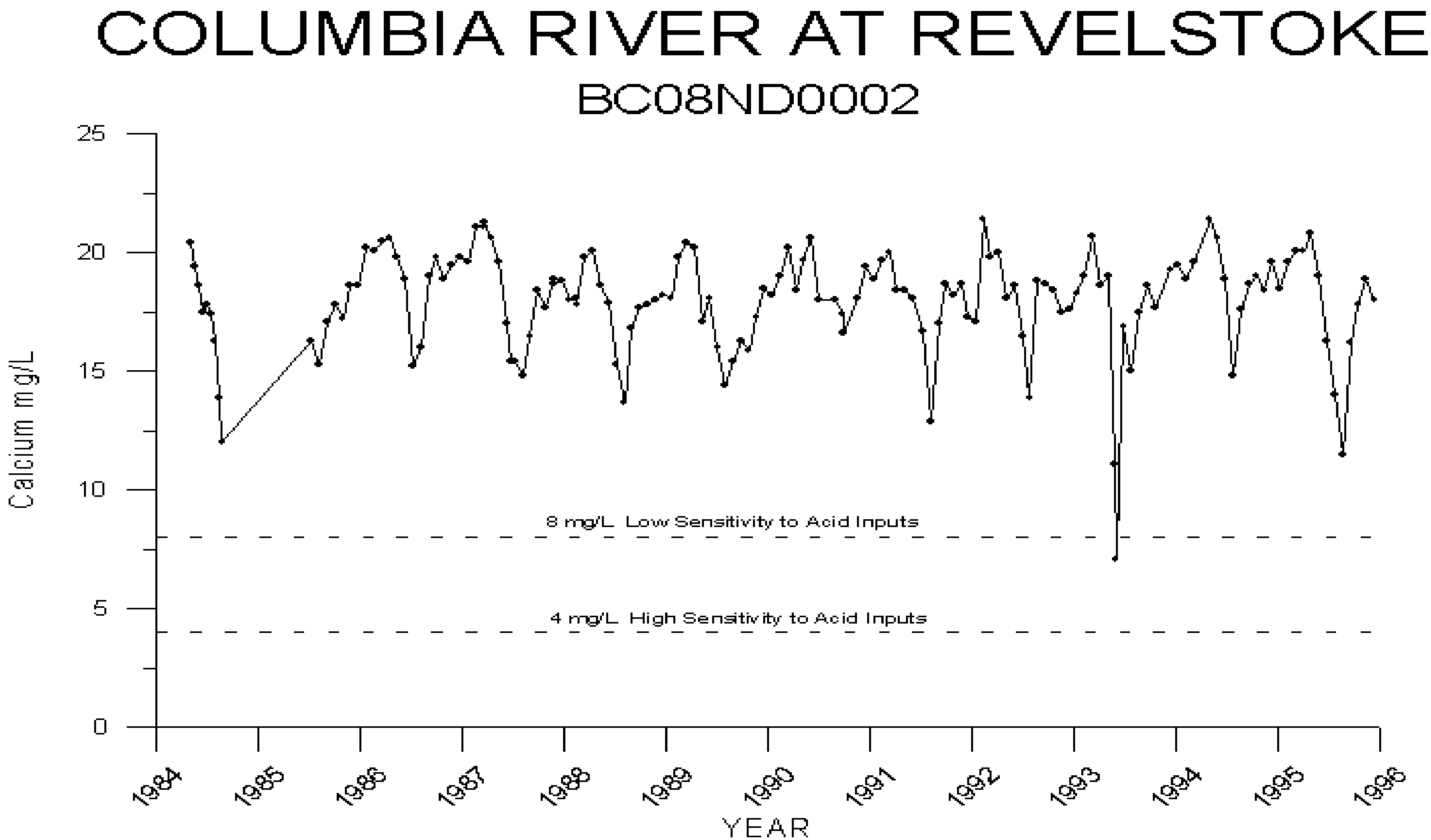


Figure 3. Columbia River Calcium Concentrations at Birchbank and Revelstoke, B.C., 1983 to 1996, from British Columbia Ministry of Environment 2010.



