Potential Economic Impact of Zebra and Quagga Mussels in B.C.

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Ministry of
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EXECUTIVE SUMMARY

Zebra and quagga mussels (ZQM) are aquatic invasive species responsible for hundreds of millions of dollars in economic damage annually in North America. Since their introduction in the 1980s to the Great Lakes, ZQM have been found in over 24 American states as well as Ontario, Quebec, and Manitoba. To date, ZQM have been prevented from establishing in the Pacific Northwest, however, favourable habitat conditions in B.C.'s freshwater systems make them a significant economic risk. ZQM pose significant economic risks due to their impacts on infrastructure and waterbodies. A previous 2013 study[1] estimated the costs of a ZQM invasion in B.C. would be $53.4 million annually (Table 1).[2] This study provides an update to the 2013 estimates based on updated information on costs and risk of establishment.

Most of B.C.'s infrastructure, equipment, and activities for sectors that are vulnerable to ZQM are located in waterbodies at moderate to high-risk of ZQM invasion, including:

- 60% of hydro facilities representing 80% of hydro-generation capacity
- 93% of irrigation infrastructure
- 63% of municipal treatment facilities
- 89% of self-supplied domestic water systems; and
- 85% of the recreational fish catch.

Updated annual cost estimates range from $64 to $129 million including (Table 1):

- $33.7 – $92.5 million in mitigation costs for water-related infrastructure; including $17.1 – $23.3 million for hydro infrastructure; $8.0 – $49.7 million for water supply infrastructure for municipal, domestic and aquaculture; and $2.5 – $5.3 million for agricultural irrigation and golf courses
- $3.7 – $8.1 million in additional annual maintenance to boats and marinas
- $2.5 – $12.6 million in lost profits and provincial revenues from losses in water-based non-resident tourism; and
- $30.2 million annualized loss in residential property values and property taxes due to reduced water quality and lost shoreline amenity values.

There are some key differences between this updated report and the previous 2013 document. The costs of mitigating the impacts of ZQM on infrastructure and equipment are rapidly evolving as new treatment technologies are developed. Compared to 2013, in this updated report, mitigation costs for infrastructure and equipment decreased for all sectors except hydro largely due to reductions in treatment costs. Additionally, overall cost estimates of economic impacts are higher due to the inclusion of impacts to tourism and property values which were not considered in the 2013 study. Similar to the 2013 report, the costs presented in this report do not include impacts to many of the benefits of healthy aquatic ecosystems such as impacts on fish populations. Additional costs to government associated with preventing invasive mussels from becoming established in B.C. and any increased monitoring and mitigation efforts were also not included.

Costs in this study are based on values transferred from reference regions that include the Great Lakes and other regions in North America and assume that ZQM are fully established in

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[1] Robinson, D C E, D Knowler, D Kyobe, and P de la Cueva Bueno. 2013. "Preliminary Damage Estimates for Selected Invasive Fauna in B.C." https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/invasive-species/guidance-resources/preliminary_damage_estimates_selected_invasive_fauna.pdf

[2] All dollar values in this report have been converted to 2022 CAD based on the forex annual historical exchange rate https://www.ofx.com/en-ca/forex-news/historical-exchange-rates/yearly-average-rates/ and the Statistics Canada Consumer Price Index Table 18-10-0005-01 https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1810000501.

all moderate and high-risk watersheds at similar densities to the reference regions. If introduced, it would take time for ZQM to establish and reproduce to reference study densities and **costs would increase gradually over time** to the levels presented in this report. How these costs evolve over time also depends on numerous factors such as patterns of boat traffic which determine the probability of ZQM introduction into waterbodies, and biophysical characteristics of waterbodies including temperature and calcium concentration which determine habitat suitability for ZQM and maximum density potential.

The range of costs presented in this study reflects the inherent uncertainty of transferring costs from other jurisdictions to the B.C. context. The impact of ZQM on boaters, property values, and tourism depends on human behavioural responses transferred from other regions and contexts for which B.C. specific information to validate behavioural parameters is lacking. Additional expert-led scenario analysis in the context of B.C. could help narrow the range of uncertainty and better inform future management strategies for ZQM for high value and vulnerable sectors. Further research is also recommended to better understand the impacts of ZQM on recreational, cultural, traditional, and other non-market values related to healthy aquatic ecosystems in B.C.

TABLE 1. Annual cost of ZQM damages in moderate and high-risk waterbodies by sector

Cost Type	Sector	Current study ($M)	2013 study ($M)
ZQM treatment cost	Agricultural irrigation	2.5 – 5.2	18.4
	Golf courses	<0.1	<0.1
	Municipal/local provider water supply	2.2 – 15.6	11.4
	Domestic self-supplied	5.1 – 27.9	---
	Aquaculture	0.7 – 6.2	---
	Hydropower	17.1 – 23.3	8.1
	Boating & marinas	3.7 – 8.1	15.4
Reduced economic activity	Tourism	2.5 – 12.6	---
	Recreational fishing	Qualitative	---
Reduced water quality	Annualized property values	24.4	---
	Municipal property taxes	5.8	---
Total cost		64 – 129.1	53.3

ACKNOWLEDGEMENTS

This report benefited from peer review from sector experts, economists, and aquatic invasive species ecologists. We would like to acknowledge and thank them for providing review and feedback on this report.

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1. INTRODUCTION

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*) (ZQM) are aquatic invasive species (AIS) that cause hundreds of millions of dollars in economic damage annually in North America. ZQM were introduced to the Great Lakes region in the 1980s by transcontinental shipping. Since then, ZQM have been found in over 24 American states as well as the Provinces of Ontario, Quebec, and Manitoba. Favourable freshwater habitat conditions make ZQM a significant economic risk in B.C.

ZQM are introduced to water bodies through the overland transport of watercraft and equipment. Newly settled mussels are difficult to detect as they are only a few millimetres in size and can survive for several weeks in cool moist environments without being immersed in water (e.g. ZQM that are attached to boats or equipment can survive a trip between different bodies of water). Furthermore, their microscopic free-swimming larvae can survive for several weeks in standing water in boats or other equipment. Once established, ZQM are extremely difficult to eradicate due to their ability to reproduce rapidly and outcompete native species for habitat when they reach high densities, emphasizing the importance of early detection and containment.

Since their introduction to North America, ZQM have caused significant damage to a range of values.

- Water Use. One of the most known impacts are to hydro, irrigation, and drinking water infrastructure, including water intakes and conveyances.
- Boats and Marinas. ZQM also damage boats and marinas by attaching to the hulls and engines, as well as docks and buoys.
- Ecosystems and Biodiversity. The high filtration rates of ZQM remove nutrients from the water column and can have cascading impacts on the food web and fish communities.
- Threaten at-risk species. ZQM can outcompete native species for habitat and food and have been responsible for the extirpation of native freshwater mussels in the Great Lakes (Ricciardi et al. 1998). In B.C. ZQM have been identified as a threat to the Rocky Mountain Ridged Mussel (COSEWIC, 2010). ZQM also pose significant risks to endangered Sockeye Salmon, endangered Chinook Salmon, and endangered Shortface Lanx. Potential direct impacts to these species at risk include competition for, and alteration of, habitat and food sources and abiotic factors leading to population declines.
- Fishing Opportunities. Food web interactions can reduce recreational and commercial fishing opportunities for some species. In the Great Lakes, ZQM have been associated with decreased growth rates and conditions for native whitefish and salmonids (Vanderploeg et al. 2002; Strayer 2009; Karatayev et al. 2015).
- Recreation, Tourism and Property Values. High filtration rates are also associated with increased water clarity and light penetration, leading to the proliferation of aquatic plants and algae, toxic algal blooms and rotting plant material on beaches (Karatayev et al. 2015). In the near shore, accumulated waste excreted by ZQM contributes to excess nutrients, increased turbidity, and the development of muddy substrate, reducing water quality and causing shell build-up on shorelines and beaches.

The impacts of zebra and quagga mussels were combined for this study, however future analysis could benefit from differentiating between the two species. Species-specific habitat requirements (e.g., substrate type, depth, and temperature) affect the geographic distribution and maximum population density for each species resulting in different ecological and economic impacts. For example, zebra mussels require hard substrate and warmer temperatures than quagga mussels and can colonize to densities of over 700,000 individuals per m^2 on hard surfaces including physical infrastructure, rocks, plants, and other bivalves such as native mussels.[3] Quagga mussels, which survive at greater depths and can attach to either hard or soft substrates, are more widely distributed on lake bottoms (Karatayev et al. 2015). ZQM densities peak three to ten years after introduction depending on lake morphology and type of mussel. In shallow lakes with zebra mussels alone, maximum abundance and impacts occur three to five years after the invasion; in shallow lakes with both species, maximum impacts occur between five and ten years with quagga mussels eventually out-competing zebra mussels in deep lakes (Karatayev et al. 2015).

1.1 Valuation Approach

Cost estimates are based on changes in societal well-being due to the impacts of ZQM on infrastructure and the health of aquatic ecosystems. Costs include additional expenditures by households and businesses to mitigate the impact of ZQM on water-based infrastructure and equipment, as well as losses in non-market values associated with recreational, cultural, aesthetic, and other benefits derived from healthy aquatic ecosystems.

Non-market values are estimated from expenditures associated with linked market goods and services. For example, the value of water-based recreation can be estimated from time costs and other expenditures associated with trips to lakes. Similarly, aesthetic and recreation benefits from beaches and lakes can be estimated from price premiums for waterfront properties.

The costs considered in this study include:

- Increased costs associated with mitigating the effects of mussels on water supply infrastructure and equipment,
- Reduced property values and municipal taxes due to reduced water quality, and
- Losses in business operating surplus (profits) and tax revenues due to reduced international demand for water-based recreation and tourism.

