MODELING HABITAT SUITABILITY FOR THE ROCKY MOUNTAIN RIDGED MUSSEL (*GONIDEA ANGULATA),* IN OKANAGAN LAKE, BRITISH COLUMBIA, CANADA

by

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Abstract

A habitat suitability model was constructed to increase knowledge of the Rocky Mountain ridged mussel (RMRM, *Gonidea angulata* Lea), a rare and endemic species, using Geographic Information Systems (ArcGIS 10.1) and the classification package Random Forest. Identifying possible relocation sites, sites of high importance, and the overall potential distribution of RMRM were accomplished using existing Foreshore Inventory and Mapping (FIM) substrate data and *G. angulata* presence data (Ministry of Environment). In addition, diverse aspects of mussel habitat quality were documented, including: clay presence, dissolved oxygen concentration, shoreline morphometry, species of fish and other mussels present, geomorphometric description, and effective fetch. Important variables, potentially limiting the distribution of RMRM, as identified in these analyses, include effective fetch > 10 km, medium-high (%) embeddedness of substrates, high (%) sand, and low (%) boulder occurrence. Effective fetch (i.e., site exposure), used as a proxy for potential energy (from wind) can explain the distribution of RMRM in Okanagan Lake. This model was successful in predicting previously unknown locations of RMRM. This model was developed as a tool for Forests, Lands and Natural Resource Operations (Province of BC) to improve management of this species in the Okanagan Valley.

Preface

This research project was undertaken as a collaboration between the University of British Columbia, the Ministry of Forests, Lands, and Natural Resource Operations (FLNRO), and the Ministry of Environment as part of the Rocky Mountain ridged mussel Management Plan in Okanagan Lake. All written works and the majority of diagrams in this document are of my own making. Lora Nield, Ian Walker, Jason Pither, Jon Mageroy, and Jeff Curtis contributed to the study design and sampling procedures. Jason Schleppe from Ecoscape Environmental Consulting Ltd. aided in answering questions related to the Foreshore Inventory and Mapping data. Ian Walker, Jon Mageroy, Jeff Curtis, Lora Nield, and Jason Pither contributed to manuscript editing. Steven Brownlee, Jerry Mitchell, Jon Mageroy, Jamie McKeen, and Jon Bepple assisted in field work. The iteration procedure for the sensitivity analysis was coded by Jason Pither.

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List of Abbreviations

EWM – Eurasian water milfoil, *Myriophyllum spicatum*

FIM – Foreshore Inventory and Mapping

FLNRO – Forests, Lands, and Natural Resource Operations

MDA – mean decrease in accuracy

ppm – parts per million

RMRM – Rocky Mountain ridged mussel

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Dedication

To my grandmother, Barbara Jean Snook.

Chapter 1. Introduction

Freshwater mussels are arguably one of the most endangered groups of animals in North America, as ca. 70% of the species have either gone extinct or have some kind of listing (Bogan 1993, Williams et al. 1993, Neves et al. 1997, Lydeard et al. 2004). This includes the Rocky Mountain ridged mussel (RMRM; *Gonidea angulata*, family Unionidae), an aquatic mollusc native to North America west of the Rocky Mountains.

Once prevalent from British Columbia, south to California and eastward to Idaho and Nevada, the RMRM has been largely extirpated from its original range for reasons including, but not limited to, human development, industrial contamination of waterways, habitat loss, river channelization, invasive species, and loss of host fish (Downing et al. 2010, Jepsen et al. 2010, Stanton et al. 2012). Many details of the RMRM's habitat preferences are unknown, making conservation decisions difficult. In the Okanagan Valley, development interests overlap with existing and potential RMRM habitat (Department of Fisheries and Oceans 2011, Stanton et al. 2012). Thus, increasing the importance of better understanding RMRM habitat requirements.

Unionids, including the RMRM, spend large portions of their life either completely or partially buried, therefore substrates, a medium for mussels to bury in, are likely important factors controlling mussel distribution (Geist and Auerswald 2007). Freshwater Unionoidea (hereafter referred to as mussels), however, are also temporarily (days-months) obligate parasites on a fish host during early stages in their development (Bogan 1993, Vaughn and Taylor 2000, Lydeard et al. 2004, Nedeau et al. 2009, COSEWIC 2010, Daraio et al. 2012, Schwalb et al. 2013). Thus, mussels rely on fish for development and dispersal

(Kappes and Haase 2011, Daraio et al. 2012, Schwalb et al. 2013). Nutrient availability and potential (wind and wave) energy, as well as host fish occurrence at each site are likely key factors for RMRM habitat selection. However, much is unknown in relation to their habitat needs.

To clarify the needs of this mussel, I set out in this thesis to develop a habitat suitability model for the RMRM. I also test specific *a priori* hypotheses concerning the mussel's distribution, including (1) RMRM are not distributed randomly, and (2) low embeddedness, substrate type (i.e., boulders and cobbles), low-moderate slope, and high fetch are useful predictors of RMRM occurrence. An additional goal is to determine how widely this species is distributed through the Okanagan Basin. Together, these studies yield a better understanding of the RMRM's distribution and habitat requirements, enhancing our ability to identify critical habitat and possible relocation sites.

Chapter 2. Literature Review

2.1 Life history

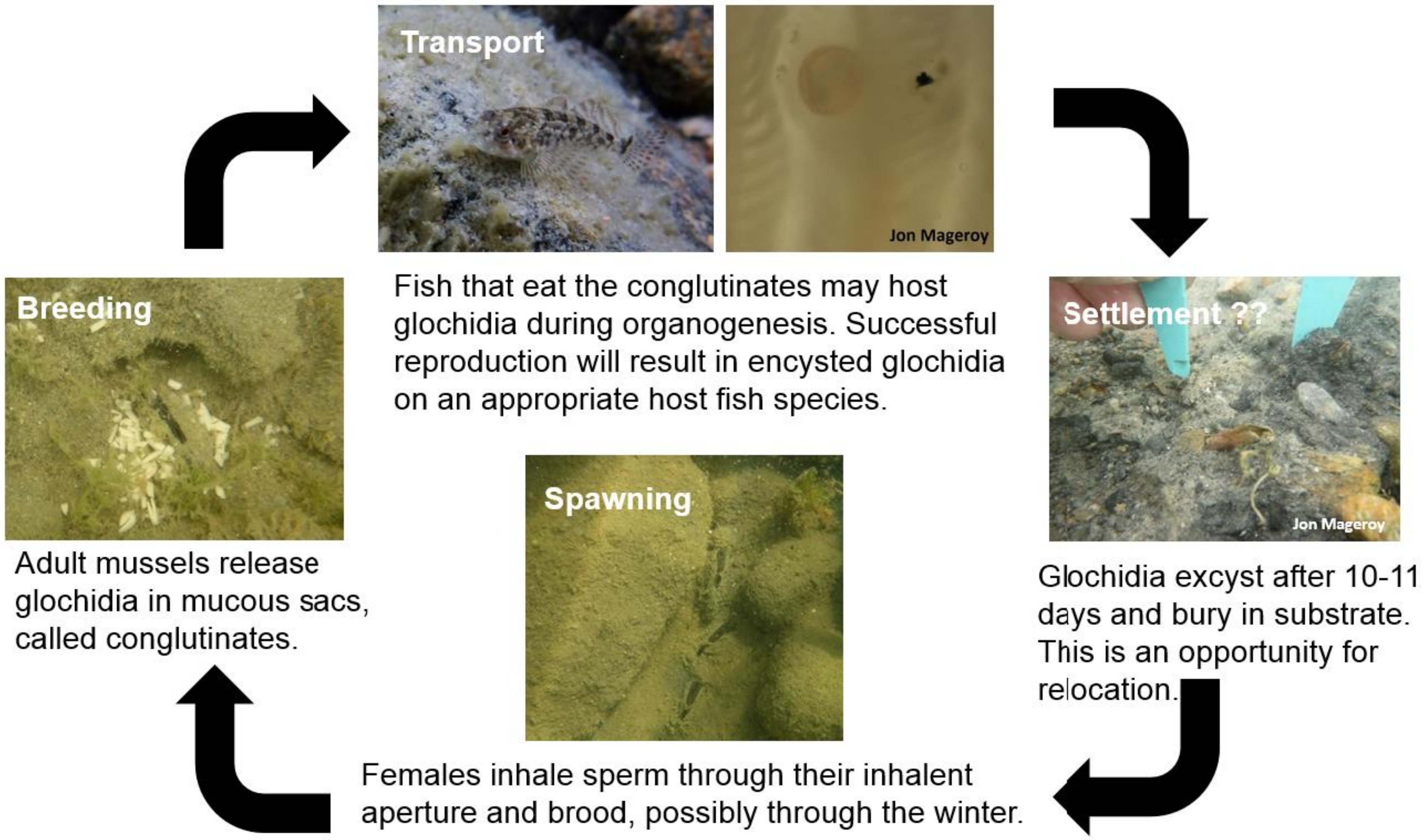
Unionoidea are long-lived animals (30-100 years; e.g., Morales et al. 2006) with a complex life history. *G. angulata* likely live between 30-50 years (Mageroy 2015). They are filter feeders and have positive influences and important functional roles in their environment: by filtering particles, releasing nutrients, serving as food sources for many animals, stabilizing substrates (providing area for benthic fauna), mixing sediments (e.g., Morales et al. 2006), providing habitat for epiphytic and epizoic organisms on their shells (Vaughn and Hakenkamp 2001, Krueger et al. 2007), and increasing the depth of oxygen penetration into sediment (McCall et al. 1979).

Fundamental to understanding any species' biology are details of its life history from conception through to reproduction, and ultimately death. Female *G. angulata* inhale sperm from the water column (Nedeau et al. 2009). Therefore, the density and distribution of male RMRM regulate sperm density, fertilization, and the probability of their reproductive success (Krueger et al. 2007). Mature female *G. angulata* later release packages of larvae (glochidia) surrounded by mucous, creating masses called conglutinates (Figure 1). Timing of their release (nocturnally) and the appearance of the conglutinates (i.e., mimic fish food) are likely evolved strategies of RMRM (O'Brien et al. 2013). When conglutinates are inhaled by a suitable fish host, the successful glochidia attach to (encyst on) the gills of their fish hosts as obligate ectoparasites (Newton et al. 2008, Stanton et al. 2012). On suitable fish hosts organogenesis (i.e., development of organs) occurs and the larvae metamorphose into juvenile mussels, which drop off the fish. This life cycle puts *G. angulata* at risk to high rudimentary and juvenile mortality, as their distribution and life cycle depend on a fish host as well as suitable habitat for the free-living juveniles and adults (COSEWIC 2003, Department of Fisheries and Oceans 2011).

Encystment on the host fish must be successful in order to complete reproduction (O'Brien et al. 2013). *G. angulata* have been found to metamorphose into juvenile mussels on three species of sculpin; margined (*Cottus marginatus* Bean, 1881), shorthead (*C. confusus* Bailey and Bond, 1963), and pit sculpin (*C. pitensis* Bailey and Bond, 1963), and in very limited numbers on two species of perch; hardhead (*Mylopharodon conocephalus* Baird and Girard, 1854), and tule perch (*Hysterocarpus traskii* Gibbons, 1854) in the Pit River system and Middle Fork John Day River, Oregon (Spring Rivers 2007, O’Brien et al. 2013). In addition, field data from Okanagan Lake suggest that sculpin (*C. asper* Richardson, 1836 and/or *C. cognatus* Richardson, 1836) are the primary hosts in this system, while longnose dace (*Rhinichthys cataractae* Valenciennes, 1842), leopard dace (*Rhinichthys falcatus* Eigenmann and Eigenmann, 1893), and northern pikeminnow (*Ptychocheilus oregonensis* Richardson, 1836) may also serve as hosts (Stanton et al. 2012, Mageroy 2015). After a short duration (10-11 days) on their host (O’Brien et al. 2013), *G. angulata* ‘sluff-off’ (excyst) and bury into the substrate as ‘juveniles’ (sexually immature mussels; Strayer 2008). If the habitat and conditions are suitable, recruitment can be successful at this new location.

This early stage in the life cycle is thought to be the most sensitive, with mortality occurring from attachment to an incompatible fish host, or unsuitable habitat where the juvenile mussels end up (e.g., Neves and Widlack 1987). The juvenile stage is mostly an interstitial stage (Strayer 2008), lasting 6-7 years in the Okanagan Basin (Mageroy 2015). At seven (+) years, the mussels then reach sexual maturity. Adult *G. angulata* are primarily epifaunal (i.e., live on the substrate of the lake or river) (Newton et al. 2008).

Predators of RMRM in Okanagan Lake include muskrats, racoons, several fish species, some gastropods, many gull species, and humans (Nedeau et al. 2009, Davis et al. 2013). Desiccation from dam drawdowns pose a potential threat to RMRM in Okanagan Lake, as water level drawdowns can trap mussels above lake or reservoir levels (Bauer and Wachtler 1937, Newton et al. 2015).



Fish that eat the conglutinates may host glochidia during organogenesis. Successful reproduction will result in encysted glochidia on an appropriate host fish species.

Adult mussels release glochidia in mucous sacs, called conglutinates.

Glochidia excyst after 10-11 days and bury in substrate. This is an opportunity for relocation.

Females inhale sperm through their inhalent aperture and brood, possibly through the winter.

Figure 1. Life history of *G. angulata* and other mussels in the superfamily Unionoidea (Images from Roxanne Snook and Jon Mageroy, 2013, reproduced with permission).

2.2 Taxonomy & morphology

Gonidea angulata (family Unionidae) is the only member of its genus. It is one of eight species representing the superfamily Unionoidea in the Pacific watersheds of North America. In the Pacific Northwest, there is also one species from the family Margaritiferidae (*Margaritifera falcata* Gould, 1850), and six *Anodonta* species (family Unionidae), all of which are difficult to distinguish (Nedeau et al. 2009). The ectoparasitic larval stage and large size are key characteristics distinguishing the Unionoidea from other native and non-native bivalves.

Gonidea angulata is easily distinguished from other Unionoidea in British Columbia. It has a unique and distinct ridge along its posterior margin, hence the name, Rocky Mountain ridged mussel (Figure 2). *G. angulata* also have a thick, heavy shell (≤ 5mm) in comparison to other native freshwater mussels (Clarke 1981, Fisheries and Oceans Canada 2010). The shell shape is ovate to trapezoidal "(≤ 125mm long; ≤ 65 mm high; ≤ 45 mm wide; Clarke 1981 as cited in Stanton et al. 2012, Fisheries and Oceans Canada 2010). The periostracum (outer shell layer) is yellowish-brown to brown to blackish-brown in colour (Fisheries and Oceans Canada 2010, Jepsen et al. 2010, Stanton et al. 2012). Slightly elevated growth lines radiate from the umbo region to the outer margins of the shell in a concentric pattern (Fisheries and Oceans Canada 2010). The nacre, or inner lining of the shell, varies in colour along the shell from white or "salmon-coloured" to light blue toward the posterior margin (Fisheries and Oceans Canada 2010, Jepsen et al. 2010, Stanton et al. 2012).

Figure 2. Left: a RMRM with a distinct ridge along its outer shell (A), along with concentric growth lines (B) radiating out from the umbo (C; Image Roxanne Snook). Right: the inner mother of pearl nacre, and a hard to distinguish pseudocardinal tooth present on the right valve (Image Steven Brownlee, reproduced with permission).

The type, absence, or presence of ‘teeth’ are used to identify mussel species (Nedeau et al. 2009). RMRM have no lateral teeth (COSEWIC 2003, Jepsen et al. 2010). *G. angulata* have small pseudocardinal teeth on the right valve, while the left valve may have one poorly developed tooth or none at all (Nedeau et al. 2009). The pseudocardinal teeth are compressed, and can be hard to observe (Nedeau et al. 2009, COSEWIC 2010). These differences are distinctive compared to other freshwater mussels with overlapping distributions in the Pacific Northwest (COSEWIC 2010).

2.3 The need for conservation

Freshwater mussels are arguably one of the most endangered groups of organisms in the world (Ricciardi et al. 1998, Lydeard et al. 2004, Bogan 2008, Christian and Harris 2008). This is partly due to the limited knowledge of their ecology, as well as the limited interest in these organisms (Lydeard et al. 2004). Parts of the life history of RMRM make this species especially prone to high mortality when young (COSEWIC 2010). This can be exacerbated by the introduction of invasive species, weir and dam developments, dam drawdowns, river channelization, shoreline development, pollution (point and non-point sources), and water temperature increases attributable to water treatment facilities and/or climate change (Bauer and Wachtler 1937, Goudreau et al. 1993, Krueger et al. 2007, COSEWIC 2010, Fisheries and Oceans Canada 2010, Stanton et al. 2012, Newton et al. 2015). Over-harvesting (Dudgeon et al. 2006), sediment toxicity, wetland drainage, and clearing of large boulders also negatively impact Unionoidea, sometimes completely extirpating them from large sections of rivers (Becker 1983, Watters 1999, Poole and Downing 2004).