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



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

Figure 4. Calcium and Temperature, Northport WA, near Canadian Border, 1996 to 2000, from NASQAN (Whittier, 2010a)

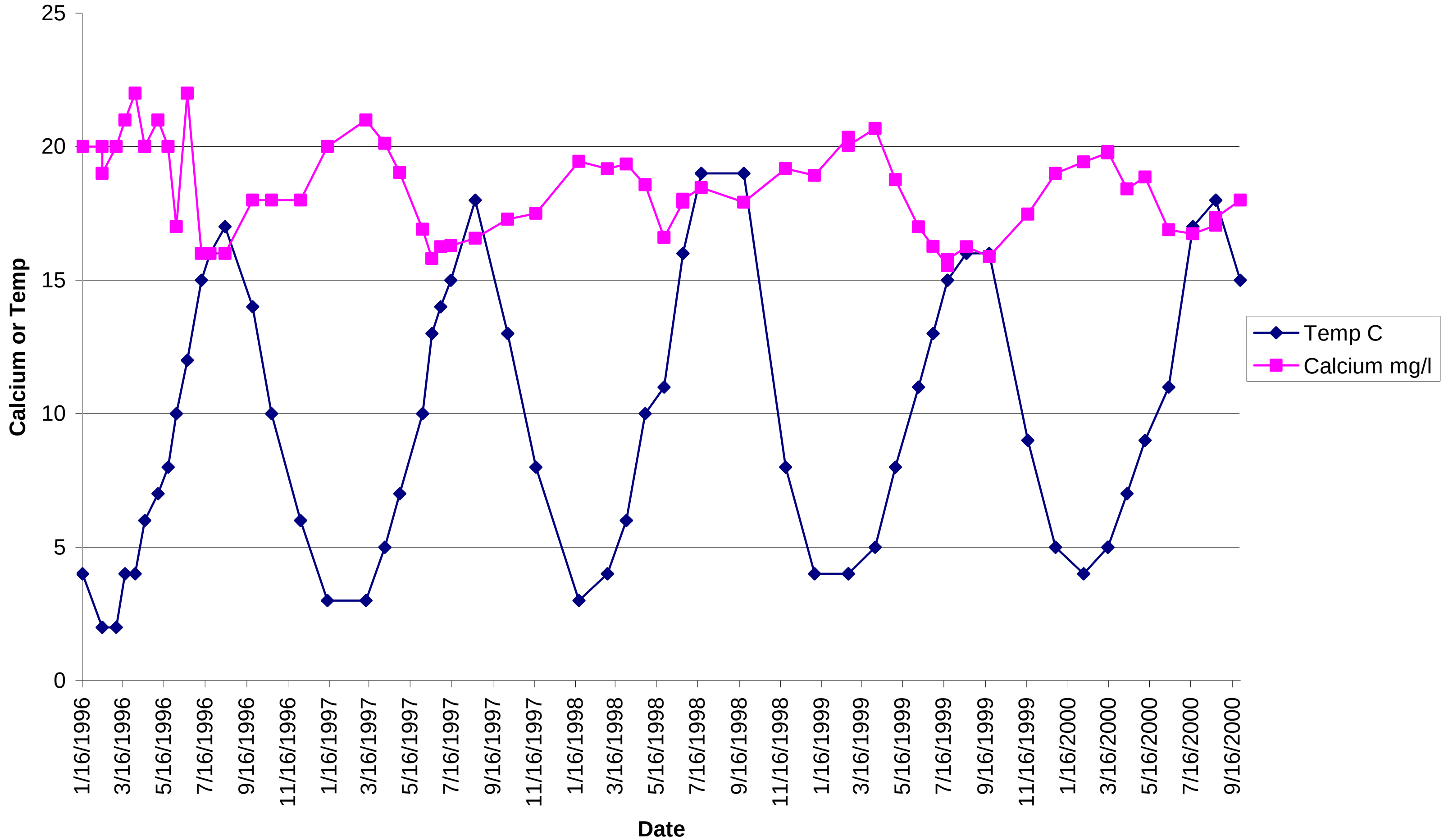


Figure 5. Calcium and Temperature, Priest Rapids, 1996 to 2000, from NASQAN (Whittier, 2010a)