An insufficient understanding of the impacts of ZQM on specific sport fish species at the provincial scale made it infeasible to assess costs of ZQM to freshwater recreational fishing. Instead, the potential exposure of the freshwater recreational fish catch to ZQM in moderate and high risk sub-watersheds is presented.

Since ZQM are not established in B.C., costs were transferred from other locations that have experienced damages from ZQM or other AIS. Cost estimates were identified by literature review and applied to the B.C. context. Data for each sector were mapped to sub-watersheds at moderate- and high-risk of ZQM establishment (Figure 1). The validity of the cost-transfer approach depends on the similarity of context between the original study sites from which benefits are transferred to the B.C. context in terms of demographic and socio-economic characteristics, size, location, quality of waterbodies, and severity of the ecological impact. ZQM densities in B.C. are assumed to be similar to densities found in the Great Lakes and other jurisdictions from which costs are transferred. However, densities of ZQM may be lower for some waterbodies in B.C. (e.g., Claudi and Prescott 2014). At the same time, the costs of ZQM to waterbodies that are already degraded, for example by other AIS, will be less than the costs of ZQM to pristine waterbodies.

[3] https://www.dfo-mpo.gc.ca/species-especes/profiles-profils/zebramussel-moulezebree-eng.html

1.2 Risk of Establishment

The risk of ZQM invasion is typically based on a combination of the risk of introduction and the risk of establishment.

Risk of introduction is driven by human behaviour and the overland transport of mussel-fouled watercraft from infested waterbodies. The risk of establishment is based on chemical and physical attributes of the waterbody that make it suitable for mussel survival and establishment. Calcium concentration is considered the most critical environmental variable for ZQM survival and establishment and is used as the primary parameter to delineate risk categories for ZQM infestation (Neary and Leach 1991; Cohen and Weinstein 1998; Whittier et al. 2008; Wells et al. 2011; Claudi and Prescott 2011; Therriault et al. 2013). Minimum dissolved calcium levels are required in a waterbody to support ZQM shell growth and mean minimum summer temperatures are required to support ZQM reproduction (Stanczykowska 1977; Baker et al. 1993; Sprung 1993; McMahon 1996; Nichols 1996).

A national ZQM risk assessment conducted by Fisheries and Oceans Canada found the majority of the Province to be at moderate or high risk for ZQM invasion based on available calcium and air temperature data (Therriault et al. 2013). The South and Central Interior and Kootenays regions of the province were found to be at high risk of ZQM invasion, while Vancouver Island and the Central and Southern Coast regions of B.C. were found to be at low risk. The remaining parts of the province, including north-eastern B.C. and the North Coast/Nechako regions, were found to be at moderate risk. The DFO risk assessment was conducted at a broad regional scale, by sub-basin, and provides insufficient resolution to isolate higher risk water bodies and infrastructure given population and income growth, accompanying changes in human use, data availability, and the spread of mussels in other provinces and states since 2012. The DFO national ZQM risk assessment (Therriault et al. 2013) was used in the previous 2013 study (Robinson et al. 2013) to assess costs in sub-basins considered highly suitable for ZQM establishment.

An updated higher resolution assessment of the risk of ZQM establishment in B.C. was conducted as part of this study at the sub-watershed scale[4] for 246 sub-watersheds, including lakes (386,018), rivers (37,083), and constructed waterbodies (1,813). The risk of establishment was assessed as high, moderate, and low using calcium data with temperature as a lower bound limiting factor; pH was also assessed but excluded from the analysis due to insufficient data coverage. Total and dissolved calcium data from the B.C. Environmental Monitoring System (EMS) were averaged at the site, waterbody, and sub-watershed scale.[5] Risk categories were assigned based on calcium ranges taken from the literature (Garton et al. 2013) (<8mg/L = low, 8-20mg/L = moderate, and >20mg/L = high) and then applied to the 246 sub-watersheds. Projected air temperature data for 2021-2040 from the WorldClim Global Climate Model MRI-ESM2 were used to assess lower bound water temperature limits for mussel reproduction.[6] Water temperature of 14°C is considered the minimum temperature required for ZQM spawning. Accurate water temperature data for the ZQM spawning period was not available. Based on the rationale that lower temperatures could be a limiting factor for reproduction, average air temperature below 10°C during the warmest quarter of the year was used as a conservative lower bound cutoff. Any sub-watershed with an average below 10°C had its risk category reduced by one level.

[4] Watershed scale was selected by using BC's closest match to the United States Hydrographic Units at the 6- and 8-digit scale. Each sub-watershed varies in size, with the range of areas measuring 0.6 million to 36.9 million hectares.
[5] Post-spatial filtering yielded 59,324 calcium values (27,065 total Ca and 32,259 dissolved Ca) across 246 sub-watersheds.
[6] The GCM model was selected based on sensitivity and accuracy. Both 245 and 370 Shared Socio-economic Pathways (SSP) scenarios were analysed and resulted in the same risk moderate- and high-risk polygons.

Calcium data were available for 180 of the 246 sub-watersheds, and the resulting risk of ZQM establishment for these 180 sub-watersheds is illustrated in Figure 1. Of these sub-watersheds, 68 were classified as high risk, 69 as moderate risk, and 43 as low risk. Insufficient data were available to classify 66 sub-watersheds. ZQM have different calcium tolerances. In North America, the minimum level of calcium required for adult zebra mussel survival is estimated to be between 8-9 mg/L; therefore, low-risk sub-watersheds (< 8mg/L) were not included in the cost analysis (Mackie and Claudi 2009). When calcium levels are >12mg/L, zebra mussels have a moderate risk of survival, while quagga mussels have a high risk of survival (Therriault et al. 2013). To capture both species' calcium tolerances, both moderate- and high-risk sub-watersheds in B.C. were included in the cost analysis.[7]

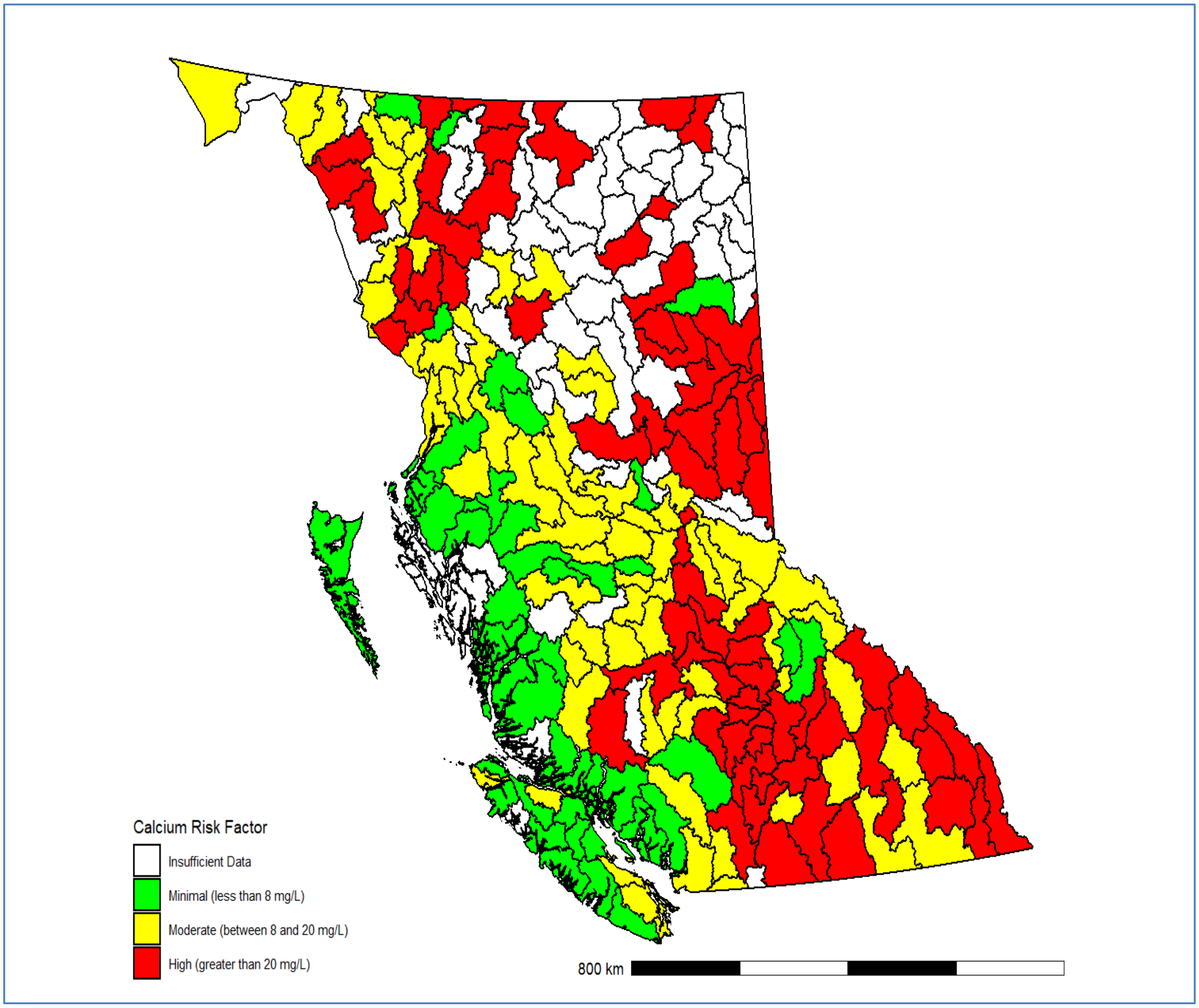

FIGURE 1. Risk of ZQM establishment in B.C. based on calcium concentrations (mg/L) and corrected for temperature by sub-watershed.

