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Information in support of the identification of critical habitat for the Rocky Mountain Ridged Mussel (*Gonidea angulata*)

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Rocky Mountain Ridged Mussel (*Gonidea angulata*, Lea 1839) is listed under the *Species at Risk Act* (SARA) as a species of Special Concern but was re-assessed as Endangered in 2010 by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). In anticipation of Rocky Mountain Ridged Mussel to be listed as an Endangered species under SARA, this report provides information required to support the identification of critical habitat. Foreshore inventory and mapping data were used in Okanagan Lake for modelling habitat suitability. There are two distinct types of habitat utilized by *G. angulata*: lacustrine and riverine. Lacustrine habitat for *G. angulata* requires a site exposure of 10–20 km and a bench or low (0–20%) slope. River habitats require stable banks with low hydraulic variability (i.e., channelized sections). Both habitats require sufficient food, suitable water quality, and particular substrate sizes, depending on the energy of the site. As a freshwater mussel in the family Unionidae, this species requires a host fish as part of its development; therefore host fish must also be available. Recommended critical habitat of *G. angulata* is geographically delineated using the Bounding Box approach, including features and attributes of importance.

1 INTRODUCTION

Freshwater mussels are arguably one of the most endangered groups of animals in North America (Bogan 1993, Lydeard et al. 2004). The Rocky Mountain Ridged Mussel, (*Gonidea angulata,* Lea 1839) is an endangered freshwater mussel in the family Unionidae. Its northern distribution lies within the Okanagan River watershed in British Columbia, Canada, and the species is decreasing in extent and numbers across its North American range (Jepsen et al. 2010, Stanton et al. 2012). *G. angulata* is an imperiled species in BC. (BC Conservation Data Centre 2015 a,b), and was listed as a species of Special Concern under the *Species at Risk Act* (SARA) in 2005. A management plan for the species was completed and posted on the Species at Risk Registry in 2011 (Fisheries and Oceans Canada 2011). *G. angulata* has since been reassessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2010) as an Endangered species. Should the species get listed as an Endangered species under SARA, critical habitat will have to be identified using the best available information.

Critical habitat is defined in SARA as “the habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species’ critical habitat in the recovery strategy or in an action plan for the species”. For aquatic species at risk, SARA defines habitat as “… spawning grounds and nursery, rearing, food supply, migration and any other areas on which aquatic species depend directly or indirectly in order to carry out their life processes, or areas where aquatic species formerly occurred and have the potential to be reintroduced.” [s. 2(1)]. This report provides information to identify critical habitat for *G. angulata* in the Okanagan River watershed.

For *G. angulata*, critical habitat is recommended using the Bounding Box approach, as described by Fisheries and Oceans Canada (2015). Recent research provides information on habitat features and attributes that are vital for biophysical functions for this species. *G. angulata* uses two distinct habitat types: lacustrine and riverine. Some important features are common to both environments, while others are different, yet support the same functions. Availability of food, specific substrate sizes, availability of host fish, and water quality ranges that are within the species tolerance are important. Riverine systems which have low hydraulic variability and stable substrates and lacustrine systems which have a bench or low slope and an optimal site exposure (i.e., effective/total fetch) are considered potential critical habitat for *G. angulata* (Snook 2015).

2 ROCKY MOUNTAIN RIDGED MUSSEL

2.1 ECOLOGICAL ROLE

Freshwater mussels filter a significant volume of water, removing fine particles from the water column which contribute to the quality of their ecosystem (Morales et al. 2006). These particles can include bacteria, algae, zooplankton, and detritus (Jepsen et al. 2010). *G. angulata* can then excrete these filtered particles as mucous packages (pseudofeces), which lower organisms can ingest as food (Jepsen et al. 2010). Therefore, *G. angulata* play a role in the distribution of nutrient flow between the water column and benthic layer (Jepsen et al. 2010). In addition, they constitute a portion of the diets of muskrats, raccoons, gulls, fish, and humans, which have been observed consuming *G. angulata* (Roxanne Snook[1]. pers. obsv.). The outer shell of *G. angulata* also provides a surface for colonization by other aquatic invertebrates.

G. angulata are a relatively long lived mussel species, with a life span of approximately 50 years in the Okanagan (Mageroy 2015). The tissues and periostracum (outer shell) retain nutrients, minerals and contaminants over time. Due to a relatively long life span and narrow species-specific environmental tolerances, *G. angulata*, as well as other freshwater mussel species, are considered suitable indicator species.