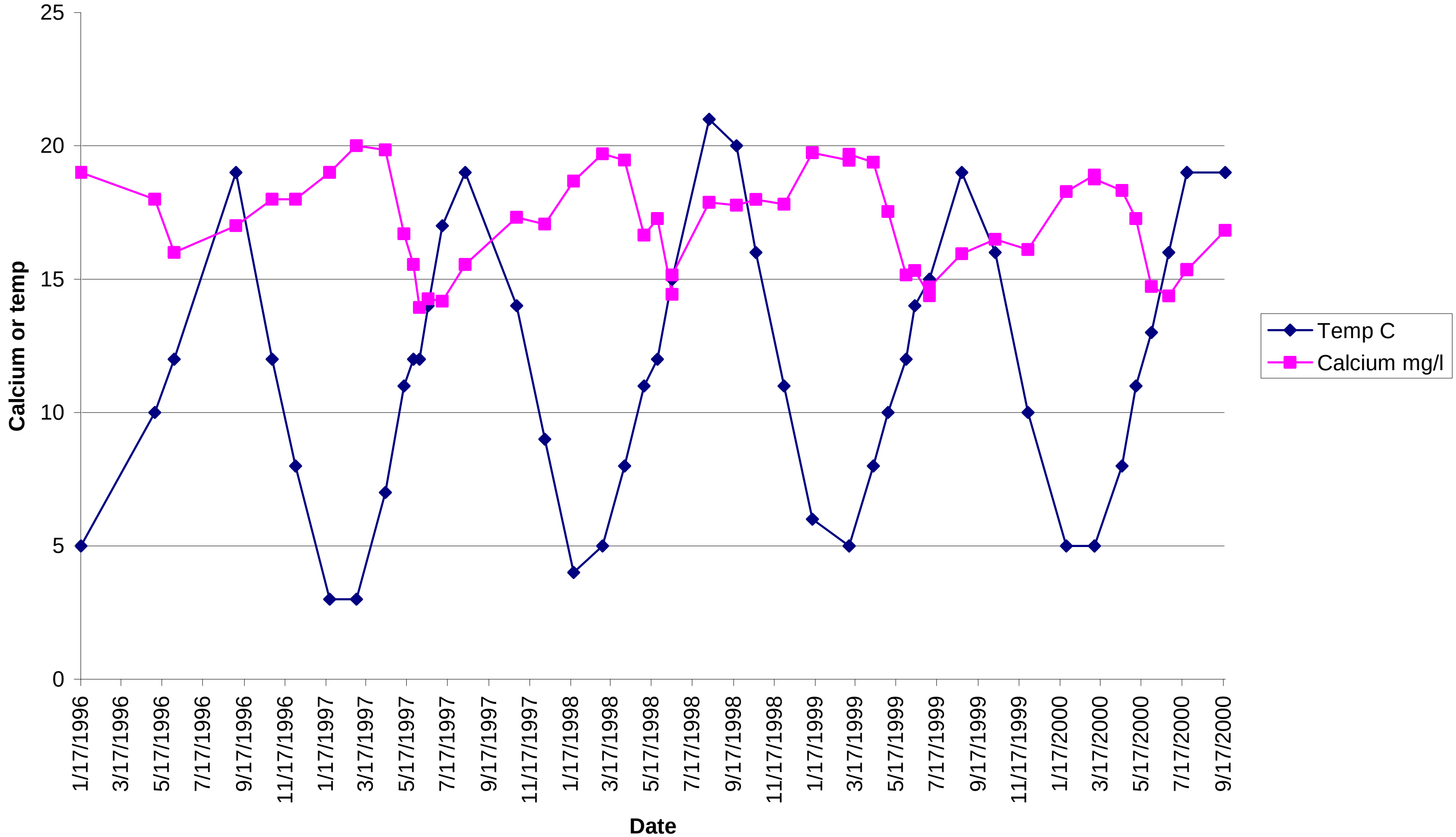


Figure 6. Calcium and Temperature, Warrendale OR, 1996 to 2000, from NASQAN (Whittier, 2010a)