Within the Okanagan Basin and Okanagan Lake, a large threat to RMRM conservation is invasive species. Some invasive species predate on molluscs (Becker 1983). These can include both fish and gastropod invaders. Non-native mussel predator fish species known to reside south of, or within, Okanagan Lake include the Common Carp (*Cyprinus carpio* Linnaeus, 1758), Black Crappie (*Pomoxis nigromaculatus* Lesueur, 1829), Largemouth Bass (*Micropterus salmoides* (Lacepède, 1802), Smallmouth Bass (*Micropterus dolomieui* Lacepède, 1802) and Yellow Perch (*Perca flavescens* Mitchill, 1814) (Fisheries and Oceans Canada 2010). Adult Common Carp (also known as European

Carp) are known to eat mainly invertebrates (including mussels), as well as detritus, fish eggs, and plant material (Becker 1983). Smallmouth Bass feed heavily on fish as adults (B.C. Conservation Data Centre 2015), and therefore likely will have impacts on the fish community structure, indirectly affecting RMRM by predating on host fish.

Okanagan Lake is also greatly impacted by Eurasian water-milfoil (EWM; *Myriophyllum spicatum* L.). This aquatic plant can survive in a large diversity of habitats, and out-competes native aquatic flora (Fisheries and Oceans Canada 2010). Excessive EWM growth may inhibit near-shore water movements; thus, increasing siltation (Dunbar 2009). Some research has suggested an increase in siltation can negatively affect unionids, as this can cause suffocation (COSEWIC 2003), while aggradation of sediments may bury mussels (Allen and Vaughn 2009). EWM can alter feeding habitats of fish, as well as water quality, and decrease aquatic macrophyte diversity (Fisheries and Oceans Canada 2010). Management of EWM involves rototilling substrate in the littoral zone, which negatively impacts RMRM (COSEWIC 2010, Mageroy 2015). Rototilling similarly alters fish habitat, and can increase turbidity (Fisheries and Oceans Canada 2010), and kill adult RMRM (Mageroy 2015). Some sites in Okanagan Lake, which are treated for EWM are home to known RMRM populations (Mageroy 2015). In addition, disturbance of substrates can lead to early release of glochidia, consequently leading to reproductive failure (Krueger et al. 2007).

Zebra and quagga mussels (*Dreissena* sp.) are very prolific and also pose a potential threat to RMRM in Okanagan Lake should they ever spread to the Okanagan Valley (COSEWIC 2010, Fisheries and Oceans Canada 2010). Their planktonic (veliger) larvae facilitate dispersal and do not require a fish host. The veligers can be suspended in the water column for 3 weeks (Ricciardi et al. 1998). Zebra mussels are spread by turbulence within water bodies and by attaching themselves to boats (Sousa et al. 2011).

Zebra mussels alone have accelerated the loss of unionids 10-fold since their introduction to North America (Sousa et al. 2011). These mussels biofoul substrate, using byssal fibers to attach themselves to any surface (Sousa et al. 2011). Using these threads to attach to native bivalves' shells, they can completely suffocate unionid mussels, which normally position themselves anteriorly while filter feeding (Jepsen et al. 2010, Mackie 2010). Zebra mussels can also outcompete native unionids for food (Ricciardi et al. 1998). Native unionids do not have defenses against these introduced species, and their introduction to rivers in the US has resulted in extirpations of native bivalves within 4-8 years (Ricciardi 2003, Sousa et al. 2011).

Dam drawdowns have a 3-fold impact on RMRM. First, desiccation may occur through stranding (McMahon 1991, Newton et al. 2015). Secondly, drawdowns may prevent the northward migration of RMRM by inhibiting movement of sculpin, or other potential hosts (COSEWIC 2010, Jepsen et al. 2010). Finally, predation by racoons or other terrestrial predators may occur (Spring Rivers 2007). Weirs are used to slow the movement of water along channelized sections of a river (COSEWIC 2010). Weir placement can also affect fish composition upstream (in Okanagan Lake), which may impact host fish availability (Jerry Mitchell MOE pers. comm., COSEWIC 2010).

Accumulating sediment and substrate can kill *G. angulata* (McMahon 1991, Kreuger et al. 2007), although juvenile *G. angulata* appear to be fairly good at excavating and orienting themselves after resurfacing (Kreuger et al. 2007). For example, adult *G. angulata* have replaced *M. falcata* in one part of the Salmon River Canyon, Idaho in sections that accumulated sand (Brim Box and Mossa 1999). Similarly, the act of dredging (clearing and bringing up debris, mud, weeds, and other items from a water body bottom) is a disruptive activity and unionids are slow to recolonize affected areas (Goudreau et al. 1993). Disrupting sediments can mobilize toxins within the substratum and kill exposed gametes, which are more sensitive to pollutants in the water column than adults (Goudreau et al. 1993). These same consequences occur during stream channelization.

2.4 Distribution

Since essentially all of British Columbia (B.C.) was inundated by glaciers during the most recent, Fraser glaciation (Walker and Pellatt 2008), the flora and fauna of the province are almost entirely relatively recent immigrants, with the first arrivals appearing about 13,000 years ago (Waitt 1985). *Gonidea angulata* presumably found refuge in valleys beyond the reach of the Okanogan Lobe of the Cordilleran Ice Sheet in the lower Columbia River (e.g., Columbia River Gorge in Washington and Oregon), the Snake River (e.g., Idaho, Oregon, Washington), and the John Day River (Oregon) during the height of glaciation. The distributions of Unionoidea species are limited by their host fish movements (Kat 1984, Kappes and Haase 2011, Daraio et al. 2012, Schwalb et al. 2013). The northward post-glacial dispersal of these species into Canada likely occurred passively on the gills of dispersing host fishes (e.g., Elderkin et al. 2007).

The historical (pre-1985) distribution of RMRM extended from the northernmost sites in the Okanagan Valley of B.C. to southern California, and eastward into Idaho and Nevada (Xerces Freshwater Mussel database 2009, Department of Fisheries and Oceans 2011). The Rocky Mountains act as a distribution barrier to RMRM, as they have not been found east of this mountain range (COSEWIC 2010). However, RMRM is now considered extirpated from much of its former range (Taylor 1981, Jepsen et al. 2010, Stanton et al. 2012). Large extirpation events likely occurred in central and southern California, with numbers also declining in many watersheds of Washington and Oregon, including the Columbia and Snake River watersheds (Jepsen et al. 2010). Extirpation from two Columbia River tributaries, the Kootenai River and Clark Fork River, may have been due to construction of impoundments or metal contamination (Gangloff and Gustafson 2000). Furthermore much of their original habitat has been lost or modified (Stanton et al. 2012).

The Okanagan River is another tributary to the Columbia River. RMRM are found within the Columbia River drainage (of which there are over 50 tributaries). *G. angulata* is much more abundant in the Okanagan River than in any of the lakes or other streams in the Okanagan Basin (Snook UBCO pers. obs.).

2.5 Habitat requirements

The key factors defining this species' distribution will likely be many, and the relative importance of each factor is likely to vary with spatial scale. At the largest scale, the global extent of this species' distribution is likely to be governed by climate, and dispersal barriers, as well as availability and distribution of host fish (Vaughn and Taylor 2000, Schwalb et al. 2013). At a somewhat smaller spatial scale, the mussels' distribution within individual watersheds may be defined by such variables as hydraulic habitat (Morales et al. 2006), fish community structure (Vaughn and Taylor 2000, Schwalb et al. 2013), geology (Strayer 1983, Arbuckle and Downing 2002), cold summer temperatures (Lysne and Clark 2009), high summer temperatures (Vaughn et al. 2008), and land use (e.g., affecting water runoff; Vaughn 1997, Strayer 1983, Arbuckle and Downing 2002, McRae et al. 2004). At yet smaller scales, within any particular lake or stream segment, the dominant influence may be substrate size distribution and embeddedness, macrophytes, flow refuges, and possibly some chemical attributes (Nicklin and Balas 2007, Strayer 2014). Embeddedness of substrates is defined as “the degree to which boulders, cobbles, and other large materials are covered by fine sediments” (Schleppe and Mason 2009). Here I review some of the key variables, and how they might impact the mussels’ distribution.

2.5.1 Physical environment

2.5.1.1 Temperature

Temperature is one of the most important determinants of freshwater mussels, and can be used for predicting presence (Allan 1995, Malcom and Radke 2005). Temperature has significant biological implications for mussels as it directly affects their metabolic rate (Brown et al. 1998, Lysne and Koetsier 2006). *G. angulata* could be extirpated locally by increased temperatures (Jepsen et al. 2010). Increased temperatures can be caused by decreased streamflow (or water diversion), a decrease in riparian vegetation (i.e., shade), and global climate change (Jepsen et al. 2010). Higher water temperatures can cause premature onset of a non-gravid period (as observed in other freshwater mussels e.g., *Anodonta* sp.) or abortion (Aldridge and McIvor 2003). The upper lethal temperature for Unionoidea, in watered and dewatered environments (of short durations, e.g., 96 hours) is 31.5°C-38.8°C (Dimock and Wright 1993, Pandolfo et al. 2010), or >29°C for longer durations (Fuller 1974). However, at the northern extent of RMRM distribution, it is possible cold summer water temperatures are more limiting than warm temperatures.

Water temperatures lower than 16°C (Mackie et al. 2008) are limiting in the fall and winter at the northern limit of *G. angulata.* Disturbed mussels in water temperatures less than 16°C must use valuable energy resources to rebury (Mackie et al. 2008). Lethal cold water temperatures are specific to each species, but < 4.8°C is known to be below one species' thermal tolerance (Mladenka and Minshall 2001). In addition, glochidia release is greatly temperature dependant (Watters and O'Dee 1998). Many species release glochidia during different times of the year and have their peak spawning period at different temperatures (Watters and O'Dee 1998). *Gonidea angulata* release glochidia when water temperatures exceed 10°-12°C (Spring Rivers 2007)

Furthermore, high amounts of pollution, low dissolved oxygen, or warm water temperatures may indirectly affect freshwater mussel populations because of the effect on fish hosts, as well as food sources (Jepsen et al. 2010). With increasing water temperatures, the O_2 carrying capacity of water decreases, while metabolic rates increase simultaneously in poikilothermic organisms, which are dependent on sufficient ambient oxygen levels. A study of *M. margaritifera* Linnaeus, 1758 (family Margaritiferidae) juveniles revealed an indirect negative correlation between growth and decreasing oxygen, because of its dependence on temperature (Buddensiek 1995).

2.5.1.2 Water movement

Water movement is known to be important to filter feeders, as both a source of food and oxygen. Water movement can be induced by wind. Fetch is the distance wind can travel over water without being impeded by land. Fetch thus provides a proxy measure of the potential energy to which each site on a lake is exposed (Hakanson 1977, Westerbom and Jattu 2006, Callaghan et al. 2015). Large fetch can create wave action/turbulence and water movement via longshore currents, which causes friction and energy transfer below the water surface (Hakanson 1977, Michaud 2008, Westerbom and Jattu 2006, Callaghan et al. 2015). Lakes can retain 30-50% of the wind and/or storm energy, which can transfer down the water column (Michaud 2008) by turbulent processes, impacting sediment erosion and accumulation dynamics (i.e., the degree of substrate embeddedness and substrate size, Hakanson 1977) and oxygen penetration to the substrate (Holtappels et al. 2015). Predictive models of species distribution have been explored with wind-induced exposure to foreshore and littoral environments (Ekebom et al. 2003, Westerbom and Jattu 2006, Callaghan et al. 2015). Because turbulence is important for vertical mixing of food (i.e., it can increase the supply and availability of nutrients), oxygen, and mobilizing fine sediment, fetch is thought to be an important variable for *Gonidea angulata*.

To try to explain wave action and sediment site characteristics (such as fine material accumulation and sediment sizes), the potential energy to which a site is exposed can be estimated using the potential maximum effective fetch (or total fetch). This approach provides a proxy measure of the potential energy from wind from every deviation angle (i.e., incident ± 6°, 12°, 18°, 24°, 30°, 36°, 42°) of the prevailing wind direction

(Hakanson 1977). Other studies incorporate the exposure of sites (measured as fetch), to explain distribution and community structure of species (Burrows et al. 2008, Cyr 2009).

2.5.1.3 Substrate

Since Unionoidea spend large portions of their life either completely or partially buried (Strayer 2008), it is likely that substrate type, as well as the distribution of oxygen, will have an effect on the probability of their presence (Morales et al. 2006, Geist and Auerswald 2007). Substrate types vary greatly among living *G. angulata* populations, from cobbles and boulders, to burying in 40 cm of organics and silt (Dr. Jon Mageroy UBCO pers. comm). *G. angulata* habitat varies greatly, from high velocity streams and rivers, to the littoral zone of lakes (Stanton et al. 2012). My research focuses on *G. angulata* in Okanagan Lake, thus flow regimes will not be assessed in this study. *G. angulata* have generally been observed in water depths < 3 m (Stanton et al. 2012). This tendency for *G. angulata* to inhabit shallow waters makes them susceptible to draw-down from control dams in reservoirs (Stanton et al. 2012).

Significant habitat variables for *G. angulata* abundance in a riverine study included substrate type (i.e., sand and gravel), flow refuges (Strayer 1999), substrate cover, and bank edge presence (defined as “sloped steeply to the water’s edge and consisted of stable, embedded boulders, bedrock, mud or other hardened substrate”; Davis et al. 2013). Flow refuges have been determined to be important features for unionid survival in several studies (Morales et al. 2006, Bartsch et al. 2009, Strayer 2014). Unionids are often found behind boulders and cobble in the first 8 cm of substratum in riffles and runs of a stream (Neves and Widlak 1987). *G. angulata* were the predominant species (>90%) in stable sand and gravel bars in Salmon River Canyon, Idaho (Vannote and Minshall 1982).

Since *G. angulata* is a species of special concern (Species at Risk Act, 2015), with limited knowledge on habitat requirements, other Unionoidea studies were reviewed for potential useful habitat similarities. In particular, *Margaritifera falcata* is a very well-studied species. It is often found in similar habitat with ranges overlapping *G. angulata*, and in some cases has been replaced by *G. angulata* (Vannote and Minshall 1982). *M. falcata* is primarily a riverine species (although also found in some lentic systems), and is generally found in areas with boulders that are thought to stabilize cobble and other small substrates, while also offering protection from scouring events (flow refuge; Vannote and Minshall 1982) and predators (Davis et al. 2013).

One study measured habitat quality (i.e., instream cover, embeddedness, velocity/depth, and sediment deposits) for instream Unionoidea, and found these variables, although all correlated, were all significant correlates of mussel density (Nicklin and Balas 2007).

High silt cover (high embeddedness) at sites had a negative relationship with *G. angulata* occurrence (Hegeman 2012). Excess silt can clog gills of mussels and inhibit light penetration for photosynthesis, both of which reduce food availability (Poole and Downing 2004, Brim Box and Mossa 1999).

2.5.2 Chemical environment

2.5.2.1 Oxygen

Water chemistry is considered important for mussels (Newton et al. 2008). For example, oxygen, is a good indicator of their non-random spatial distribution, since mussels depend on a stable substratum which contains saturated or near saturated levels of dissolved oxygen (DO; Oliver 2000 as cited in Young 2005, Geist 2005, Mackie et al. 2008), as these organisms respire through ciliated gills. Mussels have extensive gas-exchange surfaces, directly dissolving oxygen in hemolymph fluid making its O_2 carrying capacity similar to that of the surrounding water (McMahon 1991). The large hemolymph volume of mussels is responsible for delivering oxygen to the heart and tissues by immersing them (McMahon 1991).

Low dissolved oxygen concentrations (< 3-6 ppm) for *G. angulata* (or other unionids) are detrimental for many reasons, including survival, reproduction, and development (Fuller 1974, Buddensiek et al. 1993, Strayer 1993, Watters 1999). Dissolved oxygen saturation levels of 90-110% are best for cellular respiration in *M. margaritifera*, a sensitive member of the Unionoidea (Oliver 2000 as cited in Young 2005).