G. angulata also adds to the biodiversity of the Okanagan River watershed, where only a few other freshwater mussel species are found within the same range. These species include California Floater (*Andodonta californiensis/nuttalliana*), Western Floater (*Anodonta kennerleyi/oregonensis*), and Western Pearlshell (*Margaritifera falcata*) (Fisheries and Oceans Canada 2011).

2.2 POPULATION AND STATUS

While the number of known locations of *G. angulata* in the Okanagan River watershed has increased in recent years, this is likely a product of increased search efforts and not a result of further dispersion. Once prevalent from Idaho and Nevada, westward to California and north to British Columbia, *G. angulata* has been largely extirpated from its range (Jepsen et al. 2010). Reasons for *G. angulata's* decline include, but are not limited to: habitat loss, human development, invasive species, loss of fish host species, and contamination of waterways (Downing et al. 2010, Jepsen et al. 2010, Stanton et al. 2012). Within the Okanagan River watershed, historic mussel beds within Osoyoos Lake, Park Rill Creek, and Skaha Lake are now vacant or are littered with shells (Roxanne Snook[1], pers. obsv.) *G. angulata* density at different sites and within sites varies drastically; for example, densities ranged from 15.29 individuals/m^2 to 1.27 individuals/m^2 in Summerland in 2010 (Stanton et al. 2012).

Estimates of *G. angulata* population sizes of > 1000 and > 3000 exist at some sites within Okanagan River (Dr. Jon Mageroy[2], pers. comm.) and Okanagan Lake (Stanton et al. 2012), respectively. In a density study conducted over 2008 and 2009, Stanton et al. (2012) found little fluctuation of population size over the two years. However, these conclusions were drawn without much confidence, and a recommendation for continued monitoring of density was suggested. A more detailed summary of catch rates and locations of sampling efforts from 2009 and 2008 is provided in Stanton et al. (2012).

Recruitment at sites can also be variable for freshwater mussels, with little or no juvenile recruitment occurring within older, relic populations. A recent study on juvenile recruitment of *G. angulata* in the Okanagan River watershed suggests while sufficient recruitment is occurring at most mussel beds in Okanagan Lake, this is less certain for the southern Okanagan (Mageroy et al. 2015). However, there are uncertainties associated with these data and additional surveys are needed to confirm whether juvenile recruitment is sufficient to maintain *G. angulata* numbers throughout the Okanagan River watershed (Dr. Jon Mageroy[2], pers. comm.).

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2.3 KEY LIFE STAGES AND GENERAL DESCRIPTION OF HABITAT NEEDS

Freshwater mussels in the order Unionoida are epifaunal (i.e., living on the substrate of a river or lake) as adults.

Different habitat features are known to be important to *G. angulata*. In lacustrine systems *G. angulata* inhabit fine sediments and sand (0.6–2 mm) in the littoral zone, in depths of 0.5 m–5 m. Sites that have awind exposure (i.e., total fetch) of 10–20 km provide optimal habitat within Okanagan Lake (Snook 2015); exposure has not been modelled in Skaha, Vaseux, or Osoyoos Lakes. In areas with higher scouring events (i.e., wave action or longshore currents), *G. angulata* can be found below large, stable substrates (128–256 mm), coarse cobble and boulders (> 256 mm), or in some cases, pilings (i.e., flow refuges) (Morales et al. 2006, Davis et al. 2013). Bathymetric slope, or site inclinations, of 'bench' or 'low' (0–20%) are most important for the species, with steeper inclinations being correlated with fewer occurrences of *G. angulata* (Snook 2015).

In riverine habitats, *G. angulata* are found along the river banks (i.e., not in the thalweg), in channelized sections, inhabiting fine sediments and sand (0.6–2 mm). High *G. angulata* densities are also found directly below weir structures. In these faster and more turbulent waters, *G. angulata* are usually dispersed below boulders (> 256 mm) and coarse cobbles (128–256 mm), in fine sediment or sand (0.6–2 mm) deposits.

G. angulata, like all freshwater mussels, are omnivorous filter feeders. Their diets consist of detritus, algae, bacteria, and zooplankton (Vaughn et al. 2008, Nedeau et al. 2009). Feeding during their juvenile and adult life stages therefore requires an adequate supply of nutrients, detritus, and water quality parameters that support their food sources and are within *G. angulata* physiological tolerances.