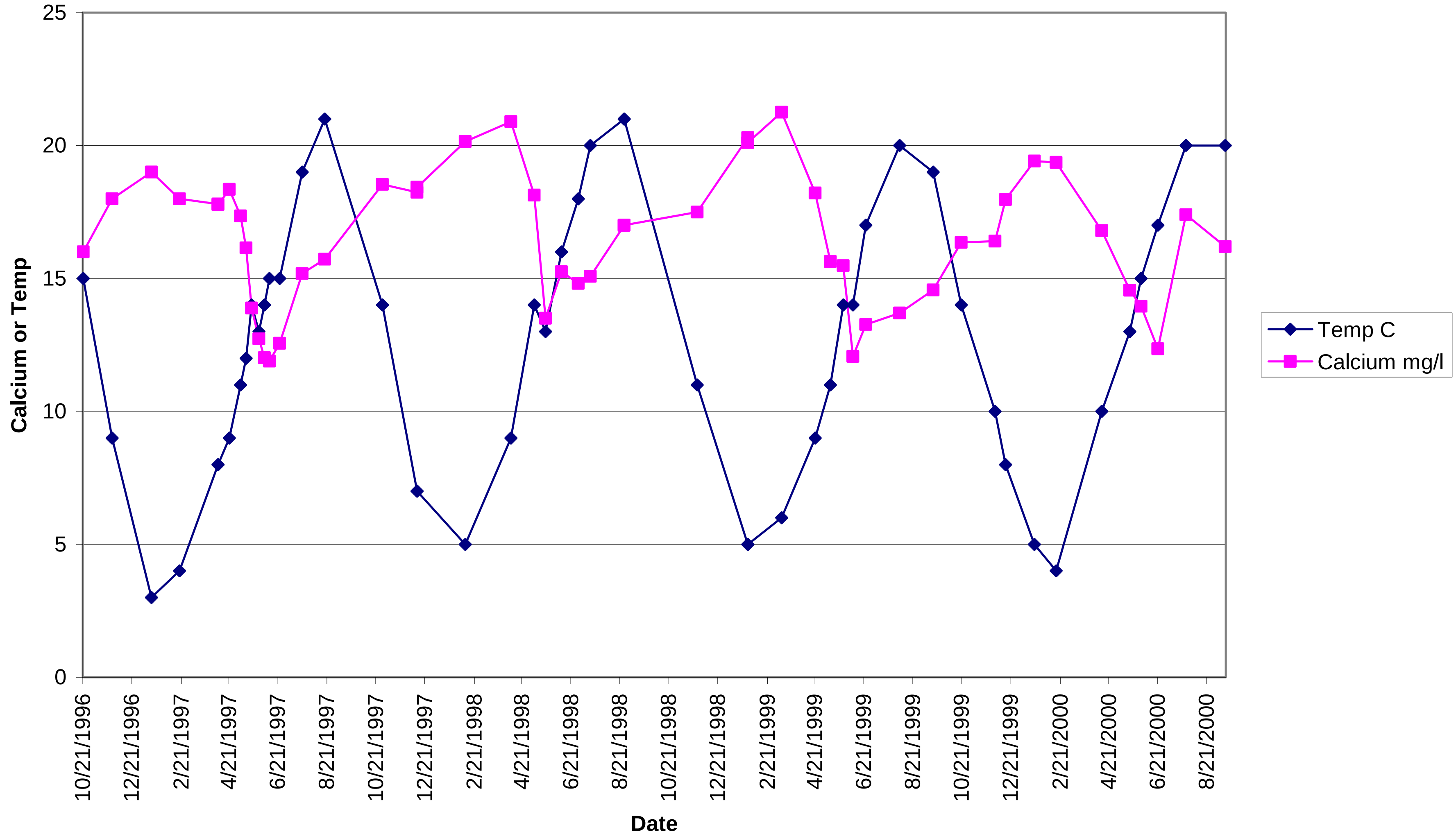


Figure 7. Calcium and Temperature, Quincy OR, Near Beaver Army Terminal, 1995 to 2000, from NASQAN (Whittier 2010a)