2.5.2.2 Conductivity/salinity

Salinity is a measure of the dissolved salt content in water including such ions as sodium, potassium, magnesium, calcium, chloride, and sulphate. Salinity can be altered via changes in land use, drought, pollution, and especially climate (Ercan and Tarkan 2014). A small increase in salinity, within a range, can increase the growth rate of mussels (and fish) (Ercan and Tarkan 2014). Very low and very high salinity concentrations have adverse effects on mussel reproduction, decrease metabolic rate, and eventually lead to mortality (Ercan and Tarkan 2014). Mussel species have species specific ranges for these dissolved salts (Ercan and Tarkan 2014).

The salinity can be estimated via the electrical conductivity of water samples, when corrected for temperature, yielding a measure referred to as specific conductance. Growth, mussel diversity, and survival of Unionoidea are thus related to conductivity (Buddensiek 1995, McRae et al. 2004, Nicklin and Balas 2007). Specific conductance values above 140 µS/cm were positively related to *G. angulata* density in the Middle Fork John Day River, Oregon, while lower ionic concentrations were negatively correlated (Hegeman 2012). Likewise, areas with higher conductivity values (> 800 µS/cm) had limited mussel (of 21 species) distribution (in south-Eastern Michagan, U.S.A.; McRae et al. 2004). However, recommended conductivity targets for a sensitive Unionoidea (*M. margartifera*) are < 100 µS/cm (Oliver 2000 as cited in Young 2005) and < 70 µS/cm (Bauer 1988). Similarly, low conductivity values (e.g., < 25 µS/cm), limited the mussel (*Margartifera hembeli* Conrad, 1838) distribution in a study by Johnson and Brown (2000), in the Red River, Louisiana, U.S.A.

Low conductivity values may indicate waters with ion concentrations (e.g., calcium) below those essential for shell formation. Other ions are important for mussels to maintain osmotic pressure in the haemocoelic fluid (Bedford 1973, Scheide and Dietz 1982). Ion transport processes are continuously functioning inside mussels as they try to maintain the steady-state flux of ions essential for metabolic functions and cellular ion balance (Dietz and Findley 1980, Scheide and Dietz 1982).

2.5.2.3 pH & calcium

Calcium is necessary for shell formation in molluscs. Their shells are composed of calcium carbonate ($CaCO_3$; McMahon 1991). Very high calcium concentrations (>10 mg/L $CaCO_3$) however are correlated with the absence or reduced density of freshwater mussels (Oliver 2000). The pH and minimum concentration of calcium required by freshwater mussels depends on interacting parameters of the habitat, and are often species specific (McMahon 1991). Environments with low calcium concentrations (2.5 mg/L) have had Unionoidea occur within them, while actively taking up Ca^{2+} (McMahon 1991). Low calcium concentrations, however, can result in small and thin shells (Williams et al. 2014).

Mussels have an open circulatory system and, like most bivalves, have no respiratory pigments that maintain blood acid-base balance (McMahon 1991). Mussels have little capacity to buffer their blood from acid buildup in their tissues during anaerobiosis and therefore rely on different mechanisms (McMahon 1991). Instead, $CaCO_3$ is mobilized from their shells as a buffer (McMahon 1991). In these conditions (i.e., acidosis) calcium released from the shell is harboured in the gill concretions so as to prevent its diffusion and loss to the environment.

Environments with low pH ($pH < 5.6$) are known to be detrimental to Unionoidea populations, because this causes shell dissolution (Fuller 1974, Kat 1984, Buddensiek et al. 1993, Strayer 1993). In addition, acidic waters are detrimental to fish populations (Harris et al. 2011, Kratzer and Warren 2013) that may serve as important hosts for freshwater mussels, thereby negatively affecting mussel recruitment. Environments of low pH usually also have low concentrations of calcium (McMahon 1991).

Very high hydrogen potential is also detrimental to unionids (Young 2005) and fish (Serafy and Harrell 1993). A pH range of 6.5-7.2 is optimal for a known sensitive Unionoidea species (*M. margartifera*; Oliver 2000).

2.5.2.4 Other

Other aspects of chemistry are also important in terms of water quality (e.g., nitrate <1.0 mg/L, or <0.5 mg/L sulphate, and phosphate <0.03 mg/L; Bauer 1988 and Oliver 2000 as cited in Young 2005, Moorkens 2000 as cited in Outeiro et al. 2008). Ammonia (e.g., from livestock access, fertilizers, etc.) and common aquatic vegetation treatments (e.g., copper sulphates) introduce sometimes lethal doses of chemicals into water bodies. Various aquatic contaminants are known to be lethal to freshwater mussels (Jepsen et al. 2010). For example, the following contaminants are lethal to unionids at the corresponding concentrations: copper sulphate (2-18.7 ppm), ammonia (5 ppm), cadmium (2 ppm), and many other known contaminants, such as zinc and arsenic trioxide (Havlik and Marking 1987). Any chemicals that are regarded as indicators of eutrophication (ammonia, phosphate, sodium, calcium, magnesium, nitrate, and conductivity) have negative relationships with the growth and survival of unionids (Buddensiek 1995, Nicklin and Balas 2007).

While important, chemistry should not solely be used to explain the distribution of rare mollusc species (Harris et al. 2011). Chemical variable measurements can easily be taken (e.g., probes), but these ‘snap-shots’ divulge little understanding of the dynamics of sites throughout the year (Nicklin and Balas 2007). Although measurements of water quality (chemical and physical) variables in mussel beds have been conducted in many previous studies (Buddensiek 1995, McRae et al. 2004, Nicklin and Balas 2007), when done correctly these measurements can quickly become time consuming and expensive.

2.5.3 Biotic environment

The flora and fauna within the region, watershed, and mussel beds impact RMRM both directly and indirectly. Directly, availability and abundance of host fish can regulate Unionoidea distributions (Vaughn and Taylor 2000). To serve as a host, the glochidia have to fully encyst on gills of the fish (Nedaeu et al. 2009, O’Brien et al. 2013). If encystment does not occur, the glochidia will die within a day or two after spawning has occurred. However, observing encystment is not sufficient to determine if a fish can serve as a host. To confirm that a fish serves as a host for RMRM, metamorphosis into juvenile mussels must be observed (O’Brien et al. 2013). While only preliminary field studies have been conducted in Okanagan Lake in 2013, the data suggest that the most important host of RMRM glochidia is sculpin (*Cottus sp.*) (Mageroy 2015). This is further supported by studies of RMRM in its mid-western range, confirming sculpin as the primary hosts for RMRM (Spring Rivers 2007, O’Brien et al. 2013). Other potential RMRM hosts in Okanagan Lake include longnose dace (*Rhinichthys cataractae*), leopard dace (*Rhinichthys falcatus*), and northern pikeminnow (*Ptychocheilus oregonensis*)

(Stanton et al. 2012, Mageroy 2015). A study of RMRM at its southern distribution limit also showed very limited metamorphosis of glochidia into juvenile mussels on tule perch (*Hysterocarpus traski*), and hardhead (*Mylopharodon conocephalus*) (Spring Rivers 2007).

Predators and competitors add another direct effect on RMRM distribution. Some fish species predate on glochidia, juvenile, and adult RMRM, such as European Carp (*Cyprinus carpio;* McMahon 1991). Other natural predators include raccoons, muskrats, and occasionally humans (McMahon 1991, Davis et al. 2013).

Both resource and spatial competitors impact RMRM distribution. Aquatic macrophytes can act as spatial competitors that can alter substrate and water movement where they are prolific (Dunbar 2009). One such species, Eurasian watermilfoil (EWM, *Myriophyllum spicatum*) establishes itself in dense beds that increase siltation and interrupt water movement (Dunbar 2009). The accumulation of organic matter and sediments in EWM (or any dense vegetation) patches can decrease dissolved oxygen along the benthic layer through decomposition. While increased vegetation can create flow refuge and was correlated with increased RMRM occurrence in a river study (Hegeman 2012), increased vegetation likely has the negative impacts discussed previously in lentic habitats. Although bivalves and other filter feeders compete for suspended nutrients in the water column with RMRM, Vaughn and Taylor (2000) have suggested spatial and resource competition are negligible in importance for unionid successfulness, and therefore do not account for the patchiness of mussel distribution.

2.6 Random Forest classification and calibration statistical background

Habitat suitability models are created from species-habitat relationships. Classification procedures in ecology have become more popular in recent years (Vezza et al. 2012). Classification trees are commonly used statistical methods used to predict species distributions and create habitat suitability models (Mouton et al. 2010, Vezza et al. 2012). Habitat suitability models can be used in conservation and management to (1) understand interactions of organisms and their environment, (2) predict species occurrence, and (3) "to quantify habitat requirements" (Vezza et al. 2012). RandomForest (RF), developed by Leo Breiman, is a low variance statistical algorithm, implemented in R, which can be used for both classification and regression to derive habitat suitability models (Breiman 2001, Grömping 2009, Chen and Ishwaran 2012).

A RF is created by hundreds to thousands of trees which branch from a bootstrap sample (approximately two-thirds) of the original data (Breiman 2001, Chen and Ishwaran 2012). The first randomized step of RF occurs when predictor variables are chosen randomly from a given number of variables denoted by the 'mtry' tuning parameter, which are then used to create a tree based off the partitioned response variable (i.e. considering one variable at a time) (Genuer et al. 2010, Murphy et al. 2010). The second layer of randomization occurs at the nodes, where RF selects a random subset of variables in which to create the next node, rather than using the entire dataset (Chen and Ishwaran 2012). The hundreds to thousands of trees produced creates the forest. Trees are then combined into a single prediction, which is then used to rank variable importance (Murphy et al. 2010).

Model Validation is a built-in application of RF with the out-of-bag cross-validation, using one-third of the original data (i.e., those data initially left out when creating the RF (Breiman 2001). RF does not compute *p* values, regression coefficients, or confidence intervals as traditional statistical analysis outputs (Cutler et al. 2007). Instead, RF can "subjectively identify ecologically important variables for interpretation" (Cutler et al. 2007) and can be very useful for determining ecologically important predictors. RF accounts for correlations and variable interactions, and ranks interactions between variables by importance (Chen and Ishwaran 2012). The popularity of this algorithm is attributed to its ability to incorporate large numbers of variables with small sample sizes, and in addition output a valid assessment (Grömping 2009, Buechling and Tobalske 2011, Chen and Ishwaran 2012). Many studies have illustrated RF outperforming other statistical analysis procedures, such as linear regression (Vezza et al. 2014), classification trees, and linear discriminant analysis (Cutler et al. 2007, Siroky 2009).

Using RMRM presence/absence data, RF selects random subsamples to predict correlations of layers (Buechling and Tobalske 2011). This technique reduces the risk of overfitting and correlation among predictor variables (Buechling and Tobalske 2011). Ensemble of trees (i.e., a multitude of decision trees) can average over step-function approximation, whereas a linear single-tree approximation is generally poor (Strobl et al. 2009). Ensemble methods, such as bagging and creating trees in RF, can approximate (linear or nonlinear) any decision boundary (i.e., the boundary between different classes of available variable measures) given a large data set and allowed to grow at a proper rate

(Strobl et al. 2009). Additional advantages to the use of random forests in comparison to other statistical classification procedures include:

(1) its high accuracy,

(2) its ability to predict variable importance in a novel way,

(3) its ability to model complex interactions among predictor variables,

(4) an ability to perform several types of statistical data analysis, and

(5) an “algorithm for inputting missing values” (Cutler et al. 2007).

Each variable is selected and considered one at a time in classification and step-wise variable selection models (Strobl et al. 2009). The order in which these variables are chosen can affect the ranking of variable importance (i.e., order effects; Strobl et al. 2009). Ensemble methods have an advantage of reducing within order effects, as opposed to logistic regression, in that parallel trees (i.e., many trees where each variable is chosen in a different order) are counterbalanced, so the overall ranking of variable importance is much more reliable than stepwise regression (Strobl et al. 2009). However, RF has been shown to be affected by the scale of variables (e.g., including fine and coarse resolution data in the same model; Breiman 2001, Strobl et al. 2009), where causation between predictor variables may be captured. Therefore, applying data of different scales to the model may skew results. This occurs from biased variable selection while building the classification and “effects induced by bootstrap sampling with replacement”(Strobl et al. 2007). In addition, highly correlated predictor variables within RF create a bias towards their selection in individual tree algorithms (Grömping 2009). Therefore, data reduction is generally necessary to remove highly correlated variables from the final model (Grömping 2009).

Chapter 3. Methods

3.1 Study site

3.1.1 Okanagan Lake, Okanagan Valley, BC, Canada

Okanagan Lake, located at 50°0’N, 119°30’W, is a long, narrow lake of dimensions: 120 km long (approximately), and 3.5 km (average) wide, encompassing a 270 km circumference (i.e., shore length; Figure 3; Stockner and Northcote 1974). It is a warm monomictic lake (Stockner and Northcote 1974) and has a watershed of 6178 km^2 (Roed 1995).

The outflow is the Okanagan River, flowing south through Penticton to Skaha Lake. Okanagan Lake reaches a maximum depth of 232 m, and has an average depth of 76 m (Stockner and Northcote 1974).

Okanagan Lake has eight communities located along its shoreline, including Kelowna, Lake Country, Vernon, West Kelowna, Peachland, Summerland, Penticton, and Naramata. These communities have a combined population of approximately 325,000 (B.C. Stats accessed March 1, 2015). Wineries, golf courses, fishing, and boating make Okanagan Lake a tourist attraction throughout the summer (Stockner and Northcote 1974).

The Okanagan Valley is regarded as a dry climatic belt in British Columbia. The climate varies from north to south, with average annual rainfall in the south being 27.5 cm/yr, with 162 frost-free days, and in the north 44 cm/yr, with 107 frost-free days. Extreme summer high temperatures can reach 41°C and extreme winter cold temperatures can reach -27°C (Stockner and Northcote 1974).

Okanagan Lake temperatures range from 1.7 to 23.0°C (Table 1; Mackie 2010), while lake level fluctuations range from ± 0.5 m to ± 0.9 m (in 2009 - 2010; Stanton et al. 2012). In years of drought or little rainfall, these fluctuations may be higher (Stanton et al. 2012).

A comprehensive analysis of Okanagan Lake (including total phosphorous, total nitrogen, zooplankton, periphyton, phytoplankton, and fish community structure, annual Secchi depth, area drainage, and water renewal) in 1970 and 1971, identified it as an oligotrophic system (Stockner and Northcote 1974). It is ranked as one of the most nutrient poor lakes in the Okanagan (Stockner and Northcote 1974). The tertiary water treatment plant at Kelowna now effectively extracts much of the nutrient load from Kelowna's waste; thus, making Okanagan Lake nearly nutrient deficient (Dr. Jeff Curtis UBCO pers. comm, Jerry Mitchell MOE pers. comm.).

Epilimnetic dissolved oxygen in Okanagan Lake is supersaturated (138%) (Mackie 2010) at times, with varying values depending on when and where these samples are taken. Hypolimnetic dissolved oxygen (DO) in Okanagan Lake is approximately 11 mg/L (BC Ministry of Environment 2013). Okanagan Lake spring overturn values of total nitrogen (TN) and total phosphorus (TP) for 2013 were TN: 246 - 249 µg/L (with the exception of the Armstrong Arm TN: 185 µg/L), and TP: 4.1 - 7.8 µg/L (B.C. Ministry of Environment 2013). Ranges in surface water chemistry for Okanagan Lake in 2010 are listed in Table 1. Calcium and alkalinity values are high throughout the year, and dissolved oxygen is high to supersaturated (Mackie 2010).

Table 1. Okanagan Lake seasonal surface water chemistry ranges in 2010 (Mackie 2010).