[7] The 66 sub-watersheds with insufficient data are in remote locations account for less than 1% of recreational boats and freshwater angling, and property values but include the Bennet Dam and Gordon M. Shrum hydropower facility, which accounts 15% of the province's hydro generation capacity.

Figure 1 is based on the risk of ZQM establishment and does not include the risk of introduction. By not including the risk of introduction, the analysis assumes conditions for establishment are the primary limiting factor and introduction is non-limiting. This assumption potentially overestimates the distribution and impact of ZQM in areas with limited human access. Recognizing the limitations of this approach, specific invasion scenarios at the provincial scale were beyond the scope of this analysis. Future studies would benefit from including the risk of introduction and assessing risk at a more regional or waterbody-specific scale to enable a more accurate assessment of risk of invasion.

2. ANALYSIS & RESULTS

2.1 Water Supply Infrastructure

Water supply infrastructure includes public and private systems that supply water for municipal, domestic, agricultural irrigation, golf courses, and other uses. Data from the B.C. Water Rights Licences (WRL) database which provides information on licenced withdrawals for surface and groundwater by type of use was used to identify vulnerable water supply infrastructure.[8] Data on local service providers for municipal and irrigation water supply were obtained from the Environmental Operators Certification Program including supply capacity, population served, and annual withdrawals for municipal and irrigation uses (Office of the Provincial Health Officer 2019).

2.1.1 Agricultural Irrigation and Golf Courses

Irrigation and stock watering infrastructure, including pumps, pipelines, sprinklers and emitters, gated pipes, and syphon tubes, are vulnerable to ZQM (Nelson 2019).[9] Chemical treatment options include chlorination, potassium chloride (potash), copper based aquatic herbicides (e.g., Natrix™), and molluscicides (Zequanox™) (Nelson 2019). Health Canada's Pesticide Management Regulatory Agency recently approved the registration of potash for use in Canada to control ZQM in open waters and authorized the use of chlorine for ZQM control in closed systems.[10] Chlorination is a low-cost, effective treatment for large systems (Nelson 2019). However, chlorination results in carcinogenic disinfection by-products, therefore additional costs for dechlorination prior to discharge may make newer chemical treatments such as potash more cost effective (Paterson et al. 2018). While potassium compounds are harmless to fish, they are toxic to other species, such as native bivalves, and their application outside of closed-loop systems must be carefully assessed. Physical treatment options include desiccation and mechanical cleaning (Paterson et al. 2018). Desiccation involves killing ZQM by periodically circulating hot or freezing air through drained irrigation pipes. Oxygen-scavenging chemicals may also be added in closed systems to hasten ZQM mortality. Cost factors influencing physical treatment costs include the temperature tolerance of ZQM, pipeline length and diameter, and regulatory requirements for water discharge temperature. Mechanical cleaning includes scraping and pigging mussels in large diameter pipelines, as well as the use of divers for hydro-blasting and underwater cleaning. Antifoul paint may also be applied to the outside of pipes.

Irrigation costs in this report are based on Coachella Valley Water District surcharges levied for chlorination treatment and range from $0.0033 to $0.0068 per m^3 of water used (Nelson, 2019). Table 2 shows there are 14,269 agricultural irrigation licences representing 93% of total irrigation licenses in moderate- and high-risk sub-watersheds. Of these, 439 licenses are for local provider irrigation, 13,790 are for private provider irrigation, and 40 are for greenhouses. A further 728 licences were identified for golf courses. Treatment costs are assumed to be based on actual water use, which is usually less than licenced withdrawal in a given year. The 2019 Government of B.C. Water Revenue Report shows the ratio of actual use to licenced withdrawals for local provider

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[8] Water Rights Licences: https://catalogue.data.gov.bc.ca/dataset/water-rights-licences-public.

[9] Damage to irrigation infrastructure could disrupt agricultural operations and reduce agricultural output. Because there is little empirical evidence of the potential magnitude of this impact it was not included in the analysis.

[10] Chlorine is currently being applied in closed systems in the Great Lakes Basin through a registration exemption with chlorine discharge controlled by individual facility permits. In 2022 potash was approved by Health Canada for the use in open water systems across western Canada to control for zebra and quagga mussels..

irrigation is 52%. This ratio was applied across all irrigation and golf course licences to determine actual water use (Table 2).[11]

TABLE 2. Annual cost of ZQM for agricultural irrigation and golf courses at risk in moderate- and high-risk sub-watersheds

Purpose use	Number of licences (% of total)	Annual licensed use (m^3)	Total cost lower bound ($0.0033/m^3$) ($)	Total cost upper bound ($0.0068/m^3$) ($)	Cost per license ($)
Private irrigation	13,790 (93.0%)	485,314,924	1,601,539	3,300,141	116 – 239
Local provider irrigation	439 (99.5%)	274,439,445	905,650	1,866,188	2,063 – 4,251
Greenhouse irrigation	78 (88.6%)	713,858	2,356	4,854	30 –62
Total irrigation	14,307 (93.2%)	760,468,277	2,509,545	5,171,184	175 – 361
Golf courses	728 (93.2%)	10,224,479	33,741	69,526	46 – 96

2.1.2 Water treatment facilities

Treatment options for municipal water treatment facilities include the application of chlorine, potassium permanganate, ozone, and ultraviolet (UV) light for pre-treatment and disinfection of drinking water. These same treatments are used to address ZQM. Treatment options for ZQM involve altering chemical applications in treatment facilities and capital improvements to retrofit or move chemical injection systems to water supply intake structures. There is no one size fits all mitigation strategy for water treatment facilities as each facility is unique in its characteristics; however, size is an important cost determinant due to the impact of fixed costs on smaller facilities.

Overall, about 63% of local provider municipal water supply infrastructure is in moderate- and high-risk watersheds. Annual supply costs for municipal treatment facilities are based on capital and operating costs for ten drinking water facilities surveyed in Canada and the United States and reported in Chakraborti et al. (2016).[12] Data for water treatment facility capacity and water use in B.C. were obtained from the Environmental Operators Certification Program (Office of the Provincial Health Officer 2019). In 2019, the data included 262 facilities with treatment capacities ranging from 400–2.3 million m^3/d. Of these, 179 are in moderate- and high-risk sub-watersheds (Table 3). Of the 179 facilities in moderate and high-risk sub-watersheds, 164 (92%) diverted water from surface water or a combination of surface and groundwater sources and were included in the analysis due to the risk that ZQM pose to surface water. Following Park and Hushak (1999), the 164 treatment facilities were categorized as small (<3,800 m^3/day), medium (3,800–38,000 m^3/day), and large (> 38,000 m^3/day) (Table 3).[13]

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[11] According to the 2019 Government of BC Water Revenue Report, 346,451,978 m^3 was licenced for irrigation from surface and groundwater sources by local providers, of which 52% was actually used.

[12] Operating costs, including costs of chemical inputs such as chlorine and potassium permanganate as well as for power, pumping and miscellaneous maintenance, were added to annualized capital costs to get a total annual ZQM treatment cost per facility. Capital costs, including costs to upgrade or retrofit treatment facilities, were amortized over 15 years at a 6% discount rate to get an annualized cost which was then added to operating costs (Chakraborti et al. 2016).

[13] Information on treatment capacity was not available for 91 facilities. These facilities were assumed to have the same size distribution as the known facilities and assigned to capacity categories accordingly.

Benchmark costs for each size category were matched to similar sized facilities reported by Chakraborti et al. (2016). The benchmark unit cost for small facilities ($0.0264 /m^3) is based on potassium permanganate treatment for a plant with 3,785 m^3/day capacity withdrawing from a small lake in the Great Lakes region.[14] For medium-sized facilities, lower bound costs were based on chlorine treatment for a plant with 68,137 m^3/day capacity in Lake Erie, and upper bound costs were based on copper ionized treatment for a plant with 24,605 m^3/day capacity on a reservoir in Kansas with a long 32km intake pipe. For large facilities, lower bound costs were based on physical cleaning for a 624,591m^3/day plant in central Lake Erie where mussel densities are relatively low, and upper bound costs were based on chlorine treatment for a plant with 10 million m^3/day capacity on a reservoir storage and distribution system in southern California.

TABLE 3. Annual cost of ZQM for local provider water treatment facilities at risk in moderate- and high-risk sub-watersheds by facility capacity

Facility capacity	Facilities (% of total)	Average capacity (m^3/day)	Mitigation cost ($/m^3/day)	Total cost lower bound ($)	Total cost upper bound ($)	Cost per facility ($)
Small	86 (61%)	1,124	0.0264	931,454	931,454	10,831
Medium	60 (66%)	12,376	0.0026 – 0.0241	704,689	6,531,929	11,745 – 108,865
Large	18 (62%)	264,412	0.0003-0.0047	521,156	8,164,778	28,953 – 453,599
Total	164			2,157,299	15,628,161	

2.1.3 Domestic self-supply and aquaculture

The domestic self-supply sector consists of households diverting water for their own domestic use. Domestic self-supply systems typically include a submerged water intake and an onshore pump and distribution system. Treatment options for domestic self-supply include in-line filtration for pumps to block veligers as well as in-line chlorine injection. While in-line filtration systems must be changed every six months, chlorine injection systems kill ZQM veligers and also address the lingering taste and odour problems caused by ZQM. Costs range from $0.5221/m^3 for in-line filtration to $2.8530/m^3 for chlorine injection based on average household consumption rates in Montana (Nelson, 2019).