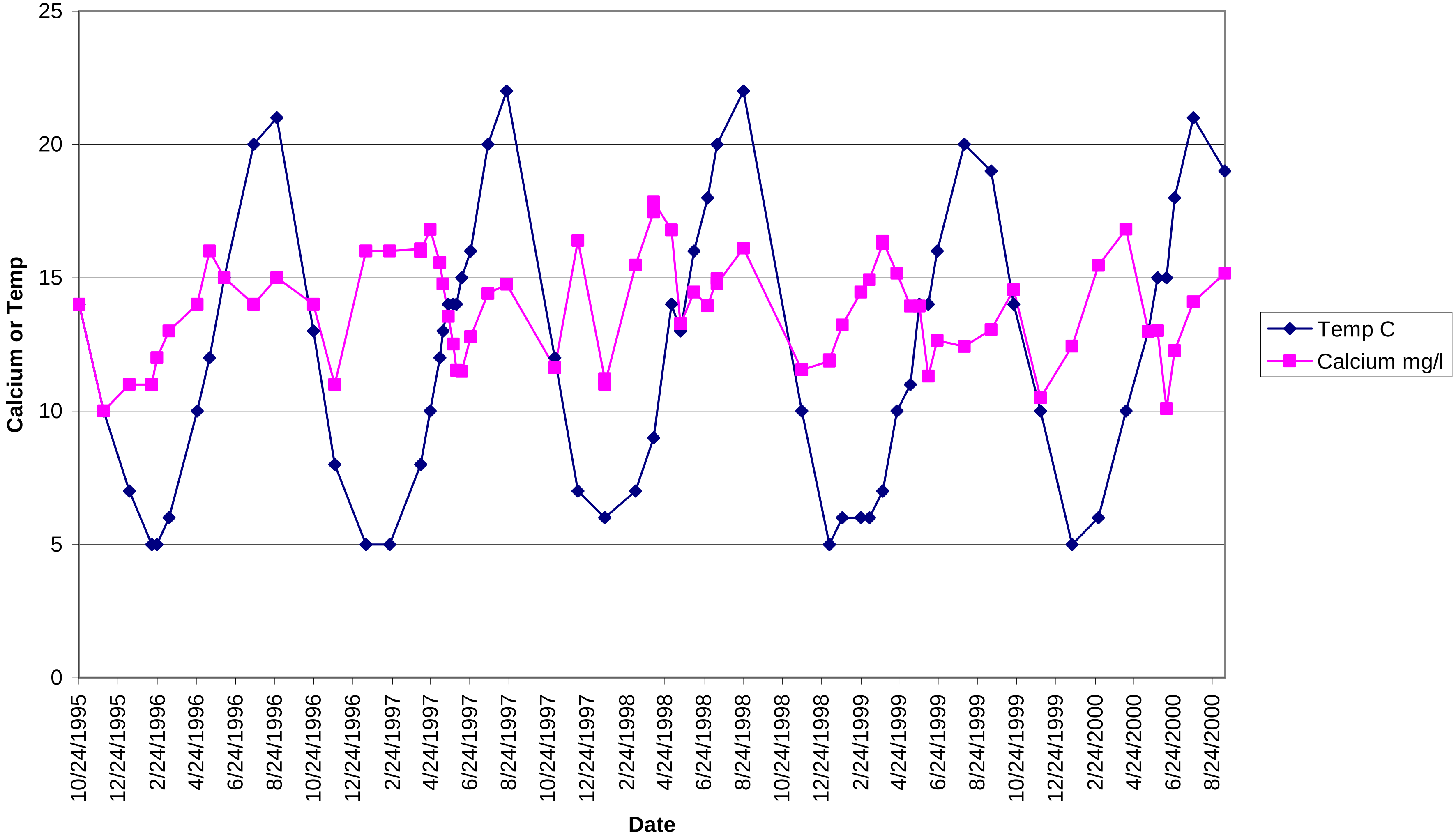


Figure 8. pH Columbia River at Quincy near Beaver Army Terminal, 1996 to 2004

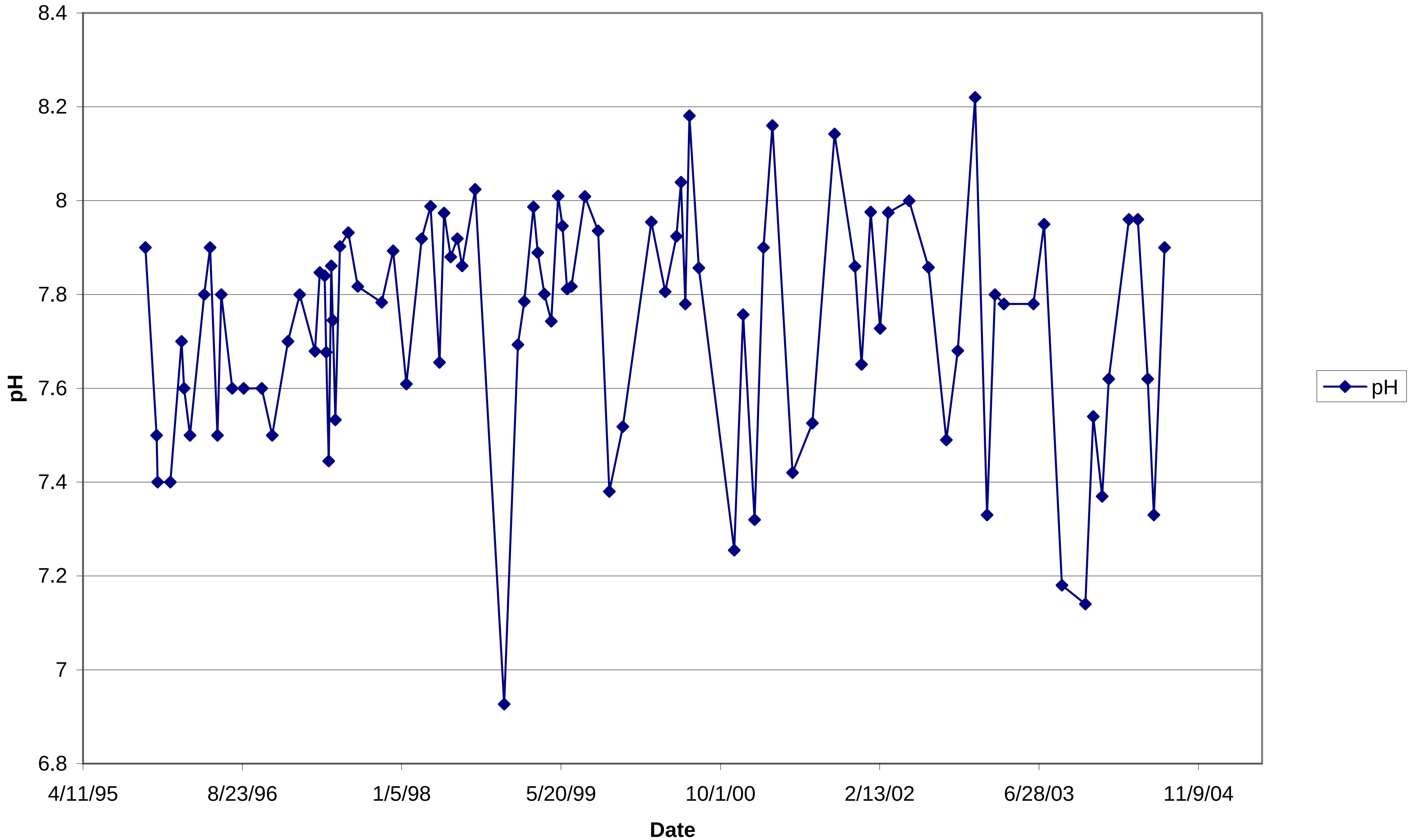


Figure 9. Calcium data by Columbia Basin subbasins, from summer grab samples, mostly on creeks and small rivers. Numbers show median calcium mg/l. Collected by USEPA EMAP Survey. From Whittier (2010)