Variable	**Range**
Alkalinity total (mg $CaCO_3$/L)	108-116
Calcium (mg/L)	30.7-34.1
Chlorophyll a (µg/L) (mean summer estimated)	0.0-1400
Dissolved Oxygen (mg/L)	8.6-13.2
Conductivity (µS/cm)	164-313 (Mitchell and Hansen 2011)
pH	7.3-8.5
Temperature (°C)	1.7 (winter) - 23.0 (summer)

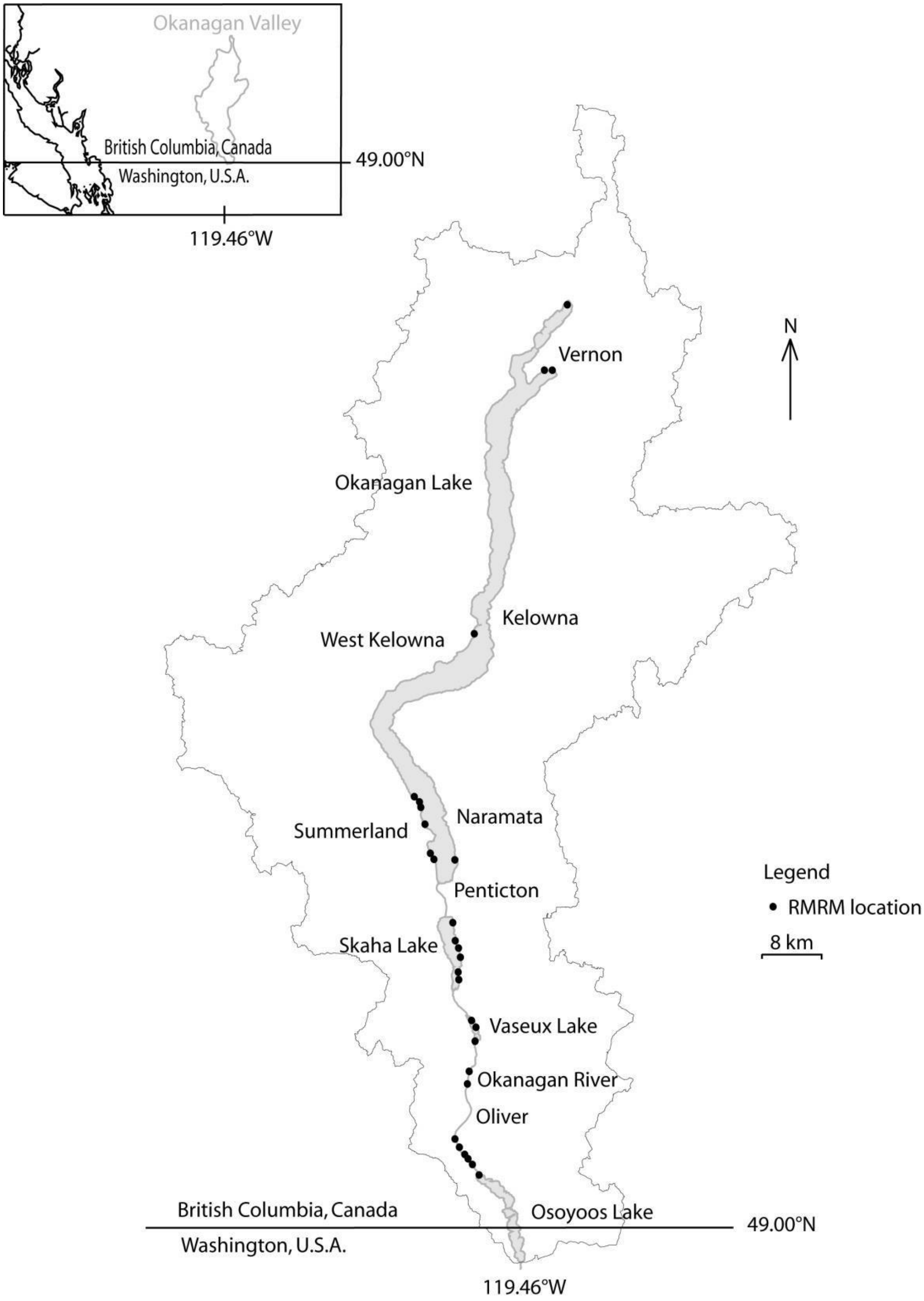


Figure 3. The Okanagan Basin in southern British Columbia, Canada and northern Washington, U.S.A.

3.1.2 Anthropogenic history of Okanagan Lakes and River

There are and were many communities of Native Americans within the Okanagan Valley (referred to as the Okanogan Valley south of the international border), and connecting watersheds of the Columbia River Valley (in Washington and Oregon). The Native Americans of the Okanagan, spanning both sides of the international border, call themselves the Sylix (Okanagan Nation Alliance, accessed March 1, 2015).

Historically, freshwater mussels were a traditional food source for the Sylix First Nation communities within the Okanagan, and also the larger Columbia River Basin (Brim Box et al. 2006). RMRM were also used for jewellery (earrings) and trade (Brim Box et al. 2006). *G. angulata* were used in Oregon by the Karuk Tribe (Davis et al. 2013). Presently, the governing bodies of these Sylix First Nations have shared interests with respect to all animals indigenous to their territory, including *G. angulata* (Hobson and Associates 2006).

Colonization of the Okanagan by European settlers began in 1860, and an intense exploitation of cattle farming and gold mining ensued (Stockner and Northcote 1974). In addition, the increasing population stressed the lakes and rivers of the Okanagan with point (e.g., waste water) and non-point source pollution (e.g., agriculture), contributing to the decreasing water quality of Okanagan Lake starting in 1920 (Stockner and Northcote 1974). The improved tertiary wastewater treatment plant at Kelowna empties into Okanagan Lake, and was introduced to reduce the overall nutrient load. Since recognising the detrimental impacts lake eutrophication can have on ecosystems and populations, restoration and better management efforts have been used to maintain an oligotrophic equilibrium in Okanagan Lake.

3.1.3 Water regulation of Okanagan Lakes and River

The Okanagan Lake Dam, Okanagan Falls, McIntyre, and Zosel dams regulate water levels and outflow from Okanagan Lake, Skaha, Vaseux, and Osoyoos Lakes, respectively (Fisheries and Oceans Canada 2010). In addition to dam construction, river channelization and severe landscape modifications occurred (Fisheries and Oceans Canada 2010). It wasn't until 2011 that restoration efforts began to re-establish the natural meandering of Okanagan River (SOSCP 2011).

3.2 Site selection

To better establish the habitat preferences of RMRM and enable better conservation management decisions for this species, a habitat selection model was developed using RandomForest. Data used for constructing this model were derived from Foreshore Inventory and Mapping data (Schleppe and Mason 2009) and new surveys for the mussels throughout Okanagan Lake. The FIM substrate data were used to avoid collecting data that had already been collected by a team of professionals at a much greater scope and accuracy than could have been done as part of this research. The sites surveyed were spatially distributed throughout Okanagan Lake to make this model inclusive of all potential habitat types.

Prior to site selection, five persons with relevant expertise (Dr. Jon Mageroy, Dr. Ian Walker, Dr. Jeff Curtis, Robert Plotnikoff, and Shelly Miller), were consulted to identify a subset of variables included in the pre-existing FIM dataset likely to be key determinants of the RMRM's distribution in Okanagan Lake. Relative percentages of each variable (e.g., relative particle size for substrates) which occurs along the foreshore, and the degree (i.e., categories of low (0 to 25%), medium (25-75%), high (>75%)) to which large substrates are covered by fine sediments (for an embeddedness measure) were selected. Slope is a categorical measure of the gradient of the shoreline. Based on these consultations five "strong" variables were identified: *low boulder* presence (<20%); low (1-20%) and medium (25-40%) *sand presence*; medium (25-75%) *embeddedness*; none and low (1-20%) *cobble*; and low (0-5%) *slope*. Weak variables identified were medium (25-40%), high (50-60%), and very high (70-80%) *boulder* occurrence; none, high (45-60%), and very high (70-100%) *sand*; low (0-20%) and high (75+%) *embeddedness*; medium (25-40%) and high (50%) *cobble*; and bench, medium (5-20%), steep (20-60%), and very steep (60+%) *slope*.

For the model, 22 sites were included where RMRM were already known to be present as of 2013. The variables identified by the expert consultation process (described above) were then used to generate 22 additional sites, selected in accordance with a stratified random design, where two sites were chosen for each variable from the 'strong' and 'weak' stratification categories (Table 2). The 'strong' categories of each variable had the most RMRM occurrence, while the 'weak' categories had the least RMRM prevalence. GIS was used to locate these sites. This resulted in forty-four sites along Okanagan Lake that were chosen (spatially random) for this project, to gain a complete representation of the lake's habitat. Sites were selected on either side of the lake and in the north, central and southern sectors of the lake.

Table 2. Stratified sampling design from Foreshore Inventory and Mapping database (bolded numbers indicate the sum of RMRM presence sites with the corresponding ordinal variable).

Variables (ordinal)	**Weak**	**Strong**
Boulder presence	Med(25-40):**1**, High(50-60):**2**, Very high(70-80):**1**	Low (0-20): **19**
Sand presence	None:**3,** High (45-60):**3**, Very High(70-100): **3**	Low (1-20), **8** Med(25-40): **6**
Embeddedness	High (75+): **4**, Low(0-20): **0**	Med (25-75): **19**
Cobble	Med (25-40): **3**, High (50): **0**	None: **7**, Low (1-20): **13**
Slope	Bench:**1**, Med (5-20):**2**, Steep(20-60):**3**, Very Steep(60+):**1**	Low(0-5): **16**

3.3 Physical characteristics

In addition to the pre-existing FIM dataset variables, several new variables were considered. These included: geomorphometric description, an underwater ledge, morphometry, total fetch, clay and dissolved oxygen, and host fish presence.

3.3.1 Geomorphometric description

Geomorphometric descriptions capture a macro-scale habitat measurement of each site. Combining multiple scales of variables in mussel habitat suitability models has been suggested to increase model accuracy (Newton et al. 2008). The geomorphometric categories used in this analysis include: cuspate foreland, alluvial fan, crag, beach, bay, cove, breakwater, bank, and a river mouth. A cuspate foreland is defined as an extension outwards from shoreline in the shape of a triangle (Craig-Smith 2005). An alluvial fan is a fan-shaped mass of alluvium deposited at the inflow of streams, in these cases, where the water velocity decreases (Roed 1995). A crag is defined as a cliff or rock face, either steep or rugged. A beach is defined as the shoreline of the lake where small gravels or sand (sediment) are accumulating (Roed 1995). A bay is a broad semicircular indentation of a shoreline, while a cove is a smaller, more sheltered bay. A breakwater is a man-made structure built out into the lake with the purpose of protecting the shoreline from waves. A bank is the land alongside the lake which slopes gradually down towards the water. These descriptions were assigned based on Google Earth images and on-site analysis.

In addition, on-site observation of an underwater ledge was recorded. An underwater ledge is defined as a narrow horizontal shelf (approximately half a meter to three meters in width) continuously submerged under water.

3.3.2 Morphometry

Shore morphometry was measured to compare convexity (points) and concavity (bays) of the shoreline’s features. Screenshots using Google Earth were taken along with a 50 m scale bar (Figure 4). Tangential lines were drawn along the shoreline. The slope (first derivative) was measured using these screenshots and the scale. The slope of this equation (second derivative; ’A’) was then calculated. Negative second derivatives represent bays, numbers nearing zero represent a straight shoreline, while positive numbers represent points or cuspates. The constant ‘C’ is the feature orientation, where a 90° fetch has negligible wind impact, and a near 0° fetch has the highest fetch impact. The morphometry, or second derivative multiplied by the feature orientation, is the potential energy of the feature. ‘Zeroes’ are sites where ‘A’ (the second derivative) was $< \pm 0.45$, as these are determined to be ‘non-features’. Sites with a major stream mouth, river, or wastewater treatment output were omitted from this analysis due to their unique energy and feature forming capacity, which allows them to respond differently to wind. The measurement program ImageJ-win32 was used to measure the first derivative of the shoreline. Increments of 50 m were used for each site to capture important variables, without including unnecessary scale. The following equation was used:

$$\mathbf{morphometry} = \mathbf{A * C}\text{ , where } C = (1- B°/90°)$$

This equation includes the second derivative ‘A’, degrees of fetch off the North-South or tangential 0° axis ‘B’, and the constant ‘C’.

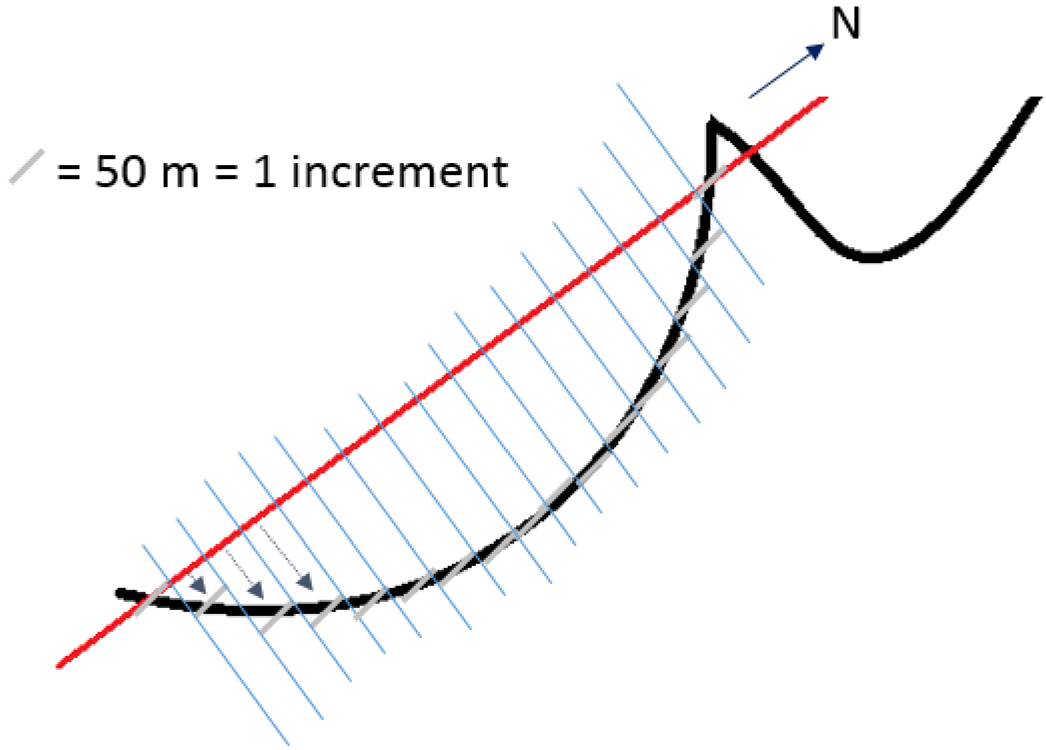


Figure 4. Determination of shoreline morphometry was done using Google Earth 7.1.2.2041 and imageJ 1.48. In this simplified diagram, the tangential line (red) of the shoreline is along the North-South axis. This is the baseline of the measurements. The grey bars indicate each 50m. This increment length was chosen to attempt capturing features at a relevant scale in Okanagan Lake. The scale of imageJ is set for each 1 increment = 50m with the first derivative taken from measuring the number of increments each grey bar is from the tangent line (thereby making this dimensionless). The slope of these measurements is the second derivative 'A'.

3.3.3 Fetch

Fetch is a proxy for wave action, turbulence, disturbance, nutrient movement, and dissolved oxygen within sites (Hakanson 1977, Cyr 2009) relating to mussel presence or absence. Effective fetch of a site is a measure of site exposure to predominant winds (Hakanson 1981, Callaghan et al. 2015). Effective fetch, also known as total fetch, was calculated using a map of Okanagan Lake following methods described by the Beach Erosion Board (1972). Prevailing wind directions were determined at each site from nearby weather stations at the ‘windfinder’ website (Table 3). Each study site had fetch calculated from the location that would give the maximum distance.

Table 3. Weather station location and prevailing wind directions used to calculate fetch of each site.

Weather Station	**Prevailing Wind Directions**	**Geographic coordinates**
Westbank	NNW, SSW	119° 33' 31.47"W 49° 50' 48.16"N
West Kelowna Yacht Club	W, NNW, E	119° 37' 26.00"W 49° 49' 0.96"N
Summerland	NE, SE, & WNW	119° 38' 59.90"W 49° 33' 55.99"N
Penticton Airport	N & S	119° 36' 2.22"W 49° 28' 7.47"N
McKinley Landing, Kelowna	W & E	119° 27' 26.35"W 49° 58' 5.16"N
Vernon, Beachcombers Bay	E & SW	119° 21' 44.46"W 50° 14' 2.61"N

Okanagan Lake has alternating and seasonal wind patterns along its shoreline from one end to the other (as observed on windfinder.com). Data for wind direction were taken from the Penticton airport, for the southern-most sites on Okanagan Lake (FIM object ID numbers 40, 42, 43, 44, 50 & 51); Summerland, for locations in Summerland and Naramata (Object ID's 20-30, 39, 41, 59, 62, 63, 70); West Kelowna's Yacht Club, for sites in Peachland and Squally point (Object ID's 4, 75 and 312); Westbank/Kelowna weather station (different than the Kelowna airport station) for sites in West Kelowna and Kelowna (object ID's 89, 101, 115, 222, 235); the McKinley Landing weather station, for most sites on the northern half of Okanagan Lake (object ID's 127, 139, 142, 146, 160, 164, 190, 201); and Vernon's Beachcomber Bay (Figure 5), for sites on or near the Vernon Arm (Object ID's 173, 259, 266, 273, 274). Since the Kelowna airport weather service is in a separate valley from Okanagan Lake, it was not used in this analysis.