Aquaculture includes water supply for freshwater fish hatcheries and aquaculture facilities. Due to a lack of information on treatment costs for aquaculture facilities, it was assumed that treatment costs would be the same as those for municipal water supply reported by Nelson (2019) ($.0044/m^3 – $.0408/m^3).[15] Data for domestic self-supply and aquaculture licenses in B.C. were obtained from the WRL database (Table 4). Actual annual withdrawals are typically less than the total amount licensed for withdrawal. Actual withdrawals were assumed to be 42.4% of licensed withdrawals based on the percent of actual to licensed withdrawals reported for local provider water treatment facilities in the 2019 Government of B.C. Water Revenue Report.

[14] Potassium Permanganate is currently under consideration but not approved for use in Canada.
[15] Note that municipal water supply costs in this study are calculated on a per-facility basis and could not be directly carried over to aquaculture licenced use. Therefore Nelson (2019) costs per m^3 for water treatment facilities were applied.

TABLE 4. Annual cost of ZQM for domestic self-supply and aquaculture infrastructure at risk in moderate- and high-risk sub-watersheds by treatment method.

Sector	Licences (% of total)	Annual withdrawal (m^3)	Unit cost ($\$/m^3$)	Total cost ($)	Cost per licence ($)
Domestic self-supply (in-line filter)	21,495 (89%)	9,776,731	0.5221	5,104,431	237
Domestic self-supply (chlorine injection)	21,495 (89%)	9,776,731	2.8530	27,893,014	1,298
Aquaculture	194 (72%)	152,432,779	0.0044 – 0.0408	670,704 – 6,219,257	3,457 – 32,058

2.2 Hydro Infrastructure

Hydroelectric power is the primary source of power in B.C. and comes from a mix of public and private utilities, independent power producers (IPPs), and industrial and residential self-generators. Previous studies have shown that hydro infrastructure is vulnerable to ZQM establishment. The most vulnerable components of hydro facilities are intakes and penstocks; gates and valves; water systems for cooling and domestic water; and pumps, turbines, and generators. Treatment costs vary significantly by facility and are based on various factors, including ZQM rate of reproduction and density, facility location, operating conditions, and design.

Hydro facility data and information on costs were obtained from Ontario Power Generation (OPG), Manitoba Hydro, BC Hydro, FortisBC Inc., and Columbia Power Corp. There are two provincial Crown corporations (BC Hydro and Columbia Power Corporation), one regionally focused Crown corporation (Columbia Basin Trust), two private utilities (FortisBC Inc. and Nelson Hydro), and 124 IPPs with hydro generating capacity. Table 5 shows the facilities and MW capacity owned by various operators as well as the percentage of provincial facilities and MW capacity in moderate- and high-risk sub-watersheds for each operator. Overall, 60% of hydro facilities and 79% of power-producing capacity is in are situated in moderate- and high-risk sub-watersheds.

TABLE 5. Hydropower facilities and generation capacity at risk in moderate- and high-risk sub-watersheds

Hydropower provider	Facilities (% of total)	Capacity (MW) (% of total)
BC Hydro	17 (54.8%)	10,987 (84.5%)
IPPs	46 (57.5%)	1,674 (51.6%)
FortisBC	4 (100%)	223 (100%)
Columbia Power Corporation and Columbia Basin Trust	4 (100%)	780 (100%)
Total	71 (59.7%)	13,664 (79.4%)

Chlorine injection and UV light systems have been shown to be effective at controlling ZQM infestations at hydro facilities. Costs for these systems include capital costs for installation as well as ongoing annual operating costs. Facilities where ZQM are detected also face increased maintenance costs that are not preventable such as increased cleaning of sills, strainers, and inlets.

Infested facilities also face additional monitoring costs, including the installation, use and monitoring of bio-boxes. Robinson et al. (2013) assumed that facilities would use sodium hypochlorite (NaOCl) control systems and apply antifouling paint on trash racks. Antifouling paint was used in several instances by OPG for ZQM prevention. However, it was found to be expensive and ineffective. Nelson (2019) includes shutdown costs for additional maintenance, however Canadian facilities have reported that shutdown time for installation of ZQM treatment systems and additional maintenance can be accommodated within existing facility maintenance shutdown schedules, resulting in no additional costs from power outages (Pucherelli et al. 2020).

Pucherelli et al. (2020) provide costs for ZQM prevention and mitigation measures including ZQM-related outages and additional monitoring, for thirteen hydropower facilities in Canada and the United States where ZQM have been detected. Costs vary significantly between facilities, with three facilities (all in the U.S. South) reporting significant cost impacts, seven reporting moderate impacts, and three (including two in Canada) experiencing little to no impact. Overall, ZQM population growth rates, growth cycles and total population were significant factors influencing cost, while the size and number of generating units were not.

Cost data from Pucherelli et al. (2020) as well as expert information provided OPG and Manitoba Hydro were used to derive hydro annual average facility treatment costs by cost component (Table 6).[16] Costs for NaOCl systems (including installation and operating costs) as well as monitoring and maintenance costs are based on averaging costs across several Canadian facilities, including Beauharnois in Quebec; the Sir Adam Beck #1 and #2, and DeCew Pump Generating Stations in Ontario; Jenpeg in Manitoba; and mobile systems in both Ontario and Manitoba. Installation and operating costs for UV light systems are based on Hoover Dam in Nevada, Parker Dam in Arizona, and Gavins Point Dam in Nebraska. Costs to specific facilities in B.C. will further depend on the facility's remoteness and proximity to material and service providers, as well as on mussel populations which depend on conditions in specific waterbodies. Colder winters appear to limit the growth of ZQM at Canadian facilities (Pucherelli et al. 2020). Claudi and Prescott (2014) found that conditions in Upper Arrow Lake would support only low to moderate zebra mussel populations upstream of the Hugh Keenleyside Dam and Generating Station, even though those facilities are in sub-watersheds categorized as high-risk.

Total annual costs for B.C. hydro facilities are derived using both a per facility and per MW cost approach for NaOCl and UV systems (Table 6). Annual ZQM mitigation costs range from $17.0 – $23.3 million using the cost per facility method and $8.8 – $18.9 million using the cost per MW method. While the facility-based method results in higher annual costs, these costs are likely more accurate as the capital costs of installing treatment systems at each facility have been shown to vary less than the production capacities of different facilities. Because the cost per MW approach underestimates costs to smaller producers, facility-based costs were used in the summary tables.

[16] Costs were converted to 2022 CAD using the Statistics Canada Industrial Product Price Index for machinery and equipment. Following Robinson et al. (2013) capital costs were annualized assuming a discount rate of 3.5% and a capital lifespan of 20 years.

TABLE 6. Average annual hydropower facility costs by component

Component	Cost per facility ($)	Cost per MW ($)
NaOCl system (capital and operating costs)	149,788	309
UV system (capital and operating costs)	239,226	1,042
Maintenance	72,602	303
Monitoring	16,787	35
Total Cost	n=71	n= 13,664
Low-cost NaOCl system	16,987,836	8,840,167
High-cost UV system	23,338,018	18,862,014

2.3 Recreational Boating and Marina Infrastructure

ZQM attach to boat hulls, engines, and other interior components of watercraft, leading to reduced fuel efficiency and, in some cases, make boats inoperable. Juvenile mussels can be drawn into engines and internal cooling systems, leading to expensive repairs and replacements of critical components. Boat owners can mitigate ZQM by storing their vessels out of water, drying hulls regularly, and performing additional maintenance. Previous studies have found costs to boat owners to be among the top three sources of damage costs from ZQM (e.g., Independent Economic Analysis Board (IEAB) 2010; Robinson et al. 2013; Nelson 2019).

Boat owners can avoid damages from ZQM by storing boats out of the water. A 1991 survey of 109 boat owners in Ohio (Vilaplana and Hushak 1994) found 20% of boat owners experienced costs of $273 annually due to ZQM including costs from direct damages to hulls and engines, application of protective paint, additional maintenance, and increased insurance rates. A more recent study for Lake Tahoe by USACE (2009) assumed annual costs to boaters from AIS (including zebra mussels) would include two hours of boat maintenance and repair per year for boats moored year-round resulting in costs ranging from $303-$604 per boat.

In B.C. private boats are either registered or licenced. Data on registered vessels in B.C. was obtained from Transport Canada including postal codes for authorized representatives. As of November 2020, there were 17,633 vessels registered in freshwater postal codes of which 9,227 (52%) were associated with postal codes in moderate- and high-risk sub-watersheds.[17] According to Transport Canada there were also 365,221 active Pleasure Craft Licences in B.C. of which 30% were assumed to be in freshwater.[18] Postal codes were not available for Pleasure Craft Licenses so the percentage of pleasure craft in moderate- and high-risk sub-watersheds was assumed to be the same as the percentage for registered vessels (Table 7). It was assumed that 20% of these boats

[17] The storage location of boats and where they are used is not tracked by Transport Canada. It was assumed that the postal code where the boat was registered was the same as where the boat was stored. In general, linking postal codes to sub-watersheds was sufficient to separate boats into marine and freshwater systems. However, the Lower Fraser sub-watershed, which is moderate risk and contains a large percentage of total boats, has both marine and freshwater areas. The Lower Fraser was subdivided by municipality, with postal codes in Abbotsford, Mission, Langley, Maple Ridge and Pitt Meadows treated as freshwater.