Juvenile freshwater mussels are generally more sensitive to environmental parameters than their adult life stage (COSEWIC 2003). However, juvenile *G. angulata* occur in many of the same locations and habitats as adults within the Okanagan River watershed (Mageroy et al. 2015). The majority of juvenile mussels are found in the substrata, 0–40 cm below the lake or river bottom (Mageroy et al. 2016[3]). Juvenile mussels require soft sediments (e.g., silt) for burial, with continual oxygen penetration into the substratum (Geist 2005).

2.3.1 Spawning

Spawning was observed in two distinct synchronized spats in May, 2015 in Summerland, Okanagan Lake. Conglutinates were observed from May 28–July 23 in 2013 in temperatures ranging from 11–25.7°C (Roxanne Snook[1], unpub. data 2013) and during June in both 2010 and 2011 (Stanton et al. 2012). Conglutinate release may be triggered by temperature, with other factors likely affecting timing as well. Conglutinates contain mature and immature glochidia (Stanton et al. 2012), which remain viable for only a short duration (hours–days) to acquire a suitable host (Spring Rivers 2007).

2.3.2 Distribution Mechanism

Fertilization occurs when sperm enters the female through the inhalant aperture and fertilizes the eggs stored in the demibranch, later releasing larvae (glochidia) wrapped in mucous. These mucous packages, called conglutinates, are thought to mimic prey for foraging fish. Upon

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[3] Mageroy, J.H., Nield, L.M., Brownlee, S., Snook, R.M. and Walker I.R.. 2016. Juvenile recruitment among Rocky Mountain Ridged Mussel (*Gonidea angulata*) in the Okanagan Valley, BC. Draft.

consumption by fish, some glochidia are ingested, while others are released from the conglutinate and come into contact with suitable attachment sites, such as gills. This strategy increases chances of encountering a suitable host, which is required for glochidia survival during this sensitive life stage. As obligate ecto-parasites, host fish presence and abundance during *G. angulata* spawning and metamorphosis are therefore critical for their survival. Sculpin (*Cottus* sp.) are the most prevalent observed host fish for *G. angulata* in the Okanagan (Mageroy et al. 2016[3]). Other fish species could also potentially act as hosts (Spring Rivers 2007, O'Brien et al. 2013, Mageroy et al. 2016[3]). Mussels are limited in their ability to disperse without the aid of host fish. With limited mobility, mussels spend the majority of their life in the same location, after excysms (sluff-off) from host fish, and therefore are generally unable to escape adverse conditions. The obligate parasitic stage enables upstream dispersal, unlike other families of freshwater mussels. *G. angulata* dependence on a host fish may cause high mortality of young, but lower adult mortality. To persist over the long term, *G. angulata* require availability of host fish within identified critical habitat boundaries, successful recruitment into suitable habitat, and availability of food, although exact quantities are not known at this time.

3 CRITICAL HABITAT

3.1 INFORMATION AND METHODS USED TO RECOMMEND CRITICAL HABITAT

3.1.1 Modeling Approach

Recent research that modeled suitable habitat for *G. angulata* in Okanagan Lake is used to recommend critical habitat (Snook 2015). A Delphic approach developed by mussel and/or freshwater ecosystem experts (Dr. Jon Mageroy[2], Dr. Ian Walker[4], Dr. Jeff Curtis[5], Robert Plotnikoff[6], and Shelly Miller[7]) was used to identify *a priori* important habitat features for *G. angulata* in order to reduce the 147 variables within the Foreshore and Inventory Mapping (FIM) data for Okanagan Lake to 12 stratified variables. Additional variables and calculations that were not within the FIM dataset (e.g., effective fetch and host fish) were also included. Statistical modeling results were used to determine and rank important variables of mussel habitat. The statistical models implemented in 'R' (version 3.02. R Development Core Team 2013) were both classification packages: 'Random Forests' (Breiman 2001) and 'Party' (Hothorn et al. 2006). Both models consistently produced similar results (Table 1, Roxanne Snook[1], unpub. data 2013).

Classification trees are used in ecology to create habitat suitability models and predict species distribution (Mouton et al. 2010, Vezza et al. 2012). Hundreds to thousands of trees are created from a bootstrap sample, producing a forest based off of a partitioned response. These forests are random in the selection of variables chosen (which are used to create the partitioned response) and selection of a random subset of variables in which to create the next node, rather than using the entire dataset (Breiman 2001). The main tuning parameter is the 'mtry' function,

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which determines the number of variables used to create the tree (Breiman 2001). Model validation occurs with an out-of-bag cross-validation, comparing the unused original data left out of the bootstrap sampling to the trees. Both packages used are classification packages; while Random Forests has powerful visual outputs (e.g., partial dependence plots, Appendix 4, Figure 16), it can also be affected by correlated variables. The Party package illustrates correlation between variables, and is therefore used to compare the results between the classification procedures. The outputs of both packages are the same, with the exception of boulder occurrence being a correlated variable, and therefore not explanatory in *G. angulata* distribution in Okanagan Lake (

Table 1).