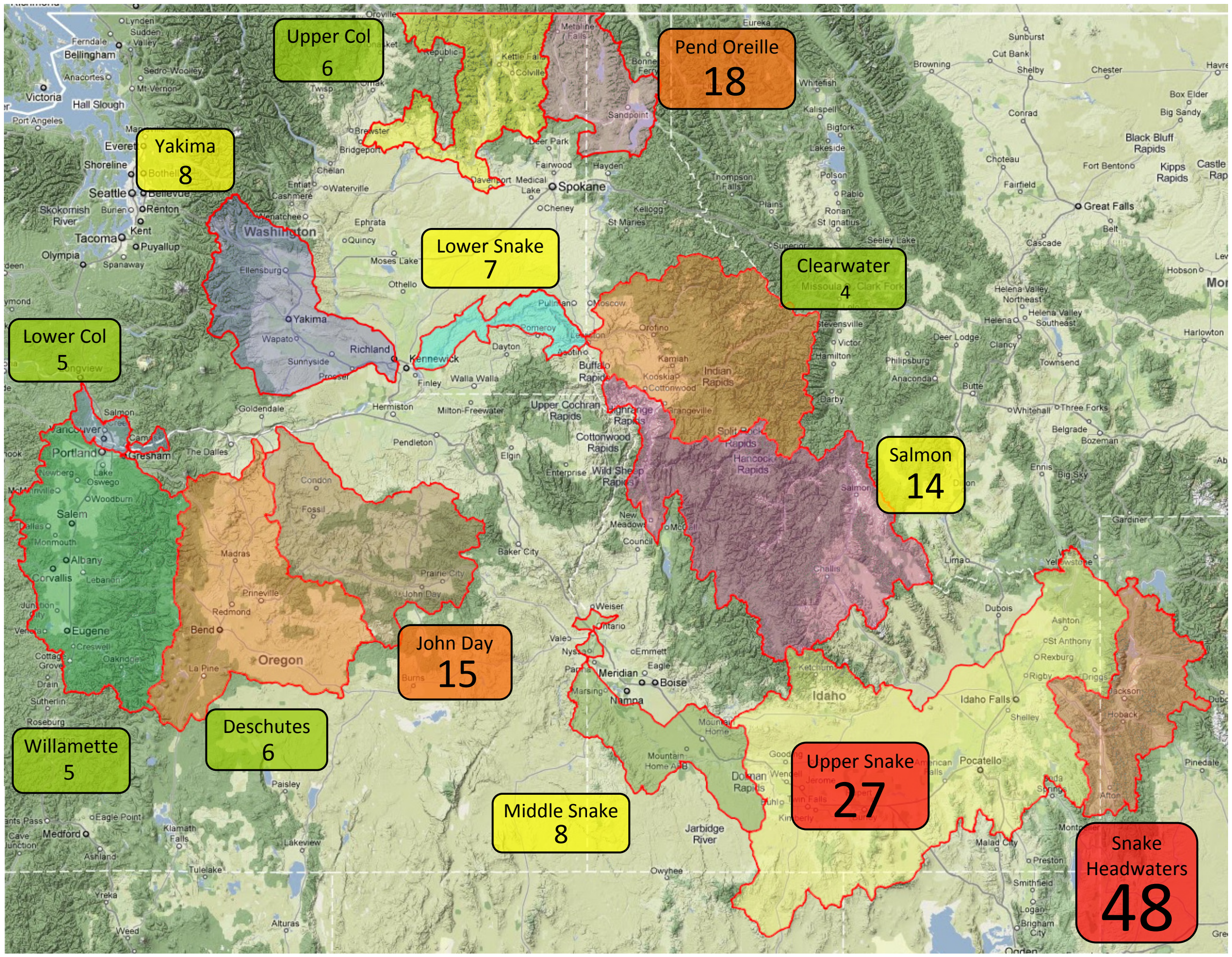
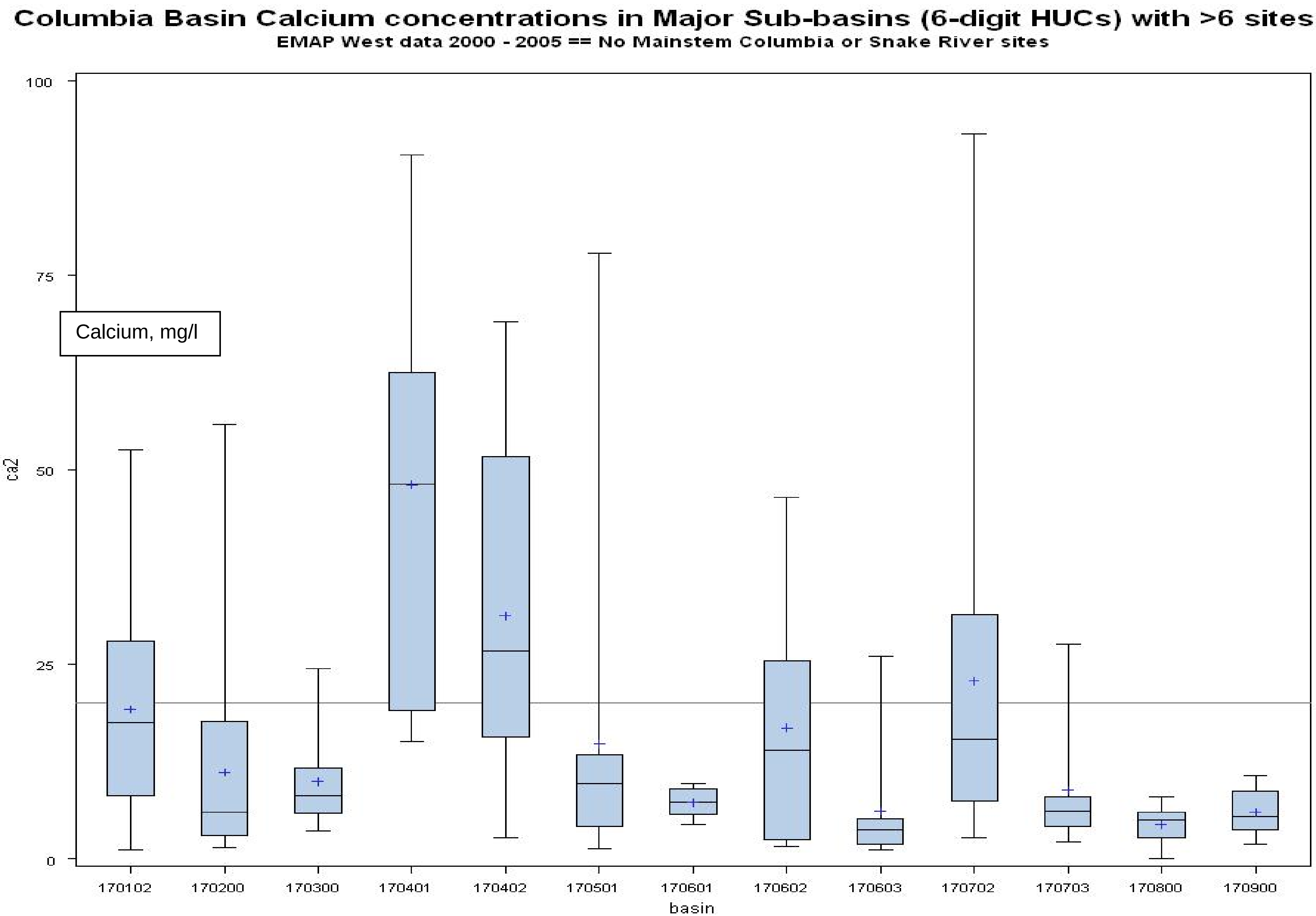


Figure 10. Data Collected by USEPA EMAP Survey



Pend Or/Upper CO/Yakima/Snake H./U. Snake/M. Snake/L. Snake/Salmon/Clearwater/John D./Deschutes/Lower C/Willamette

Figure 11. Schematic of Fish Bypass System at McNary Dam