[18] Based on Transport Canada as reported by Robinson et al. (2013).

will experience increased maintenance costs due to ZQM leading to annual costs ranging from $6.3 million to $13.8 million (Table 7).[19]

TABLE 7. Annual cost of ZQM for recreational boaters and marinas at risk in moderate- and high-risk watersheds

Type of boat	Number of boats	Cost per boat ($)	Total annual cost ($)
Registered vessels	9,227	273 – 604	3,614,629 – 7,997,202
Licenced pleasure craft	56,975		
Total boats	66,202		

ZQM attach to marina infrastructure, including docks, buoys, anchors, and chains. Costs to remove mussels from marina infrastructure are assumed to be additional to costs for boat maintenance considered above. Data on marinas located in watersheds suitable for ZQM invasion were extracted from the B.C. Crown Land Registry, which registers authorizations for marinas on shorelines. A total of 294 records for marinas were identified, of which 112 were in freshwater.[20]

Interviews with five marinas on Lake Ontario were used to determine marina mitigation costs.[21] Three marinas indicated they had no direct costs associated with ZQM. One marina reported replacing 1,220 metres of chain at a cost of $22,072 ($18.1/m) due to erosion from zebra mussel secretions and indicated that chains needed to be replaced every ten years. The marina has between 6,100 and 7,600 meters of chain for 400 slips. Assuming chain replacement is spread out evenly over a ten-year period it will cost $11,041 – $13,756 to replace 610 to 760 metres of chain per year, or $28 – $34 per slip. A second marina reported regularly removing mussels from chains due to safety concerns for handling chains when moving docks. The second marina estimated an annual mitigation cost of $2,318 for 218 slips or approximately $11 per year per slip (Table 8).

Data on the number of slips in B.C. freshwater marinas is unavailable. Based on marina information published by the Kootenay Lake Sustainable Boating Society[22] marinas located on Kootenay Lake have an average of 50 slips per marina. This average was used to benchmark the average number of slips for marinas in B.C.[23]

TABLE 8. Annual cost of ZQM for freshwater marinas

Number of freshwater marinas in B.C.	Average number of slips per marina	Cost per slip ($)	Cost per marina ($)	Total cost ($)
112	50	11 – 34	550 – 1,700	61,600 – 190,400

[19] Vilaplana and Hushak (1994) is the only primary source of information on the percentage of boaters affected by ZQM. IEAB (2010) assumed 17% of boats would be affected in the Columbia basin. Robinson et al. (2013) assumed 20% of boats would be affected.

[20] Due to data limitations it was not possible to determine which marinas were in moderate- to high-risk sub-watersheds. Because costs are low for this sector, the assumption has little impact on overall results.

[21] Marinas selected for interviews were identified through an online search.

[22] Kootenay Lake Sustainable Boating Society. https://klsb.org/marinas/

[23] The average number of slips is likely underestimated in popular lakes such as Lake Okanagan and Shuswap, where marinas can have hundreds of slips. The largest marina, the Kelowna Yacht Club, has over 1,000 slips. On the other hand, the average number of slips is likely overestimated for more remote locations.

2.4 Tourism

Freshwater lakes are a primary attraction for water-based tourism; however, few studies have quantified the potential impact of ZQM on tourism. Economic costs to the tourism sector consist of lost operating surpluses for businesses and tax revenues from reduced tourism expenditures by non-residents.[24]

Community-level data on tourist accommodation expenditures from April to September 2019 (months when most water-based tourism occurs) in moderate- and high-risk sub-watersheds were obtained from Destination BC which collects taxes on short-term tourist accommodation under the Municipal and Regional District Tax Program.[25] Destination BC also provides information on the distribution of expenditures by non-resident tourists across different expenditure categories including accommodation and food, transportation, retail and miscellaneous services. The 2019 Statistics Canada Visitor Travel Survey indicates that 2.6% of non-resident tourists participated in water-based activities such as kayaking, boating, fishing, and swimming.[26] This percentage was applied to determine non-resident tourist expenditures on water-based activities. Tourism reduction scenarios of 2% and 10% were applied based on Nelson (2019) resulting in reduced expenditures by non-resident tourists from ZQM of $6 million to $30 million (Table 9).

TABLE 9. Annual impact of ZQM on non-resident tourism expenditures in moderate- and high-risk sub-watersheds

Tourism sub-sector	Non-resident tourism expenditures ($)	Non-resident expenditures on water-based activity ($)	Reduction in non-resident tourism expenditures from ZQM ($)	
			2%	10%
Accommodation	707,121,192	18,385,151	367,703	1,838,515
Transportation and related	3,078,251,122	80,034,529	1,600,691	8,003,453
Retail	2,121,341,597	55,154,882	1,103,098	5,515,488
Recreation and related	818,561,160	21,282,590	425,652	2,128,259
Food services	3,120,516,906	81,133,440	1,622,669	8,113,344
Miscellaneous	1,683,238,441	43,764,200	875,284	4,376,420
Total	11,529,030,418	299,754,791	5,995,096	29,975,479

Impacts on tourist revenues result in net economic damages due to losses in profits or operating surpluses by businesses in B.C., as well as losses in tax revenues generated from tourism expenditures. BC Stats provides information on gross operating surplus and product taxes per dollar of tourism expenditure by category for 2016 (Table 10). These coefficients were applied to

[24] Reduced expenditures for water-based tourism by B.C. residents do not result in a net cost for the B.C. economy since it is assumed that residents will substitute water-based tourism with another tourism expenditure in the province. Similarly, while impacts to B.C. businesses and tax revenues are considered, additional welfare losses to non-resident tourists are out of scope.
[25] https://www.destinationbc.ca/what-we-do/funding-sources/mrdt/
[26] https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5261

expenditure impacts to determine total reductions in operator surplus and government revenue resulting in total economic costs to the tourism sector of $2.5 to $12.6 million.[27]

TABLE 10. Annual cost of ZQM for tourism in medium- and high-risk sub-watersheds

Tourism sub-sector	Gross operating surplus per $	Net taxes on products per $	Tourism Costs ($)	
			2%	10%
Accommodation	0.313	0.057	136,050	680,251
Transportation and related	0.426	-0.011	664,287	3,321,433
Retail	0.418	0.050	516,250	2,581,248
Recreation and related	0.337	0.051	165,153	825,764
Food Services	0.313	0.057	600,388	3,001,937
Miscellaneous	0.449	0.041	428,889	2,144,446
Total			2,511,016	12,555,080

2.5 Freshwater Fishing

The freshwater fishing sector provides important economic, social, and cultural benefits in B.C. In 2015, 353,500 anglers purchased a freshwater recreational fishing license in B.C., spending approximately $498 million and contributing $299 million towards GDP and $73 million in provincial, federal, and municipal tax revenues (Freshwater Fisheries Society of BC, 2019).[28] There is insufficient information to estimate the impacts of ZQM on the freshwater recreational fishery at the provincial scale. The impacts of ZQM on fish species depend on multiple factors including lake morphology, water chemistry, and food web interactions (Kao et al. 2018). Woodruff et al. (2021) simulated the impact of zebra mussels on fish species in Shuswap Lake and found declines in rainbow trout, lake trout, and non-anadromous kokanee salmon but little effect on anadromous sockeye salmon. The study illustrates the challenge in drawing generalizable conclusions about the impact of ZQM on individual species at the provincial scale. Furthermore, economic impacts from individual species losses are partially offset as anglers switch their fishing effort more abundant species and unaffected water bodies (Ready et al. 2018; Hunt et al. 2020; Lauber et al. 2020).

Data on fish stocks and fishing effort obtained from the 2015 Survey of Recreational Fishing in Canada (Department of Fisheries and Oceans Canada, 2019) illustrate the exposure of the recreational fishery to ZQM. Eighty-eight percent of angler days and 85% of the total catch were in moderate- and high-risk sub-watersheds (Table 11), with the majority of the catch (82%) concentrated on just 4 species: rainbow trout (56%), cutthroat trout (11%), freshwater salmon (10%), and kokanee (5%). In addition, the four main recreation species are concentrated in moderate- and high-risk sub-watersheds (91% of rainbow trout, 73% of cutthroat trout, 58% of freshwater salmon, and 98% of kokanee). The concentration of fishing effort and catch on a small

[27] B.C. Input-Output Model - Province of B.C. (gov.bc.ca)
[28] 2020, Southwick Associates. [This citation is incomplete. If unpublished, should be a footnote. If published, should be in the bibliography.]

number of species in moderate- to high-risk sub-watersheds suggests that recreational fishing in B.C. may be particularly vulnerable to ZQM.

TABLE 11. Distribution of fishing effort and species by ZQM risk category

ZQM risk	Angler days	Total catch	Rainbow trout	Cutthroat trout	Kokanee	Freshwater salmon
Moderate	40%	30%	26%	22%	42%	54%
High	48%	55%	65%	51%	56%	4%
Total	88%	85%	91%	73%	98%	58%

2.6 Water Quality and Shoreline Amenity Values

The impacts of ZQM on beaches, shorelines, and nearshore water quality may reduce the amenity value of waterfront properties. Empirical evidence suggests property values are sensitive to odour, water clarity, weed growth and eutrophication, beach closures due to bacteria and algal outbreaks, the quality of recreational fishing, and shoreline quality (Horsch and Lewis 2009; Nicholls and Crompton 2018). Impacts of ZQM on water quality include increased nearshore plant and algal growth (Nelson 2019; Vanderploeg et al. 2001). Residents of Lake Winnipeg have reported odours from rotting shells that periodically wash up on the shores as well as negative impacts from sharp shells which cover piers and beaches and pose a risk to people and animals.