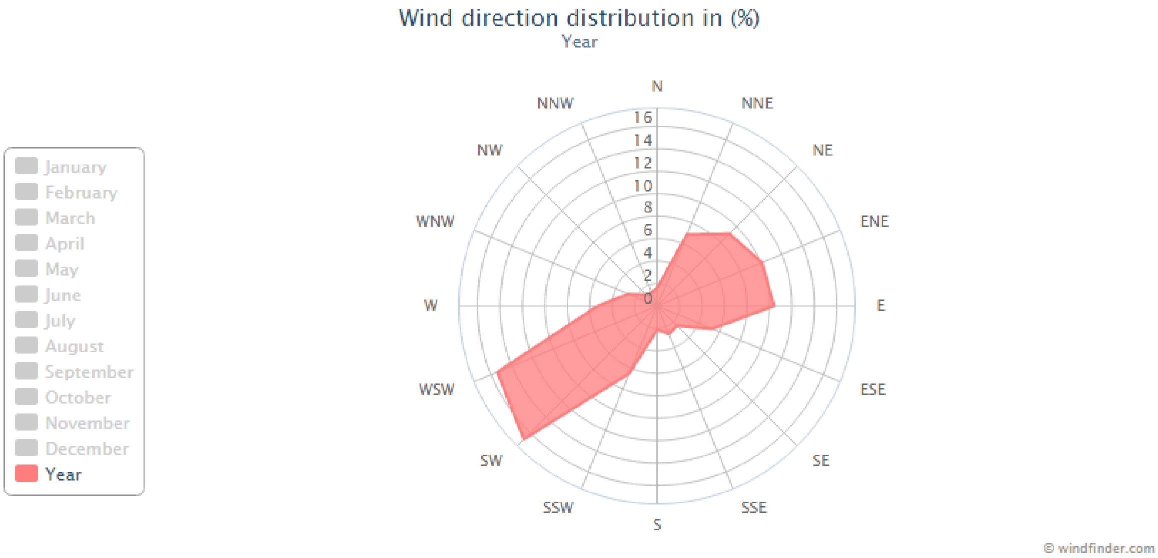


Figure 5. Prevailing wind direction in Beachcomber Bay, Vernon with the incident (0°) coming from the E and SW, reproduced with permission (windfinder.com).

Each site's prevailing wind direction was measured from every deviation angle: 0° (+/-) 6°, 12°,18°, 24°, 30°, 36°, 42° (Hakanson 1981). Total fetch is the combined prevailing winds, and calculated via the equation,

FETCH = Xcos(Y)*S / cosY,

where Y = the deviation angle from the prevailing wind direction,

x = distance between the site and a land mass (in cm units) of 'Y' deviation angle,

S = the scale constant; S = 1.1 for the map scale of Okanagan Lake (where 1 cm = 1.63 km; B.C. Ministry of Environment, Bathymetric Maps Query, accessed in 2014).

Sites located at stream or river mouths will have different current action that is not controlled by the total fetch (Hakanson 1977). As such, sites that were located at stream or river mouths were omitted from the final model. These sites will likely act independently of a fetch effect; being affected by advective water movement, rather than turbulence from wind and wave energy dissipation.

3.3.4 Clay & dissolved oxygen

Clay presence, and depth to anoxic conditions were measured at each site. This was accomplished by the use of ribbed rebar (driven into the substrate at each site), for two reasons. One, clay will stick to the ringed rebar surface during extraction; thus, upon rebar removal, observations of clay presence within the top 30 cm of substrate could be noted. The ungalvanized rebar also facilitated an assessment of dissolved oxygen. Rust formation on the rebar indicates oxidation, and thus, the presence of oxygen. This allows a long-term evaluation of substrate conditions (Per Jakobsen Professor at the Department of Biology, University of Bergen, Norway, pers. comm.).

Before placing the stakes, the rebar was scrubbed with wire brushes and acid rust remover to ensure no prior rust was present. At each of the 44 sites, rebar (one, two or three stakes with a ringed rebar surface) was driven 30 cm into the substrate, unless this was impossible. At each site the stakes were driven either in very close proximity to where mussels were present (positive sites), or, where mussels were absent (negative sites), into a substrate that would allow rebar penetration. The rebar were not placed along the entire length of each site.

The rebar stakes were deployed at each site for a minimum of 8 weeks. Upon removal, the rebar were photographed next to a ruler for scale. Notes were made recording where rust occurred and, most importantly, the depth to anoxia (i.e., where rust no longer occurred).

3.4 Surveying *G. angulata*

Surveys were conducted at each site to assess mussel presence or absence. Survey efforts for *G. angulata* included a minimum of two snorkelers swimming beside each other, making parallel sweeps along the shoreline. Sweeps progressed farther out (at greater depths) once the entire length of the site was reached. This is a common survey approach for rare freshwater mussel species (Smith 2006, Mackie et al. 2008, Stanton et al. 2012). Survey depths are limited to approximately 4m with this method.

3.5 Host fish

Potential host fish presence or absence at each site was observed while snorkelling for *G. angulata*. Sculpin are very well camouflaged, small, and quick. They are easiest to locate in the shallows (<1m) and could be found by gently moving the cobble or large woody debris, beneath which they often hide (Snook pers. obs.). Only sculpin were surveyed, although other fish species may be hosts for *G. angulata* glochidia (Spring Rivers 2007, Stanton et al. 2012, O'Brien et al. 2013, Mageroy 2015).

3.6 Sensitivity analysis

Highly correlated predictor variables are known to cause bias towards their selection (Strobl et al. 2009) thus, a series of data reductions were conducted to remove highly correlated variables from the final model. The main tuning parameter in RF models is the 'mtry' function, which dictates how many "randomly preselected predictor variables" are used to create each split in a node in a classification tree (Breiman 2001, Strobl et al. 2009). Multiple models, listed below, were run as iterations with data reductions and 'mtry' ranging for each series from 2 (minimum mtry) to 6 (where applicable). The average mean decrease in accuracy (MDA) over 100 iterations is used to calculate and compare the lowest misclassification rates. The (MDA) is determined during the out-of-bag error calculation phase (Breiman 2001).

Variables were removed from the original twelve sequentially, with the least important variable being removed upon completion of each iteration, to produce a model with the lowest average misclassification rate (Grömping 2009, Strobl et al. 2009), by tuning the 'mtry' parameter. Each model run generated 5000 trees of 100 iterations each. The various scenarios explored included: A) no depth to anoxia, B) no clay, C) no underwater ledge or depth to anoxia, D) no geomorphometric description, E) no shoreline morphometry, F) no clay, underwater ledge, and no depth to anoxia, G) no clay, underwater ledge, depth to anoxia, and no cobble, H) no sculpin, underwater ledge, geomorphometric description, and no depth to anoxia. Finally, the most important predictor variables were used to generate a final model incorporating the top five predictor variables.

3.7 Variable importance

Variable importance was assessed using the mean decrease in accuracy (MDA). The MDA for each variable was determined by normalizing the difference between the classification accuracy for variable data ‘observed’ and the classification accuracy for the variable randomly permuted (Cutler et al. 2007). The higher the value of the mean decrease in accuracy, the more important the variable is within the classification (Cutler et al. 2007).

Each variable’s effect on the probability of RMRM occurrence was visualized in a partial dependence plot. The partial dependence plots y-axis is a logit function, which is the log of the odds (probability/ 1-probability). The x-axis is the independent predictor variable. Partial dependence plots illustrate the probability of *G. angulata* occurrence based on one predictor variable in the best model after averaging out the effects of all other predictor variables (Cutler et al. 2007).

3.8 ArcGIS 10.1 model

The final model was produced from the Foreshore Inventory and Mapping data as a vector map in ArcMap10.1. Layers within the FIM that were used included the most favorable habitat ranges of embeddedness, sand, and boulders, in addition to a ‘mussels’ (known presence) layer. Of these overlapping sites with favorable variables, total fetch was calculated.

Chapter 4. Results

4.1 Model data reductions

For the model that included all data, the most important variables for predicting occurrence of RMRM were embeddedness, effective fetch, sand, boulders, and slope (Figure 6). The least important variables for predicting RMRM occurrence were geomorphometric description, underwater ledge presence/absence within the foreshore, sculpin presence (*Cottus* sp.), and depth to anoxia (Figure 6). The latter variables were then eliminated in a series of reductions while altering the main RF tuning parameter 'mtry' to establish the most accurate model with the lowest percent misclassification rate. This procedure aims to identify the variables that add noise to the model and diminish model accuracy. The variables clay, underwater ledge presence within the foreshore, and depth to anoxia were eliminated through this procedure. Subsequently, a model was produced which included nine variables (see appendix 2 Figure A2) with a misclassification rate of 10.08%. In both of these models, embeddedness, total fetch, sand, boulders, and slope were ranked as most to least important respectively. Therefore, the final model for RMRM includes these top five predictor variables (Figure 7), with a misclassification rate of 12.75% in the sensitivity analysis.

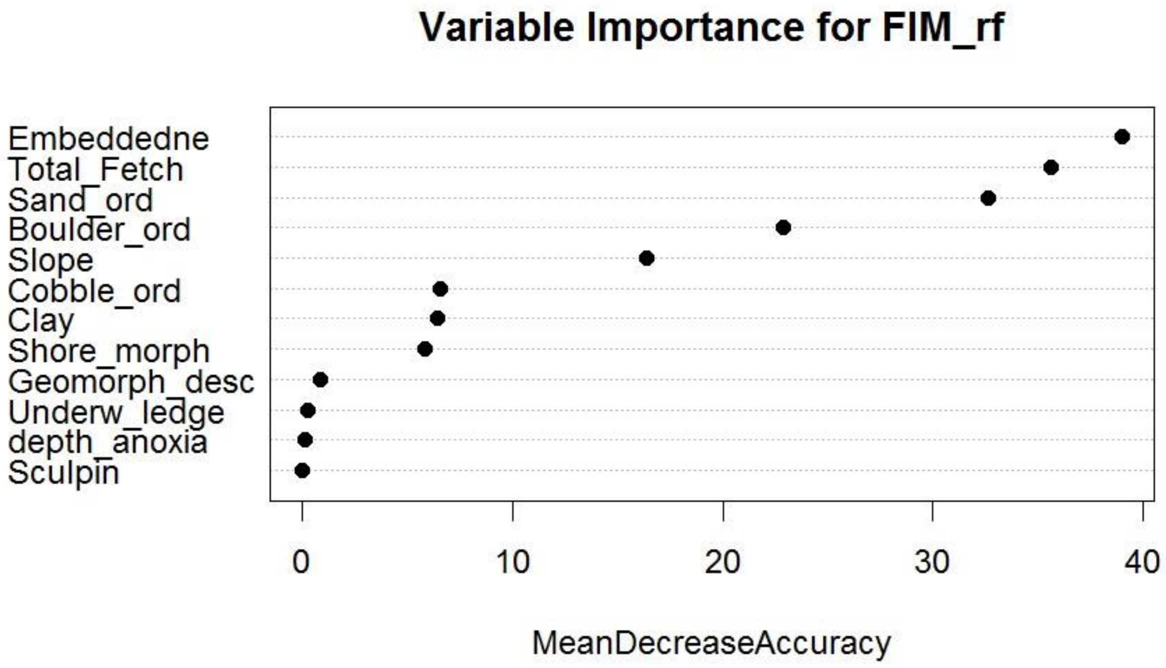


Figure 6. Variable importance plot for the full RF model (including all twelve predictor variables) of habitat suitability for *G. angulata*. The misclassification rate for this tuning parameter, set at mtry=3, is 11.65%.

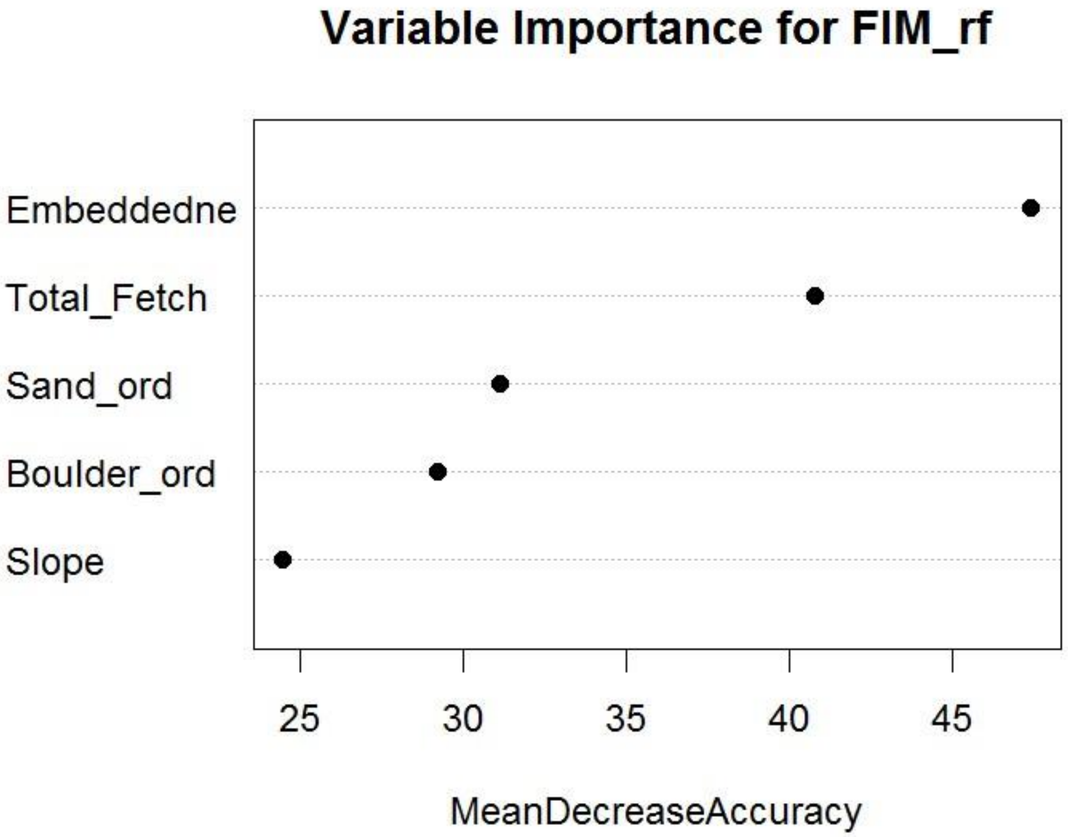


Figure 7. The mean decrease in accuracy (MDA) with the top five predictors in the random forest with the lowest misclassification rate (12.75%) in the sensitivity analysis (mtry = 2).

4.1.1 Stratified random sampling of RMRM

The stratified random sampling approach was successful in locating three additional presence sites for RMRM. This model, which was based on the predictor variables (Table 2) recommended by experts (e.g., Dr. Jon Mageroy, Dr. Ian Walker, Dr. Jeff Curtis, Robert Plotnikoff, and Shelly Miller) for detecting suitable habitat and increasing the likelihood of finding RMRM (for surveying from June - August 2014), had a misclassification rate of 70% (i.e., three sites of the predicted ‘strong’ sites correctly predicted RMRM, while the remaining seven sites did not appear to have RMRM) (Table A2.1). In comparison, the random forests model has a 12.75% misclassification rate.

4.2 Partial dependence of variables

The substrate partial dependence plot (Figure 8) indicated that the likelihood of RMRM occurrence increased with increasing embeddedness, while ‘low’ embeddedness was negatively correlated with RMRM occurrence. The trend of the marginal effect of effective fetch on the probability of RMRM presence appears limiting below approximately 6 km, dependent at 6-12 km, saturated at 12-20 km, and possibly inhibiting after 20 km with a slight decrease in probability of RMRM occurrence. This relationship is non-linear.

Increasing percentages of sand indicated increasing probability of RMRM occurrence, with low sand appearing to limit RMRM. The highest probability of RMRM occurrence occurred with low boulder presence in the foreshore, the lowest at medium boulder presence, and increased again at high and very high boulder presence.

An increasing slope was correlated with decreasing RMRM occurrence (Figure 8). As slope changed from bench to low inclination, there was a slight decrease in RMRM probability of occurrence. With an increasing inclination of slope (i.e., from low to steep) the probability of RMRM occurrence dropped. From steep to very steep inclination there is little change in probability of RMRM occurrence.

4.2.1 Partial dependence of variables omitted from the final model

The highest probability of RMRM occurrence was when there were no cobbles present (Figure 8). The probability of RMRM occurrence decreased as cobble presence increased.

The site morphometry variables included geomorphometric description and shoreline morphometry (in addition to slope, Figure 8). Geomorphometric descriptions of bank (the land alongside/sloping down to the lake) and bays were the most important land forms, as well as crag, for RMRM occurrence. Bays (negative shoreline morphometry of -0.45<) provided habitat for RMRM, with decreasing probability of RMRM occurrence at near zero values (i.e., straight shorelines), and again increasing and highest RMRM probability of occurrence in points/convexity (larger positive shoreline morphometry).

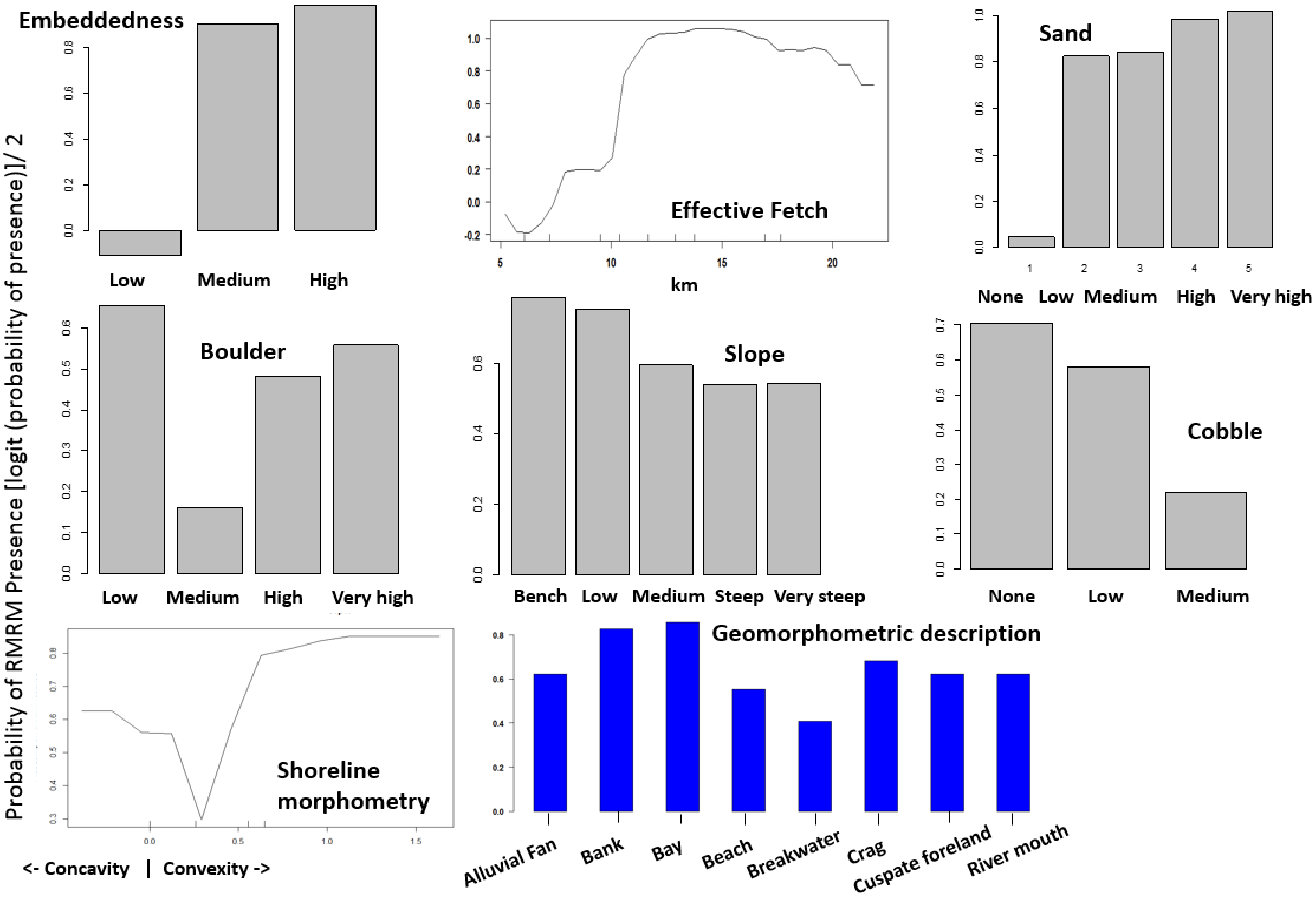

Probability of RMRM Presence [logit (probability of presence)]/ 2
Embeddedness
0.0
0.2
0.4
0.6
0.8
Low
Medium
High
Effective Fetch
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
5
10
15
20
km
Sand
0.0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5
None
Low
Medium
High
Very high
Boulder
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Low
Medium
High
Very high
Slope
0.0
0.2
0.4
0.6
Bench
Low
Medium
Steep
Very steep
Cobble
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
None
Low
Medium
Shoreline morphometry
0.3
0.4
0.5
0.6
0.7
0.8
0.0
0.5
1.0
1.5
<- Concavity
Convexity ->
Geomorphometric description
0.0
0.2
0.4
0.6
0.8
Alluvial Fan
Bank
Bay
Beach
Breakwater
Crag
Cuspate foreland
River mouth

Figure 8. Partial dependence plots of the variables in the random forest models. Plots indicate probability of *G. angulata* occurrence based on each predictor variable in the best models after averaging out the effects of all other predictor variables in the model. Embeddedness is an ordinal variable including low (0-25%), medium (25-75), and high (>75%) categories. Total fetch (effective fetch, km) is a continuous measure. Sand is an ordinal variable including none, low (1-20%), medium (25-40%), high (45-60%), and very high (70-100%). Boulder is an ordinal variable including the following categories of boulder: low (0-20%), medium (25-40%), high (50-60%), and very high (70-80%). Slope is an ordinal variable including categories bench, low (0-5), medium (5-20), steep (20-60), and very steep (60+). Cobble is an ordinal variable, with categories including: none, low (1-20%), and medium (25-40%). Shoreline morphometry is the combination of the angle of fetch off of the shoreline tangent and of the shoreline's second derivative, which includes negative values for bays (concavity) and positive values for points (convexity). Geomorphometric description includes eight categories (alluvial fan, bank, bay, beach, breakwater, crag, cuspate foreland, and river mouth). The main tuning parameter (mtry) is 2, there are nine predictor variables, and the misclassification rate is 10.08%.

Chapter 5. Discussion

5.1 Predicting habitat suitability for at-risk species; importance for management

Habitat suitability models are a common and accurate tool to assist in management of at-risk species (Suzuki et al. 2007, Vezza et al. 2012, 2014, Lauria et al. 2015). Statistical applications are important in determining classification, variable importance, and assessment of parameters (Suzuki et al. 2007, Strobl et al. 2009). The application of these models has had cases of success where populations of rare and at-risk species have been located, numbers have been maintained or increased, or by describing and locating niches and travel corridors (Suzuki et al. 2007, Vezza et al. 2012, 2014). Current research focuses on accurate and robust statistical modelling packages, as well as incorporating variables that will enhance a model's predictive power. For mesohabitat and Unionidae habitat suitability studies, recommendations include incorporating biotic and abiotic interactions to increase model performance (Vezza et al. 2012, Davis et al. 2013).

Unionids are declining worldwide (Bogan 2008, Lydeard et al 2004, Strayer et al. 2004). This creates a vital need to understand their biological and ecological needs to assist in sound recommendations for constructive conservation approaches. While most unionids have narrow ranges of habitat parameters in which they can survive, they also have species specific habitat preferences (Nicklin and Balas 2007, Steuer et al. 2008, Wolf and Smith 2010). Predicting habitat suitability for at-risk species is useful for both conservation management and analyzing relationships between organisms and the environment (Guisan and Zimmermann 2000, Guisan et al. 2006, Buechling and Tobalske 2011, Humphries et al. 2012).

5.2 Rocky Mountain ridged mussel

RMRM reaches its most northern extent in Okanagan Lake, BC. RMRM is listed as a special concern (Species at Risk Act, 2015), declining in numbers throughout most of its range (Davis et al. 2013), and is continuously facing habitat modification (Stanton et al. 2012). One main objective of this study was to develop a habitat suitability model to determine important habitat variables within Okanagan Lake for RMRM.

The RandomForest classification package has been used to accomplish this objective, and a robust RMRM habitat suitability model for Okanagan Lake has been developed (Figure 6, 7). Of the complete Okanagan Lake circumference, 16.2 % was surveyed for this project. Results from this model are similar to other findings with regard to RMRM habitat and other unionid species with range overlap. For example, substrates for mussels to bury in, such as sand and embedded boulders (Vannote and Minshall 1982, Strayer and Ralley 1991, Bodis et al., 2011, Davis et al., 2013), as well as sufficient exposure (i.e., fetch) (Cyr, 2009) are important predictors for unionid distribution in other studies. The second objective was to use this model to develop recommendations for potential relocation sites and to predict and to depict where suitable habitat exists in Okanagan Lake. This product will assist the Ministry of Forests, Lands, and Natural Resource Operations and the Ministry of Environment in conservation management for RMRM in Okanagan Lake.

I hypothesized that the RMRM is not distributed at random with respect to habitat in Okanagan Lake. This hypothesis is supported, in that top predictor variables clearly provide favorable habitat in determining RMRM distribution. I predicted, based on previous research that this species' habitat preferences are for 'low' embeddedness, presence of boulders and cobbles, low-moderate slope, and high fetch. While some of the hypothesized predictors are supported, others are different than expected. Specifically, high total fetch (seven and a half kilometers or higher) and slope (low and bench) are supported by this model. Hypotheses that are not supported included boulder substrate, where low boulder occurrence and high substrate embeddedness provide suitable habitat.

5.3 Key findings

The most important variables for RMRM, in this model, include high embeddedness (>75%) as most important, followed by total fetch (>10 – 16 km), increasing sand (>20%) presence, and low or very high boulder occurrence (Figure 8). Embeddedness of substrates, sand and boulder substrate types have been highlighted in earlier studies of RMRM (in the USA) and other unionids (Morales et al. 2006, Cyr 2009, Allen and Vaughn 2009, Bodis et al. 2011, Davis et al. 2013). Site exposure (measured as effective fetch) also affected unionid behaviour (Cyr 2009). RMRM are generally found in lotic habitats, where water velocity can easily be measured (e.g., cm/s) and/or categorized directly (e.g., glides, riffles). While embeddedness is often analyzed in unionid studies, it surprised experts that RMRM are better adapted to medium and high embeddedness conditions in Okanagan Lake. However, there are very different hydrodynamic properties for lotic and lentic habitats. In lotic habitats, water movement enables finer sediments and organics to move downstream, delivering a constant source of food to mussels. In lentic habitats, there must be significant wind and wave action to transport and load sites with organics and fine sediments. Higher embeddedness measures observed in lentic habitats supporting RMRM, as observed in Okanagan Lake, can translate to food availability.

Host fish was recommended by experts as a biotic component to include in this model (Steuer et al. 2008, Davis et al. 2013), but was surprisingly ranked as one of the least important variables. However, this is likely because sculpin (*Cottus* sp.*)* are found at every site, and as such are likely not important in predicting or limiting the distribution of RMRM in Okanagan Lake. Therefore, I would argue host fish is still one of the most important biological components for RMRM survival, but is an independent and saturated variable in this lake system. In addition, model accuracy increased with the removal of 'clay' and 'underwater ledge'. These were also unexpected, as clay can contribute to an alkaline environment, thereby lowering the risk of acid shell erosion. An underwater ledge was thought to provide a suitable anchorage environment and stable substrate as mussels were often observed along these features, with organics and fine sediments accumulating below them (Snook pers. obs.).

The most accurate model for RMRM habitat suitability included nine predictor variables (10.08%; Appendix 2 Figure A2). There is a higher percent misclassification with models using all twelve predictor variables (11.65%; Figure 6) and with only the top five predictor variables (12.75%; Figure 7). While increasing the number of variables can produce a more accurate predictive model, the efficiency of collecting and analyzing fewer explanatory variables makes a model more useful. While this study's functional approach was designed to highlight important variables the mussel needs from its surroundings, focusing solely on substrate types is not substantial in its explanation

(Davis et al. 2013, Strayer 2014). Although there are studies that explain abundance and distribution of Unionidae species from substratum properties (Brim Box et al. 2002, Colle and Callil 2012), additional variables can act as proxies to explain multiple relationships (Davis et al. 2013).

5.4 Comparison with previous work - RMRM habitat relationships

5.4.1 RMRM relationship with substrate

Experts were surprised by the importance of high embeddedness (70-100%) of substrates in this model. It was expected that high substrate embeddedness would result in suffocation of mussels, thus leading to conditions unlikely to support RMRM. Components of fine sediments that make up the ‘embeddedness’ measure may include organics that decompose, creating low oxygen environments from bacterial oxidation reactions. Embeddedness is often used to assess macroinvertebrate habitat (Sylte and Fischenich 2002). Higher embeddedness is associated with a limited area for fish, macroinverterbrates, and periphyton to live in (Sylte and Fischenich 2002). High embeddedness is not necessarily where one would expect to see RMRM in river habitats (Bogan 1993, Brim Box et al. 2002). This is due to the hydrodynamic differences between river and lake habitats (i.e., the downstream transport of finer materials in a higher energy environment will reduce embeddedness), where rivers containing RMRM may have little fine sediment accumulation in RMRM vicinity. However, a high embeddedness measure appears to be the optimal habitat within a lake system. Okanagan Lake is a well circulated lake (pers. comm. Dr. Curtis), and likely has abundant oxygen throughout its littoral benthic environment.

RMRM have well developed siphons and appear to be positioned mostly buried while not having filtering functions affected, making them suitable inhabitants of fine sediment and sand (Vannote and Minshall 1982). High embeddedness, however, may still suffocate these filter feeders (Bogan 1993) without a sufficient amount of oxygen delivered. The relationship between low (0-20%) embeddedness and the negative probability of RMRM occurrence can be explained by the absence of food for the mussels in this environment. Unionid presence with medium or high embeddedness has been suggested to reflect the increase in organic matter presence (i.e., food availability) or other factors such as sediment stability where the deposition of fine sediments occurs in low energy environments (Brim Box et al. 2002).

In accordance with earlier studies, absence of sand indicated zero likelihood of RMRM occurrence, while increasing sand abundance was correlated positively with the probability of RMRM presence (Vannote and Minshall 1982). Sand provides a suitable medium for RMRM to bury in (Vannote and Minshall 1982, COSEWIC 2003, Davis et al. 2013, Strayer 2014) and does not inhibit movement. Sand will also allow oxygen penetration, whereas clay or silt will allow little or none (Dr. Walker, professor at UBCO, pers. comm.). High amounts of sand and medium embeddedness do not appear to negatively impact RMRM (Snook pers. obs.). In sand and gravel, RMRM have been recorded to move an astounding 5 cm/hour, vertically (Allen and Vaughn 2009).

Low boulder occurrence is the most important category of this variable for RMRM. While ‘medium’ boulder occurrence predicts a sharp decrease in RMRM occurrence, there is an increase in predicted RMRM occurrence with ‘high’ and ‘very high’ boulder percentages. Consistent with other (riverine) studies, boulders play an important role for RMRM and other unionid distributions. Boulders may provide microhabitats below them, capturing fine sediments with eddies and currents at their base and thereby supplying dissolved oxygen, nutrients, and plankton (Davis et al. 2013).

Boulders offer stable substrate and refuge from bed shear stress and scouring (i.e., high energy water movement) which may remove glochidia, juveniles or adults (Vannote and Minshall 1982, Strayer and Ralley 1991, Strayer 1993, Layzer and Madison 1995, Cyr 2009, Daraio et al. 2012, Davis et al. 2013, Strayer 2014). In this way, boulders may act as protection from large fetch influences (i.e., surface and internal waves). Areas of refuge can then provide stable substrate, and possibly explain some, but not all, of the 'patchiness' observed in mussel locations which may be subject to disturbances, such as drought (dam drawdowns) or scouring from storm events (Strayer 2014). Stable substrate was found to be correlated with unionid occurrence in earlier studies (Vannote and Minshall 1982, Strayer and Ralley 1991, Strayer 1993, Di Maio and Corkum 1995, Strayer 2014). Although substrate stability was not measured in this study, it can be inferred from the occurrence of embedded boulders and the increasing probability of RMRM occurrence in these locations.