Only a few studies have examined the impact of ZQM on property values in North America with mixed results. Some studies find a positive relationship or no relationship between the presence of ZQM and property values (Johnson and Meder 2013; McGrew 2013; Tolkinnen 2020). In some cases, improvements in water clarity and increases in recreational fish species that benefit from ZQM may offset other negative impacts of ZQM on property values (Limburg et al. 2010). However, property value estimation is fraught with challenges with the validity of estimates depending on a number of factors including the extent of the market analysed, the availability of substitute waterfront properties, and regional real estate market drivers (Zhang et al. 2019). Lakes with higher recreational value are also likely to have a higher probability of ZQM introduction (Horsch and Lewis 2009). Impacts to property values from ZQM are dependent on the effects of other pollutants and AIS on water quality which are correlated with higher populations and market prices (Johnson and Meder 2013). Waterbodies with high levels of water quality and clarity may be relatively insensitive to improved water clarity but will have higher sensitivity to degradation (Nelson 2019). Overall, just 27% of lakes in B.C.'s interior regions have eutrophic status and it is assumed that most lakes will be sensitive to reduced quality and nearshore eutrophication.[29]

The total willingness to pay for waterfront property includes the direct cost of the waterfront property as well as the additional municipal tax burden associated with higher waterfront property values. BC Assessment (BCA 2019) provides data on attributes for all residential property parcel characteristics for 270 municipal jurisdictions and 19 regional assessment areas, including land class codes that identify whether the property is classified as waterfront, riverfront, or bordering waterfront for assessment purposes. Data for 11 interior assessment areas, which roughly overlay moderate- and high-risk sub-watersheds, include 167 jurisdictions with 10,734 properties classified

[29] Trophic status of B.C. lakes. https://www2.gov.bc.ca/assets/gov/environment/research-monitoring-and-reporting/monitoring/lake-program/final_bc_2015_trophic_lake_report_map3_wrk3_wide4d.pdf

as waterfront or bordering on waterfront.[30] Waterfront properties represent a small fraction (<2%) of the 682,380 residential properties in these assessment areas (Table 12).

The Government of B.C. provides information on local government municipal tax rates, including representative assessed values and tax burdens for 161 municipalities.[31] Representative values were linked to BCA data to determine the number of waterfront properties in each municipality. A 2013 study on the effect of wildfire risk on property values found a price premium of 292% for waterfront property in Kelowna (Xu and Van Kooten 2013).[32] This premium was applied to representative house values to derive representative waterfront property values. Nelson (2019) suggests ZQM could reduce property values in Montana from 5.8% to 10% due to reduced water quality and increased algal blooms. Assuming B.C. lakes are similar in quality to those in Montana, these ranges are used to evaluate changes in assessed property values and tax impacts for each assessment area (Table 12).

TABLE 12. Impact of ZQM on waterfront property values and municipal taxes for interior region assessment areas of B.C.

Assessment area name	Avg. variable tax rate (%)	Avg. value of waterfront property ($'000)	Number of waterfront properties	Total value change (-5.8%) ($'000)[33]	Total value change (10%) ($'000)	Annual property tax impact low ($'000)	Annual property tax impact high ($'000)
Cariboo	0.975	641	1,028	44,712	79,842	491	877
Central Okanagan	0.519	2,164	970	122,347	213,117	641	1,116
East Kootenay	0.803	1,073	906	74,648	128,712	572	987
Fraser Valley	0.501	2,151	1,215	141,031	239,888	742	1,273
Kamloops	0.820	998	1,449	111,969	193,049	844	1,455
Nelson/Trail	0.851	912	1,239	69,612	120,351	604	1,044
North Okanagan	0.654	1,364	968	76,030	135,520	497	886
Northwest	1.053	666	1,117	61,837	110,044	525	935
Peace River	0.905	667	320	15,937	27,476	156	268
Prince George	1.358	569	664	37,352	64,717	401	694
South Okanagan	0.716	1,082	858	56,228	97,441	352	609
Total	0.842	1,080	10,734	811,702	1,410,159	5,824	10,144

[30] Coastal assessment areas were excluded to limit the analysis to freshwater systems. Riverfront property was excluded based on the assumption that shoreline water quality and beach apply primarily to lakefront property. Waterfront view properties were also excluded though they would likely also experience some negative impacts from reduced shoreline amenities.

[31] Schedule 704 - Taxes and Charges on a Representative House – 2020 (https://www2.gov.bc.ca/gov/content/governments/local-governments/facts-framework/statistics/tax-rates-tax-burden) provides representative housing values, variable tax rates and fixed fees for each jurisdiction.

[32] Xu and Van Kooten (2013) estimated a log-linear model which included a dummy variable for waterfront. The percent increase of property value for waterfront is given by p=(b+var(b)/2)*100 where b is the estimated coefficient on the waterfront dummy variable and var(b) is the estimated standard error squared (Kennedy 1981). From Xu and Van Kooten (2013), b=1.3727 and the standard error is 0.1083 resulting in a price premium on waterfront in Kelowna of 292%. This value was applied to the representative house values to derive a value for representative waterfront property values for each jurisdiction.

[33] Inconsistency between columns is due to underlying analysis being undertaken at a municipal rather than regional level.

Under the low (high) impact scenario, reductions in the assessed value of representative waterfront housing range from $15.9 million ($27.5 million) in the Peace River region to $141.0 million ($239.9 million) in the Fraser Valley. Total one-time costs of $812 million based on 5.8% reductions in assessed property values due to ZQM are included in the summary tables. The one-time reduction results in an annualized cost of $24.4 million ($2,269 per property) and decreased annual municipal revenues of $5.8 million.[34]

[34] A 3% discount rate was assumed to derive annualized values. Biases in both directions influence the property value estimates. Assessed property values are usually lower than market values, and nearby properties that are influenced by proximity to waterfront were not included in the analysis resulting in an underestimate. On the other hand, the transfer of waterfront property values from Kelowna, an urban centre on an iconic lake, overestimates the value of waterfront in more remote rural municipalities.

3. DISCUSSION

Much of B.C.'s infrastructure, equipment, and activity for sectors vulnerable to ZQM infestations is located within moderate and high-risk sub-watersheds including: 60% of hydro facilities and 80% of hydro generation capacity; 93% of agricultural irrigation systems; 63% of municipal treatment facilities; and 89% of self-supplied domestic water systems. In addition, 88% of freshwater angler days and 85% of the freshwater recreational fish catch occur within these sub-watersheds. Compared to the 2013 study, ZQM mitigation costs have declined due to improved treatment options resulting in lower per unit and total costs for most sectors (Table 13). However total annual costs increased due to the inclusion of ZQM impacts to tourism and property values. Cost drivers and key uncertainties for each sector are discussed further below.

Irrigation comprised the largest cost category in the 2013 study, representing 34% of potential damages. Irrigation costs in 2022 ranged between 14% and 28% of 2013 levels even though nearly twice as many irrigation licenses were considered in the analysis. Cost differences are driven by assumptions about per unit treatment costs for local providers which are an order of magnitude higher in the 2013 analysis ($55,287 per license compared to $2,069 – $4,278 per license). Due to lack of experience with ZQM in the arid west, there was little empirical information on treatment costs for irrigation systems in 2013 which were based on expert opinion. Since 2013, ZQM have spread to Western North America and cost assumptions in the current study have been updated based on actual experience from an irrigation district in Southern California.

Cost assumptions for local provider municipal water supply that underpinned the 2013 analysis were based on studies from the early 1990s, only a few years after ZQM were introduced to the Great Lakes. Since that time mitigation options for water treatment facilities have evolved. Local provider costs in the current study are based on detailed facility analysis from a 2016 survey of water treatment facilities across North America resulting in costs ranging from 18% to 138% of 2013 levels. The wide range in treatment costs for local providers reflects the effect of local conditions such as infrastructure age and ZQM density on optimal treatment options and highlights the difficulty in transferring cost assumptions at a provincial scale.

The effect of local conditions is also important for estimating potential costs for the hydro sector. The 2013 study applied a constant cost of $689 per MW of generation capacity but this approach does not account for the greater impact of retrofit capital costs on average costs for smaller facilities. The facility-level analysis undertaken for this study resulted in a higher but likely more accurate average costs per MW, ranging from $1,244 – $1,708 per MW. Costs for treating hydro infrastructure were based on engineering studies for facilities in Ontario and the U.S. and are only valid for analogous conditions. For some waterbodies, mussel densities in B.C. may be less than those experienced in other regions. For example, Claudi and Prescott (2014) estimated that the ZQM infestation in Upper Arrow Lake would be moderate due to biological factors limiting the population which would reduce costs for facilities in B.C.

Domestic self-supply, which was not considered in 2013, represents 21,495 licenses in B.C. Because of the large number of licenses, provincial cost estimates are sensitive to assumptions about treatment costs which were based on Nelson (2019) and vary by an order of magnitude ($237 – $1,298 per license). The B.C. Water & Waste Association reports that the average B.C. household pays about $500 per year for water and sewer services.[35] If the cost estimates are valid, this would represent a significant increase in water costs for over 21,495 households which could

[35] http://www.valueofwater.ca/water-facts/what-does-water-cost/

have important distributional consequences for low-income households. Given the number of licenses at risk, treatment and adaptation options for this sector should be further explored.

Boat maintenance is often one of the largest components of ZQM damages and represented the second highest cost category in 2013. Similar to domestic self-supply, due to the large number of boats in the province, cost estimates are sensitive to assumptions about the percentage of boats impacted by ZQM as well as annual maintenance costs. Annual maintenance costs vary by a factor of two in the current analysis and represent an important source of uncertainty.[36] Robinson et al. (2013) assumed that all boats licensed in freshwater would be exposed to ZQM. Using postal code data, the current study was able to determine that only 52% of freshwater boat licenses are located in moderate- and high-risk sub-watersheds. The assumption that 20% of these boats would require additional maintenance is based on a survey of boaters in the Great Lakes from the early 1990s (Vilapana and Hushak 1994) which would likely have been before ZQM reached peak densities. Costs of cleaning marina infrastructure were assumed to be additional to boat maintenance costs. Although the costs to marinas are small, ZQM still represent a nuisance.

The current study includes the effect of changes in water quality and beaches on property values and water-based tourism. Both of these values are sensitive to how people will respond to changes in amenities which depends on personal preferences as well as the availability of substitute properties and tourism opportunities, particularly if ZQM are introduced in competing tourist destinations. While water-based tourism is a small percentage of overall tourism in the province, local impacts may be significant in moderate- and high-risk sub-watersheds in the Kootenay and Okanagan regions, where water-based activities are a more significant draw for tourists. The range of tourism impacts ($2.5 million – $12.6 million) reflects only the loss of operating surplus and tax revenues. Impacts on expenditures will be higher which could have impacts on local jobs and businesses.