In Okanagan Lake, the variable category 'very high sand' is only associated with 'low boulder' occurrence (Schleppe and Mason 2009). This model doesn't explain why medium boulder correlated with low RMRM probability of occurrence. However, of the 314 sites within Okanagan Lake, only one site contained mussels with a 'medium' boulder measurement. This site also had a 'low' sand measurement. Therefore, it can be assumed that this extremely low RMRM presence, coupled with unfavorable sand availability, was reflected in the final model.

Zero cobble in the foreshore correlates with the highest probability of RMRM occurrence in this model. *G. angulata* have been found to inhabit interstitial substrates between cobbles and boulders in a river study (Vannote and Minshall 1982). An increasing presence of cobbles may inhibit mussel movement, both vertically and along the lake bottom. A low and medium percentage of cobble presence can still allow mussel movement, and possibly provide some refuge from large fetch as well. While RMRM is observed in many sites with cobbles in Okanagan Lake, this model suggests the embeddedness of this substrate size, and not the persistence of cobbles in each site, is the more powerful explanatory variable for RMRM distribution.

5.4.2 RMRM relationship with total (effective) fetch and substrate

Fetch (the distance wind can travel without being impeded by land) can play a role in lakes analogous to water velocities in streams and rivers, where RMRM are generally found. Very large fetch, however, can result in scouring, bed shear stress, excess turbulence, and removal of the fine sediments necessary for burying, while possibly creating unstable substrate (Hakanson 1977, Cyr 2009). In addition, *Gonidea* may potentially be dislodged as juveniles and/or adults by scouring events (i.e., high fetch) (Cyr 2009, Davis et al. 2013), as well as be “crushed/scoured by large mobile substrate” (Strayer 1999). This may be what is illustrated with effective fetch greater than 16 km (Figure 8)

Considering the long and narrow morphometry of Okanagan Lake, winds are able to travel great distances, making fetch an important variable for a model such as this. Sites with exposures less than 7.5 km are negatively associated with RMRM occurrence. Probability of occurrence sharply increases (non-linearly) from 10 km (approximately) to 16 km (approximately), thereafter decreasing. As fetch increases, this potentially supplies sites and therefore benthic organisms with food and dissolved organics (Cyr 2009). Sites with exposures greater than 16 km may limit RMRM occurrence. Fetch creates surface waves, internal waves, and longshore currents which deliver dissolved oxygen, plankton, and nutrients to benthos in littoral zones (Cyr 2009). Total fetch is therefore a measure for the potential energy from wave action, turbulence, and water movement at each site. Fetch is also responsible for sediment distribution throughout the lake. Erosion-transport-accumulation dynamics of fine sediments result from wind energy and lake bottom dynamics, where wind direction, wind duration, and wind velocity affect longshore currents and longshore sediment transport (Hakanson 1977).

Wind action interacts differently at sites with different slopes (e.g., bench vs. slope > 60%), where steeper slopes will have “no fine material deposited” (Hakanson 1977). The importance of ‘bench’ and ‘low’ gradient sites for RMRM occurrence may be linked to the turbulence arising from total fetch interacting with the need for an environment where anchorage is accessible (i.e., fine material is present with an optimal fetch range), food is available, and oxygen is delivered to the benthic layer.

The accumulation of fine sediments and organic matter in habitats occur in low energy locations (Hakanson 1977). An excess of turbulence (e.g., fetch >16 km), in a high energy site, will result in the scouring and bed shear stress that transports fine sediments away from the site, resulting in a low embeddedness measure for that location (Hakanson 1977). However, in this model we see an increase of fetch (to 16 km) correlating with increasing RMRM occurrence, as well as high embeddedness being an important habitat parameter. Fetch in excess of 16 km likely causes too much turbulence and inhibits RMRM from establishing in these locations, but a fetch range of 10-16 km will create the necessary turbulence RMRM need for dissolved oxygen, nutrients, and embeddedness around boulders and in deeper sections than the immediate shoreline.

Solely using substrate size is not sufficient to determine mussel distribution (Davis et al. 2013). Hydraulic environments in combination with substrates will provide more relevant information (Allen and Vaughn 2009). Substrate size can be used as a proxy for “the real controls; hydraulics and substrate stability” (Davis et al. 2013). Therefore, site exposure (i.e., effective fetch) and substrate embeddedness biologically make sense for explaining RMRM distribution, since these variables, although correlated, reveal suitable habitat

5.4.3 RMRM relationship with shoreline morphometry

Slope is a site characteristic often measured for unionid studies (Korzeniak et al. 2004, Davis et al. 2013). Slope is an important determinant of stream velocities, but for lakes it indicates anchorage possibilities, substrate stability (Davis et al. 2013), and wave energy dissipation in the foreshore (i.e., waves interact with the lake bottom) (Hakanson 1977). Therefore, it is not surprising that a ‘bench’ feature is the most important slope characteristic of a site, allowing stable substrate formation and therefore preferable habitat for RMRM. Increased gradient may prevent favorable anchorage, both in stream and lake foreshore environments, by increasing erosion and removing sand and mud, which must be present for mussel foot holding (Korzeniak et al. 2004, Davis et al. 2013).

Substrate relationships, such as the increasing embeddedness with increasing probability of RMRM occurrence, can be explained within the shoreline morphometry relationship (Brim Box et al. 2002). Convex features (points or cuspates along the foreshore) and concave features (bays) are correlated with increasing RMRM occurrence (Figure 8). High energy hydrodynamics exist at convex features, with medium and high embedded substrates existing on the leeward side of these locations.

Similarly, this explanation can be used for bays along the foreshore of Okanagan Lake. Bays are more sheltered habitats, generally having less wave action, and therefore accumulate finer sediments more readily (i.e., have higher embeddedness, Hakanson 1977), as sufficient energy is not available to remove them. Fewer plankton and lower suspended nutrients are expected in more sheltered areas than cuspates, but the dynamics of water movement in bays are more suitable for RMRM than straight shorelines. Since straight shorelines are exposed to all deviation angles of total fetch, maximum shear stress would occur here (as with cuspates), and less refuge may be present for RMRM. This is also observed in the partial dependence plot for the description, where ‘bay’ is ranked as the most important feature. The more protected sites, in locations with high fetch nearby, likely have longshore currents positively affecting RMRM success.

5.4.4 RMRM and host fish in Okanagan Lake

Unionid distribution is passive and generally limited by their host fish movement (Kat 1984). Therefore, host fish movement has important implications for the distribution of RMRM. RMRM glochidia have been found to encyst on several species of fish in Okanagan Lake (Stanton et al. 2012, Mageroy 2015). However, the prevalence and intensity of glochidial encystment on the fish suggest that sculpin (*Cottus* sp.) are the most important hosts for RMRM in the lake. Indeed, sculpin were present at all sites. This explains why sculpin were unimportant in predicting RMRM habitat preference. From these data, sculpin are assumed to not be a limiting factor for RMRM success in Okanagan Lake.

5.4.5 RMRM & other variables not measured

Although other variables may be important at larger scales than Okanagan Lake (i.e., comparing variables between lake systems), many of those (e.g., pH, specific conductance) were not identified by experts as worthy of inclusion in a model focused on Okanagan Lake. The lake, although large, is well mixed; thus most measures of water chemistry vary relatively little among locations in Okanagan Lake.

Okanagan Lake water chemistry generally supports RMRM and other unionids. Okanagan Lake conductivity values reported by BC Ministry of Environment (2013) support RMRM (i.e., RMRM are distributed throughout the lake at all measured conductivity values). This is also true for temperature, dissolved oxygen, total phosphorus, total nitrogen values, and other measured water quality variables (BC Ministry of Environment 2013). The ranges of pH and calcium which Mackie (2010) reported for Okanagan Lake are within the ranges required for unionid shell development and survival (McMahon 1991). These measurements were all taken in the four distinct basins of Okanagan Lake; the north basin, central basin, south basin, and Armstrong arm (BC Ministry of Environment 2013).

Chapter 6. Conclusion

6.1 Management implications

The 2014 stratified random sampling approach correctly predicted three RMRM occurrence (positive) sites in Okanagan Lake, out of the ten predicted (Appendix 1 Table A2.1). These sites are recommended for protection (RMRM occurrence sites: current distribution). Additional sites are recommended as potential relocation sites (red sites; Figure 9) based on the habitat model. The surveyed sites are additional RMRM absence (negative) sites surveyed in the summer of 2014.

Additional sites recommended for protection include 2 new occurrence sites (Table 4). These sites occur on the south-east side of Okanagan Lake, in Naramata. Two additional sites were surveyed and considered decent RMRM habitat (Site # 4 and 222), based on researchers who have worked with this species (Snook, UBCO pers. comm., Jerry Mitchell, MOE pers. comm). One of these sites occurs in Peachland, (FIM objectID 4, Table 4). No mussels were observed here, yet this site appeared to provide decent unionid habitat. In addition, objectID 222**,** or Bear Creek in Westbank also appeared to provide suitable unionid habitat. This site has a creek mouth and a variety of fish species were observed (Snook, UBCO pers. obs.).

Table 4. Locations for recommended protection and relocation of *G. angulata*.

Site # and UTM	**Habitat or RMRM**	**Effective Fetch**
#70 (Naramata) 11U 308926.00 E 5504822.00 N UTM	RMRM	13.9 km
#63 (Naramata) 11U 310434.00 E 5503072.00 N UTM	RMRM	10.0 km
# 4 (Peachland) 11U 305112 E 5518511 N UTM	low (0-20%) sand presence, low cobble, low boulder, medium embeddedness	9.7 km
# 222 (Bear Creek, Westbank) 11U 319975 E 5533587 N UTM	moderate slope, low sand, low boulder occurrence, medium embeddedness	8.5 km

ArcGIS 10.1).

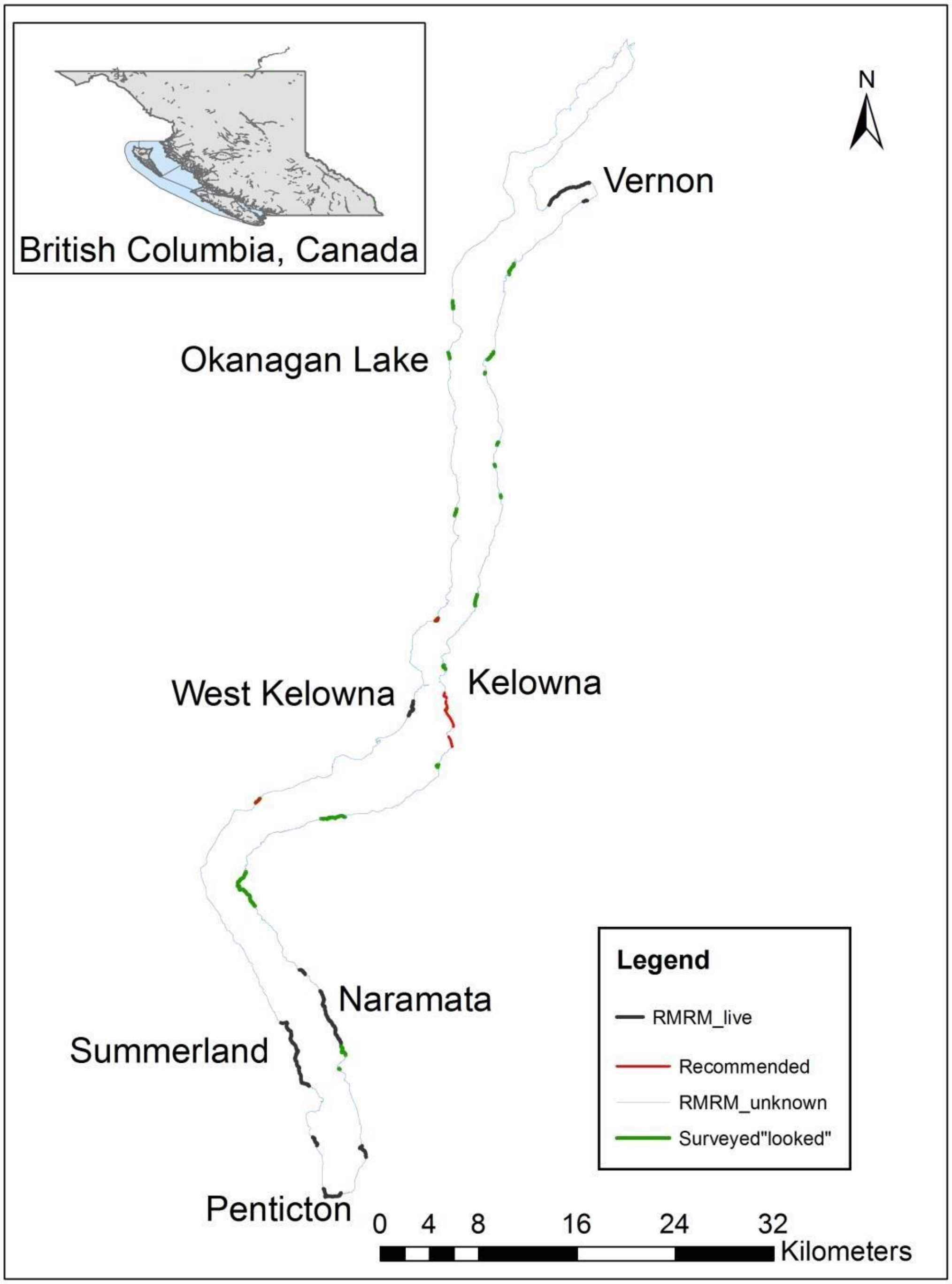


Figure 9. Okanagan Lake, B.C., with sites of current *G. angulata* distribution, recommended sites for potential relocation, and sites with no *G. angulata* found (made in ArcGIS 10.1).

Recommended sites for protection within Okanagan Lake based on this models' outputs are derived from the 44 sites analyzed to create this model. Effective fetch was calculated for each site included in the FIM for the whole of Okanagan Lake, with the most important habitat variables (i.e., low boulder, very high sand, high embeddedness). The recommended sites for further surveys and possible relocation sites include object ID's: 92, 96, 97, 98, 99, and 100 (Table A2.2, Figure 9). Sites with effective fetch exceeding 10 km are further recommended for surveying and predicting sites of RMRM suitable habitat and RMRM occurrence. Because this model suggests these sites contain the top four favorable habitat conditions for RMRM, they are more likely to contain RMRM, and if not, then potentially support future populations of RMRM.

Including analysis of fetch, with the greatest predictability above 10 km, is recommended for any potential relocation sites within Okanagan Lake. In addition to fetch, the next top three predictor variables discussed above should be included in the analysis of additional potential relocation sites and protected areas for RMRM. Sand must be present according to this model. High and medium embeddedness values and a boulder presence of low, high, and very high, but not 'medium' for suitable RMRM habitat must also be present. These four variables are the top predictors in this model (Figure 9), and therefore should be assessed at each site for RMRM habitat suitability. An additional, and potentially useful variable is 'bench' slope, for appropriate anchorage. The other predictor variables rank lower in importance, and therefore do not necessarily need to be considered for further RMRM habitat.

6.2 Limitations

Most studies and locations of RMRM are in lotic habitats (located in riffles and glides in rivers and streams) (Goudreau et al. 1993, Lysne and Clark 2009, Stanton et al. 2012, Davis et al. 2013). This should be taken into consideration when investigating this model's top predictor variables and their partial dependence plots. It is likely patches within Okanagan Lake provide optimal habitat for RMRM. However, optimal habitat for RMRM may be more common in riverine systems. Long large natural lakes are more prevalent in B.C. than farther south (Dr. Walker, professor at UBCO, pers. comm.), and as such, RMRM may not occur in many lakes south of the border because of the lack of longshore currents and effective fetch.

While RF is known to create bias towards highly correlated predictor variables, data reductions were carried out to eliminate highly correlated predictor variables from the final model. However, there are some inherent correlations among some of the predictor variables. For example, large fetch would result in a lack of embeddedness and sand, as finer materials may be mobilized and deposited elsewhere (Hakanson 1977). Embeddedness may include sand. These correlations are unavoidable when comparing variables at these meso (10m-100m) and macro (>100m) scales.

Within predictor correlations can be somewhat accounted for using the Mean Decrease in Accuracy (MDA), which has robust outputs, despite within predictor correlations (Nicodemus 2011). These correlations are taken into account when explaining these mussel-habitat relationships.