Reduced property values represent the largest cost component in the current study. While studies suggest that property values are sensitive to changes in water quality, the extent to which property values might decrease due to ZQM is uncertain and depends on several factors including the degree to which water quality is already degraded due to other factors (such as other AIS and agriculture runoff) and the availability of substitute waterfront property in the region. Although not included in the current study, costs to the freshwater recreational fishing sector may be significant given the importance of the sector to the B.C. economy, and exposure of recreational fish stocks to ZQM.

Care was taken to avoid double counting of costs across different categories. Property value losses are based on lost amenity values due to changes in water quality and do not include maintenance costs for docks and boats or the impacts of ZQM on beaches. Boater costs were restricted to owner costs for boat maintenance and not losses in recreation values. Similarly, marina costs are restricted to the costs of cleaning buoys and replacing chains in slips and do not include maintenance costs for boats. Losses in water-based recreation are captured under changes in producer surplus from non-resident tourism. Losses in recreation values for B.C. residents were not included in the analysis.

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[36] Both the current study and the 2013 analysis use costs from Vilapana and Hushak (1994), however the 2013 study summed the costs reported by boaters which overestimated the average cost per boat.

TABLE 13. Comparison of unit and annual cost of ZQM by water use sector between current and 2013 study

Water use	Current study			2013 study		
	Total Cost ($)	Number of units (% provincial total)	Cost ($) per unit	Total Cost ($)	Number of units	Cost ($) per unit
Irrigation – private	1,601,539 – 3,300,141	13,790 licences (93%)	116 – 239	1,801,480	7,250 licences	248
Irrigation – local provider	905,650 – 1,866,188	439 licences (99.5%)	2,063–4,251	16,586,031	300 licences	55,287
Irrigation - greenhouse	2,356 – 4,854	78 licences (88.6%)	30 – 62	---	---	---
Golf courses	33,741 – 69,526	728 licences (93.2%)	46 – 96	13,490	38	355
Local provider municipal supply	931,454	86 small facilities (61%)	10,831	11,391,185	183 medium and small facilities	54,951
	704,689 – 6,531,929	60 medium facilities (66%)	11,745 – 108,865			
	521,156 – 8,164,778	20 large (62%) facilities	28,953 – 453,599		7 large facilities	190,736
Domestic self-supply	5,104,4311 – 27,893,014	21,495 licences (89%)	237 – 1,298	---	---	---
Aquaculture	670,704 – 6,219,257	194 licences (72%)	3,457 – 32,058	---	---	---
Hydropower	16,987,836 – 23,338,018	71 facilities (59.7%)	239,265 – 328,704	8,102,360	10,661 MW	760
Boating	3,614,629 – 7,897,202	13,240 boats (4%)	303 – 604	15,386,022	21,429 vessels	718
Marinas	61,600 – 191,585	112 marinas	550 – 1,700	---	---	---
Tourism	2,511,016 – 12,555,080	N/a	N/a	---	---	---
Municipal tax revenue	5,824,000	10,734 waterfront properties	543	---	---	---
Property values	24,349,966		2,269	---	---	---

4. CONCLUSION

Invasive species like ZQM pose a significant threat to biodiversity and ecosystem services and, along with natural disasters, are ranked as one of the top economic risks from global environmental change [1]. This study provides an overview of the economic risks to B.C. if ZQM were to establish to maximum densities in all moderate- and high-risk sub watersheds. Economic damages could be widespread across the economy with tens of thousands of households and businesses facing potential costs ranging from hundreds to thousands of dollars per year from damages to infrastructure, property values, and lost business opportunities with total costs ranging from $64 to $129 million annually. These costs will emerge over years depending on the probability of ZQM introduction and spread. As previously noted, the risk of introduction was not included in the analysis, and its exclusion could potentially overestimate the impact of ZQM in sub-watersheds with limited human access. On the other hand, sub-watersheds with limited human access are also more likely to have limited infrastructure and other economic values at risk.

Over time the costs of mitigating damages from ZQM to infrastructure and equipment have decreased due to improvements in treatment technologies. However, costs due to changes in aquatic ecosystems may be much larger and are poorly understood including impacts on nutrient cycles and the food web.

The costs considered in this study are limited by the available data particularly regarding impacts on freshwater ecosystems and fish species. Additional research should address important data and knowledge gaps associated with the potential impacts of ZQM on ecosystems and their services. In the meantime, expert-led scenario analysis can narrow the range of uncertainty and guide management decisions, and should be prioritized for economically and culturally important fish species which are significantly exposed to ZQM including anadromous wild salmon populations.

Although the establishment of ZQM may take years to unfold, the impacts are cumulative and may be irreversible. Proactive investment strategies that reduce the probability of ZQM introduction will yield long term benefits and may be one of the most cost-effective ways to manage for biodiversity and ecosystem health.

[1] WEF_The_Global_Risks_Report_2022.pdf (weforum.org)

5. REFERENCES

Baker, Patrick, Shirley Baker and Roger Mann. 1993. "Criteria for predicting zebra mussel invasions in the Mid-Atlantic Region." School of Marine Science, College of William and Mary, Gloucester Point, VA.

BC Assessment (BCA). 2019. "BCA user guide for BCA commercial inventory extract. Version 1.0." Accessed on January 26, 2022 at: https://www.bcassessment.ca/Files/Misc/UserGuide/Commercial_Inventory_Extract_External_User_Guide.pdf

Chakraborti, R., P.M. Sharook, and J. Kaur. 2016. Costs for controlling dreissenid mussels affecting drinking water infrastructure: case studies. J. Am. Water Works Assoc. 108(8): E442–E453. DOI:10.5942/jawwa.2016.108.0104.

Claudi, R. and T. Prescott. 2011. Examination of calcium and pH as predictors of Dreissenid mussel survival in California state water project. Prepared for California Department of Water Resources, Division of Operations and Maintenance Aquatic Nescience Species Program. RNT Consulting Inc.

Claudi, R. and T. Prescott. 2014. The Potential Impact of Invasive Mussels on Keenleyside Dam and Lock. Prepared for: BC Hydro. Date: June 13, 2014. PO Number: 330479-001

Cohen, Andrew N, and Anna Weinstein. 1998. "Methods and Data for Analysis of Potential Distribution and Abundance of Zebra Mussels in California," Accessed on February 08 at: https://calisphere.org/item/ark:/86086/n2t152jn/.

COSEWIC. 2010. COSEWIC assessment and status report on the Rocky Mountain Ridged Mussel Gonidea angulate in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottaw. X + 56 pp.

Department of Fisheries and Oceans. 2017. "Socio-Economic Risk Assessment of the Presence of Zebra Mussel in Lake Winnipeg , Red River , Nelson River and Cedar Lake Policy and Economics."

Department of Fisheries and Oceans. 2019. (Fisheries and Oceans Canada). Survey of Recreational Fishing in Canada, 2015. Fisheries and Oceans Canada, Ottawa, ON, 26 pp.

Freshwater Fisheries Society of BC. 2019. 2019 BC Freshwater Sport Fishing Economic Impact Report. https://www.gofishbc.com/PDFs/Footer/economic_impact_report.aspx (accessed July 22, 2022).

Freshwater Fisheries Society of BC. 2020. 2019-2020 Annual Report. Untitled-1 (gofishbc.com). Accessed July 22, 2022).

Garton, David .W., Robert McMahon, Ann Stoeckmann. 2013. "Limiting environmental factors and competitive interactions between zebra and quagga mussels in North America." CRC Press, Taylor and Francis Group, Boca Raton, Fla.

Horsch, E. J. and D.J. Lewis. 2009. The effects of aquatic invasive species on property values: evidence from a quasi-experiment. Land Econ. 85(3): 391–409. doi:10.3368/le.85.3.391

Hunt, Len M., Daniel J. Phaneuf, Joshua K. Abbott, Eli P. Fenichel, Jennifer A. Rodgers, Jeffrey D. Buckley, D. Andrew R. Drake, and Timothy B. Johnson. 2020. “The Influence of Human Population Change and Aquatic Invasive Species Establishment on Future Recreational Fishing Activities to the Canadian Portion of the Laurentian Great Lakes.” Canadian Journal of Fisheries and Aquatic Sciences 78 (3): 232–44. https://doi.org/10.1139/cjfas-2020-0159.

Idaho Aquatic Nuisance Species Taskforce (IANST). 2009. “Estimated potential economic impact of zebra and quagga mussel introduction into Idaho.” Accessed on March 16, 2021 at: http://www.aquaticnuisance.org/wordpress/wp-content/uploads/2009/01/Estimated-Economic-Impact-of-Mussel-Introduction-to-Idaho-Final.pdf.

Independent Economic Analysis Board (IEAB). 2010. “Economic risk associated with the potential establishment of zebra and quagga mussels in the Columbia River Basin.” Portland, Oreg. Task Number 159. Document IEAB 2010-1.

Johnson, Marianne and Meder, Martin. 2013. “Effects of Aquatic Invasive Species on Home Prices: Evidence from Wisconsin.” Available at SSRN: https://ssrn.com/abstract=2316911. or http://dx.doi.org/10.2139/ssrn.2316911 (accessed January 26. 2022)

Kao, Yu Chun, Mark W. Rogers, and David B. Bunnell. 2018. “Evaluating Stocking Efficacy in an Ecosystem Undergoing Oligotrophication.” Ecosystems 21 (4): 600–618. https://doi.org/10.1007/s10021-017-0173-5.

Karatayev, Alexander Y., Lyubov E. Burlakova, and Dianna K. Padilla. 2015. “Zebra versus Quagga Mussels: A Review of Their Spread, Population Dynamics, and Ecosystem Impacts.” Hydrobiologia 746 (1): 97–112. https://doi.org/10.1007/s10750-014-1901-x.

Kennedy, Peter.E. 1981. “Estimation with correctly interpreted dummy variables in semilogarithmic equations.” American Economic Review 71, 801

Larratt Aquatic Consulting. 2013. “Limiting the spread of aquatic invasive species into the Okanagan.” Accessed on January 26, 2022 at: https://www.obwb.ca/fileadmin/docs/2013_obwb_ais_report.pdf.

Lauber, T. Bruce, Richard C. Stedman, Nancy A. Connelly, Richard C. Ready, Lars G. Rudstam, and Gregory L. Poe. 2020. “The Effects of Aquatic Invasive Species on Recreational Fishing Participation and Value in the Great Lakes: Possible Future Scenarios.” Journal of Great Lakes Research 46 (3): 656–65. https://doi.org/10.1016/j.jglr.2020.04.003.

Limburg, K., V.A. Luzadis, M. Ramsey, K.L. Schulz, and C.M. Mayer. 2010. The good, the bad, and the algae: perceiving ecosystem services and disservices generated by zebra and quagga mussels. J. Great Lakes Res. 36(1): 86–92. DOI:10.1016/j.jglr.2009.11.007.

Mackie, G.L. and R. Claudi, 2009. Monitoring and control of macrofouling mollusks in fresh water systems. CRC Press, Boca Raton. 550 p. https://doi.org/10.1201/9781439804414

Mcgrew, Spencer Crowley. 2013. “Exploring the impact of zebra mussels (Dreissena polymorpha) on residential lakeshore property values in Otter Tail and Becker Counties, Minnesota.” Univ. of North Dakota, Grand Forks, N. Dak. Accessed on January 26, 2022 at: https://commons.und.edu/theses/1453.

McMahon, Robert F. 1996. “The Physiological Ecology of the Zebra Mussel, Dreissena Polymorpha, in North America and Europe.” American Zoologist 36 (3): 339–63. https://doi.org/10.1093/icb/36.3.339.

Neary, B. P., and J. H. Leach. 1992. “Mapping the Potential Spread of the Zebra Mussel (Dreissena Polymorpha) in Ontario.” Canadian Journal of Fisheries and Aquatic Sciences 49 (2): 406–15. https://doi.org/10.1139/f92-046.

Nelson, Nannete M. 2019. “Enumeration of Potential Economic Costs of Dreissenid Mussels Infestation in Montana.” Accessed on January 26 2022 at: https://edit.doi.gov/sites/doi.gov/files/uploads/dnrc_economic_cost_dreisseid_mussels_0119.pdf

Nichols, Susan Jerrine. 1996. “Variations in the Reproductive Cycle of Dreissena Polymorpha in Europe, Russia, and North America.” American Zoologist 36 (3): 311–25.

Nicholls, S. and J. Crompton. 2018. A Comprehensive Review of the Evidence of the Impact of Surface Water Quality on Property Values. Sustainability 10 (2): 500. https://doi.org/10.1093/icb/36.3.311.

Park, J., and L. J. Hushak. 1999. “Zebra Mussel Control Costs in Surface Water Using Facilities Technical Summary No. OHSU-TS-028,” 1–15. Accessed on January 26, 2022 at: https://eos.ucs.uri.edu/seagrant_Linked_Documents/ohsu/ohsus99002.pdf

Paterson, B., R. Claudi, and D. Butts. 2018. “Dreissenid mussels and Alberta’s irrigation infrastructure: strategic pest management plan and cost estimate.” Paterson Earth & Water Consulting Ltd., Lethbridge, Alta. Accessed on January 26, 2022 at: https://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/irr15127/$FILE/2018_dreissenid_mussels_and_albertas_irrigation_infrastructure.pdf

Office of the Provincial Health Officer. 2019. Clean, Safe, and Reliable Drinking Water: An Update on Drinking Water Protection in BC and the Action Plan for Safe Drinking Water in British Columbia. Provincial Health Officer’s Drinking Water Report: 2012/13-2016/17

Pucherelli, Sherry., R. Claudi, T. Prescott, L. Willett, and T. Van Oostrom. 2020. “Case studies: impact and control of invasive mussels at hydropower plants.” U.S. Department of the Interior, Bureau of Reclamation. Final Rep. ST-2020-1876-01.

Ready, Richard C., Gregory L. Poe, T. Bruce Lauber, Nancy A. Connelly, Richard C. Stedman, and Lars G. Rudstam. 2018. “The Potential Impact of Aquatic Nuisance Species on Recreational Fishing in the Great Lakes and Upper Mississippi and Ohio River Basins.” Journal of Environmental Management 206: 304–18. https://doi.org/10.1016/j.jenvman.2017.10.025.

Ricciardi, R., Neves, R. and Rasmussen, J. 1998. Impending Extinctions of North American Freshwater Mussels (Unionoida) Following the Zebra Mussel (Dreissena polymorpha) Invasion. Journal of Animal Ecology, 67 (4): 613-619

Robinson, D C E, D Knowler, D Kyobe, and P de la Cueva Bueno. 2013. “Preliminary Damage Estimates for Selected Invasive Fauna in B.C.” Accessed on January 26, 2022 at: https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/invasive-species/guidance-resources/preliminary_damage_estimates_selected_invasive_fauna.pdf

Rossi, Frederick., Damian Adams, and Donna.J. Lee. 2004. “The use of cost-transfer analysis to estimate the economic impacts of a potential zebra mussel infestation in Florida.” South. Agric. Econ. Assoc. 2004 Annu. Meet., February 14–18, 2004, Tulsa, Okla. DOI:10.22004/ag.econ.34774.

Southwick Associates. 2020. “The Economic Contributions of Freshwater Angling in BC” Prepared for the Freshwater Fisheries Society of BC, February 11, 2020.

Sprung, M. 1993. “The other life: an account of present knowledge of the larval phase of Dreissena polymorpha.” In: Nalepa TF, Schloesser DW. (Eds.) 1993. Zebra Mussels, Biology, Impacts and Control. Lewis Publishers, Boca Raton, Florida, 810 p.

Stanczykowska, A. 1977. “Ecology of Dreissena polymorpha (Pall) (Bivalvia) in lakes.” Pol. Arch. Hydrobiol. 24:461-530.

Strayer, David L. 2009. “Twenty Years of Zebra Mussels: Lessons from the Mollusk That Made Headlines.” Frontiers in Ecology and the Environment 7 (3): 135–41. https://doi.org/10.1890/080020.

Therriault, Thomas W., Andrew M. Weise, Scott N. Higgins, Yinuo Guo, and Johannie Duhaime. 2013. “Risk Assessment for Three Dreissenid Mussels in Canadian Freshwater Ecosystems.” Canadian Science Advisory Secretariat 3848: 88. www.dfo-mpo.gc.ca/csas-sccs/.

Tolkinnen, Karen. 2020. “Do invasives harm lake property values? Study takes a look.” Grand Forks Herald, Grand Forks, Grand Forks, N.Dak. Accessed on May 18, 2021: https://www.grandforksherald.com/northland-outdoors/6677402-Do-invasives-harm-lake-property-values-Study-takes-a-look

USACE. 2009. Lake Tahoe Region Aquatic Invasive Species Management Plan, California - Nevada. 84 pp + Appendices.

Vanderploeg, H.A., T.F. Nalepa, D.J. Jude, E.L. Mills, K.T. Holeck, J.R. Liebig, I.A. Grigorovich and H. Ojaveer. 2001. “Dispersal and emerging ecological impacts of Ponto-Caspian species in the Laurentian Great Lakes.” Canadian Journal of Fisheries and Aquatic Sciences 59: 1209-1228.

Vilaplana, J.V. and L.J. Hushak. 1994. “Recreation and the zebra mussel in Lake Erie, Ohio.” Technical Summary. OHS-TS-023. Ohio Sea Grant College Program. Columbus, Ohio.

Wells, Steve W, Timothy D Counihan, Amy Puls, Mark Sytsma, and Brian Adair. 2011. “Prioritizing Zebra and Quagga Mussel Monitoring in the Columbia River Basin,” 93.

Whittier, Thomas R., Paul L. Ringold, Alan T. Herlihy, and Suzanne M. Pierson. 2008. “A Calcium-Based Invasion Risk Assessment for Zebra and Quagga Mussels (Dreissena Spp).” Frontiers in Ecology and the Environment 6 (4): 180–84. https://doi.org/10.1890/070073.

Woodruff, Patricia, Brett T. van Poorten, Carl J. Walters, and Villy Christensen. 2021. “Potential Effects of Invasive Dreissenid Mussels on a Pelagic Freshwater Ecosystem: Using an Ecosystem Model to Simulate Mussel Invasion in a Sockeye Lake.” Aquatic Invasions 16 (1): 129–46. https://doi.org/10.3391/ai.2021.16.1.09.

Xu, Zhen, and G. Cornelis van Kooten. 2013. “Living with wildfire: the impact of historic fires on property values in Kelowna, BC” Resource Econ. & Policy Analysis Res. Group, Department of Econ., Univ. of Victoria. Working Paper 2013-05. https://ideas.repec.org/p/rep/wpaper/2013-05.html#download (accessed May 19, 2021).

Zhang, Yuan, Yiguo Sun, and Thanasis Stengos. 2019. “Spatial Dependence in the Residential Canadian Housing Market.” Journal of Real Estate Finance and Economics 58 (2): 223–63. https://doi.org/10.1007/s11146-017-9623-2.