Additional research into host fish presence and availability was not feasible for this study. Dispersal of RMRM “may be as critical a limiting factor as local habitat conditions” (Vaughn and Taylor 2000). While host fish presence and population size can be repressed by various factors, the loss of host fish can create a cycle where viable mussel beds will grow old and die without successful recruitment and dispersal into areas of perhaps more suitable habitat (discussed in e.g., Jepsen et al. 2010, Stanton et al. 2012, Mageroy 2015). Imperfect knowledge of all *G. angulata* host fish species, their distribution, and the host’s life cycle (i.e., foraging in shallow waters while *G. angulata* are spawning) may limit the success of conservation efforts for RMRM in Okanagan Lake. Knowledge of all the suitable host fish species and their distribution, would likely add a useful component to the biological aspect of this model. However, at this time Okanagan Lake appears to be saturated with a known host fish of RMRM (*Cottus* sp.) (Snook pers. obs.).

6.3 Future directions/speculation

A dam (the Okanagan Lake Dam) exists on Okanagan River, the outlet of Okanagan Lake. If the Okanagan Lake dam is opened, it is unknown how invasive fish will affect sculpin populations, other host fish of RMRM, and juvenile RMRM in Okanagan Lake. Smallmouth bass have recently been discovered in Okanagan Lake (in 2014, Jerry Mitchell MOE pers. comm.) and these fish could greatly affect RMRM (Dr. Jon Mageroy UBCO pers. comm.), as these non-native fish are a generalist predator and can survive in a large range of systems (Beck 2013). The reduction in host fish availability for RMRM (and any unionid) could greatly reduce the recruitment of this species (Newton et al. 2008). Monitoring of invasive species will show if relocation sites are necessary over the next decade or two. From the surveys in 2013, 2014, and 2015, host fish availability is unlikely to be limiting to RMRM proliferation at this point.

Since optimal habitat for *G. angulata* appears to include higher values of total fetch, further research into currents, water velocities, and wave action at each site may be useful in explaining their current distribution in Okanagan Lake. While currents are too minimal to capture with current meters in Okanagan Lake, water-dissolution experiments or calculations may be useful for determining these site characteristics. Preliminary results from an agent-based model may provide information on future dispersal patterns for RMRM, as decisions based upon mussel-host interactions and subsequent movements can be observed on a GIS map. The potential from a model such as this includes future RMRM distribution based on different environmental scenarios (e.g., warmer water temperatures and lower lake level). An additional recommendation is to acquire distribution data for RMRM from a (or many) paleoecological study. This may help determine if this species is shrinking in its distribution, or in fact a more recent immigrant.

Replacement of the RandomForest statistical package with the Party package is recommended when correlated predictor variables are present (Strobl et al. 2009). A model produced with Party will have more confidence, as its approach produces unbiased outputs.

The transferability of habitat suitability models (i.e., the applicability of species predictive models in a different area) has been tested in many studies, with varying success (Randin et al. 2006, Strauss and Biedermann 2007, Acevedo et al. 2014, Lauria et al. 2015). The concept of transferring habitat suitability models to different regions for conservation and management reasons is still debated in the scientific community (Lauria et al. 2015). Generally, a case study such as this RMRM model is static in space and time (e.g., is built on data specific to a certain location) and may not have the ability to account for species distribution in another time or place (Guisan and Zimmerman 2000, Bulluck et al. 2006, Lauria et al. 2015). Although a successful methodological approach to generalization of a model for transference to a new location (or time) can be found in Acevedo et al. (2014), there are likely minimal instances where RMRM occur in long and deep lakes where this model can be applied (i.e., this model is spatially explicit). However, the central importance of this model comes from understanding the role of wind energy in sediment size distribution, substrate embeddedness, and transportation of oxygen and food for RMRM (e.g., Westerbom and Jattu 2006, Callaghan et al. 2015). This knowledge can be transferred to other lake systems, and potentially to other mussel species, to give a deeper understanding of the mechanisms shaping RMRM habitat and dispersal.

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Appendices

Images

Roxanne Snook, Figure 1, 2013, University of British Columbia, Okanagan campus

Dr. Jon Mageroy, Figure 1, 2013, University of British Columbia, Okanagan campus

Steven Brownlee, Figure 2, 2015, University of British Columbia, Okanagan campus

WindFinder.com, GmbH & Co. KG (Figure 5), Germany, accessed June, 2014

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Appendix 1. Additional experiments

A.1 Water movement experiment

The rate of dissolution of a soluble substance, NaCl, was used as a proxy measurement for water movement. Faster dissolution is expected where water movement is high. Salt licks (animal grade, 96.9-96.0% NaCl), were cut into salt tiles (5 cm x 3 cm x 1 cm), and were epoxied around all surfaces except for the 5cm x 3cm top surface (Figure A1). A glass fiber filter paper was epoxied to this top surface around the edges. Each tile's weight was recorded at this step. These tiles were then mounted onto a rebar stake at each site with the aid of a polyethylene tube glued on, to form a sleeve to ensure the tile would remain in the same position and location. The tiles were left in the water for 4-13 days, depending on when researchers could return to each site.

After retrieval of these tiles, each one was heated in an oven at 100°C for an hour to remove any carbonaceous particles (e.g., algae). Erosion (%/day or mg/day) was used as a proxy for estimating relative water movement at each site (Table A1.1, advice from Jeff Curtis). Although I am unaware of other studies where NaCl tiles have been used for this purpose, gypsum-dissolution has be used elsewhere, in the same way, as an indicator of mass-transfer within aquatic systems (Porter et al. 2000). These results were not used in this model due to the minimal numbers of recovered intact tiles.

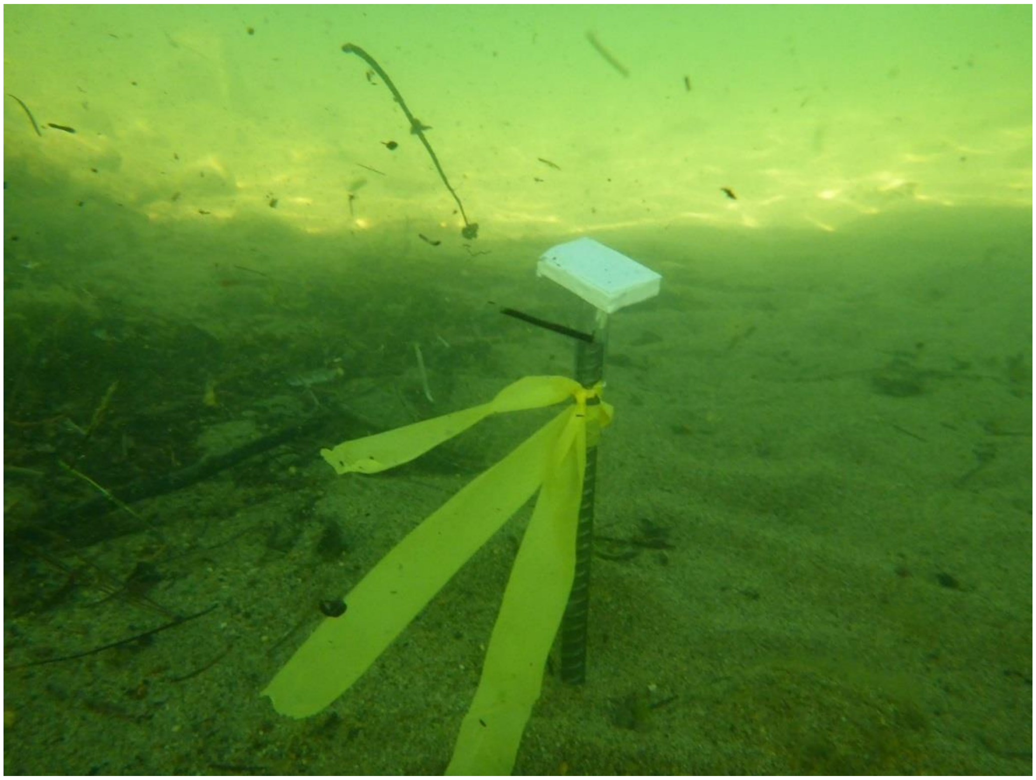

Figure A1. Epoxied salt tile with sleeve attached to rebar stake.

Table A1.1 Results of water movement experiment for intact current meters.

Object ID	RMRM	pre-weight	post-weight	weight lost (g)	%weight lost/ day
142	no	29.753	5.964	23.789	4.009
160	no	31.746	6.627	25.119	4.175
201	no	31.074	6.136	24.939	3.949
173	no	27.268	6.072	21.196	4.453
312	no	34.127	6.272	27.855	3.676
70	yes	33.698	6.468	27.230	3.839
63	yes	30.541	6.177	24.365	4.045
62	no	32.937	6.206	26.731	3.768
59	no	30.983	6.032	24.951	3.894
28	yes	34.309	5.933	28.376	3.459
222	no	28.724	6.044	22.680	1.619
25	yes	31.480	5.948	25.532	3.779
24	yes	25.994	5.571	20.423	4.286
39	yes	34.806	6.175	28.631	3.548

Appendix 2. Additional data collection

Water chemistry data were collected during the first field season throughout Okanagan Lake, as well as Okanagan River, Skaha Lake, Osoyoos Lake, and Vaseux Lake. These measurements included conductivity, pH, temperature, and salinity. Vegetation data (% cover by species, % cover by total vegetation and large woody debris), fish species, and other freshwater mussel species were also noted. A total of 75 sites were visited and surveyed in 2013 (Snook 2014). These findings were not included in the model for Okanagan Lake, as these original surveys were conducted throughout the Okanagan Basin and not measured while collecting data for the model.

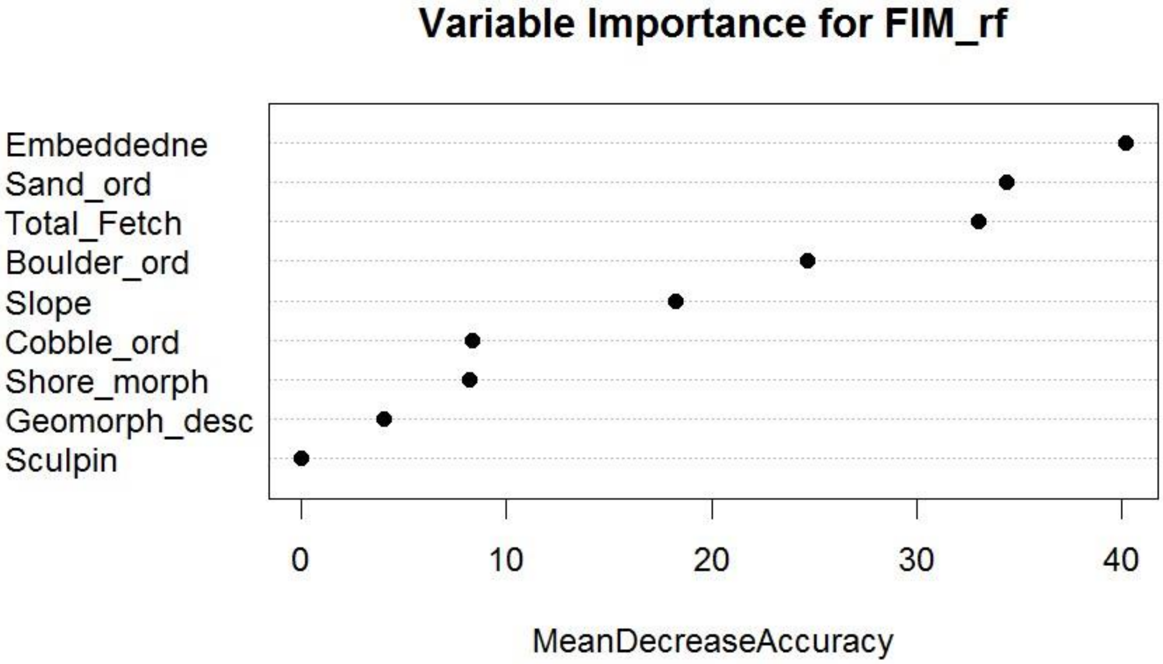

Figure A2. Variable importance plot with nine predictor variables, after reductions, to construct the habitat suitability model for *G. angulata*. Eliminated variables include:

‘Clay’, ‘Underw_ledge’ (underwater ledge), and ‘depth_anoxia’ (depth to anoxia). This misclassification rate for this model is 10.08%, and mtry = 2.

Table A2.1 Sites generated for this project based off of weak and strong predictors for RMRM occurrence in a stratified random sampling procedure. Bolded* sites were correctly predicted RMRM occurrence locations.

Variable	**Embeddedness**	**Slope**	**Cobble**	**Sand**	**Boulder**
Weak	164	4	115	142	201
	180	222	139	173	259
Strong	**63***	101	62	89	74
	70*	**266***	146	59	312

Table A2.2 Sites on Okanagan Lake with 'very high' sand, 'low' boulder, and 'high' embeddedness characteristics. Fetch was calculated for each potential site to determine if they are potentially 'optimal' habitat for RMRM.

Object	Fetch (km)	Object	Fetch (km)
92	16.45*	**105**	4.92
93	Mission Creek	**106**	7.08
96	14.34*	**107**	< 7.08
97	12.99*	**108**	< 7.08
98	12.29*	**109**	< 7.08
99	11.10*	**110**	< 7.08
100	11.10*	**111**	5.73
101	9.84 WWT Plant outlet	**112**	5.73
102	8.14	**116**	4.83
103	8.14	**118**	5.71
104	8.14	**268**	Brant creek
		314	7.94

* Are sites that are recommended for further surveys, based on effective fetch > 10 km. The prevailing wind direction for these sites were taken from the Rotary Beach in Kelowna weather station and Beachcomber Bay (for Object 314).

Appendix 3. RandomForest code implemented in ‘R’

```
>library(randomForest)
>FIM<-read.csv("Datacollection_RS2014d.csv", header=TRUE, stringsAsFactors=T)
>FIM <- na.omit(FIM)
>FIM$RMRM_live <- as.character(FIM$RMRM_live);
>FIM$RMRM_live[FIM$RMRM_live=="yes "] <- "yes"
>FIM$RMRM_live <- as.factor(FIM$RMRM_live)
>FIM$RMRM_live <- ordered(FIM$RMRM_live,levels=c("no","yes"))
>FIM$Embeddedne<- ordered(FIM$Embeddedne, levels= c("Low (0-25%)", "Medium (25-75%)", "High (75%+)"))
>FIM$Slope<- ordered(FIM$Slope, levels= c("Bench", "Low (0-5)", "Moderate (5-20)", "Steep (20-60)", "Very Steep (60+)"))
>FIM$Boulder_ord<- ordered(FIM$Boulder_ord, levels= c("Low (0-20)", "Medium (25-40)", "High (50-60)", "Very high (70-80)")) ##in FIM_RS_2.csv
>FIM$Cobble_ord<- ordered(FIM$Cobble_ord, levels= c("None", "Low (1-20)", "Medium (25-40)", "High (50)"))
>FIM$Sand_ord<- ordered(FIM$Sand_ord, levels= c("None", "Low (1-20)", "Medium (25-40)", "High (45-60)", "Very High (70-100)"))
```

```
### Random forest for five most important predictors
> FIM_rf <- randomForest(RMRM_live ~ Total_Fetch_km+ Sand_ord+ Boulder_ord+
    Embeddedne+ Slope, data=FIM, ntree=5000,proximity=TRUE,importance=T, mtry = 2)
### Random forest for nine most important predictors
> FIM_rf <- randomForest(RMRM_live ~ Shore_morph+ Total_Fetch_km+ Geomorph_desc+
    Sculpin+ Sand_ord+ Cobble_ord+ Boulder_ord+ Embeddedne+ Slope, data=FIM,
    ntree=5000,proximity=TRUE,importance=T, mtry = 2)
### Below are all of the partial dependence plot commands
>partialPlot(FIM_rf, FIM, Total_Fetch, "yes", xlab="Total Fetch", ylab="Probability of RMRM
    Presence")
>partialPlot(FIM_rf, FIM, Underw_ledge, "yes")
>partialPlot(FIM_rf, FIM, Geomorph_desc, "yes")
>partialPlot(FIM_rf, FIM, Shore_Type, "yes", xlab="", las=1, font=2, ps=3, space=1)
>partialPlot(FIM_rf, FIM, Sculpin, "yes")
>partialPlot(FIM_rf, FIM, Embeddedne, "yes")
>partialPlot(FIM_rf, FIM, Embeddedne, "yes", xlab="Embeddedness", ylab="Probability of
    RMRM Presence")
>partialPlot(FIM_rf, FIM, Clay, "yes")
>partialPlot(FIM_rf, FIM, Slope, "yes")
### plot variable importance for the random forest (using mean decrease in accuracy)
> varImpPlot(FIM_rf, type=1, pch=19, col=1, cex=1.5, main="Variable Importance for FIM_rf")
```

For the data used in this analysis, please contact myself at roxannesnook@hotmail.com.