Variables that were originally considered to be important include both biotic and abiotic attributes of mussel habitat. A proxy for energy at each site (i.e., site exposure/fetch) was required, since experiments on water movement were unsuccessful and time consuming, and therefore not easily replicated. Substrate sizes were included, as at a micro-site level certain substrate sizes are correlated to mussel distribution (Vannote and Minshall 1982, Strayer 1999). Host fish presence is considered to be one of the most important biotic components of a freshwater mussel's lifecycle. Water chemistry was not included, for reasons including inter and intra-site variability, and resources required to obtain data. Furthermore, the connectivity throughout the Okanagan River watershed indicates that this species is already, being widely distributed through the entire system.

Polygons were calculated based on occupancy records (2005–2015) of *G. angulata* at these locations. The features and attributes described within the polygons were determined from the Random Forest and Party classification packages, while modeling habitat suitability within Okanagan Lake. A projection of these variables throughout the other lakes in the Okanagan River watershed, or Okanagan Lake, is an exercise that has not been conducted, but is recommended as a future study (Section 5). The end points of the polygons in Okanagan Lake are based off of the foreshore, inventory, and mapping (FIM) data points, and may be refined to more conservative end points when ground truthing of mussel beds occurs. The FIM end points are ground truthed G.P.S. coordinates of shoreline segments with similar land use, shore type, vegetation, and substrates (Schleppe and Mason 2009). End points of polygons throughout the rest of the Okanagan River watershed are based on distinct landmarks, described by researchers (while snorkelling) that could then later be pin-pointed via Google Earth. No river model for habitat suitability has been conducted, therefore the features and attributes described in the river polygons are based on observations (Roxanne Snook[1], pers. obsv., Dr. Jon Mageroy., BC, pers. obsv.) and literature review (e.g., Davis et al. 2013).

3.1.2 Survey Efforts

Recent survey efforts in Okanagan lakes, rivers, and streams, have been used as a source for *G. angulata* distribution data. These include studies by Mageroy et al. (2016[3]), used for determining juvenile recruitment, and exploratory surveys of *G. angulata* in BC, conducted by Stanton et al. (2012). Historic, museum, and current surveys are summarized by COSEWIC (2003 and 2010), while threats, species assessment, and ecosystem considerations are described in the Recovery Potential Assessment for *G. angulata* (DFO 2011, Lauzier and Stanton 2012).

When habitat attribute values are unknown for *G. angulata*, values from similar species with similar range overlap have been used for comparisons; however freshwater mussels have species-specific environmental ranges. Knowledge gaps for *G. angulata* are listed in section six.

3.2 IDENTIFICATION OF CRITICAL HABITAT

An important step in delineating critical habitat is the use of population targets and species relationships with habitat types to determine quantities of different habitats required to maintain a viable population, and to then identify the specific locations of these habitats in the wild. However, population and distribution targets have not been identified for *G. angulata*. As *G. angulata* is part of the declining freshwater mussel population trend in North America, efforts to quantify these targets are recommended for future studies to prevent *G. angulata* extirpation from the Okanagan River watershed.

Minimum viable population (MVP) has been used as a proxy for population targets when population targets have not been defined. MVP is a concept defined as "the number of individuals required to have a specified probability of persistence over a given period of time" (Shaffer 1981). For example, MVP has been explored for two Wavy-rayed Lampmussel populations. For the Wavy-rayed Lampmussel to persist over 250 years (24–40 generations for this species), MVP was calculated for three simulated random catastrophic events. These events were "i) 5% chance of catastrophe per generation, affecting all life stages, ii) 15% chance of catastrophe per generation, affecting all life stages, iii) 15% chance of catastrophe per generation, with 4/5 events affecting only immature individuals and 1/5 affecting all life stages" (DFO 2010).

The resulting MVP in each scenario simulated in the Grand River populations were: ~5200, ~197 000, or ~3600 adults respectively of the magnitude of each catastrophe (DFO 2010).

MVP is likely species dependent, based on life history strategies and habitat characteristics, where threshold limits would be hard to calculate (Haag 2012), and therefore should not be transferred across species or space. Area-abundance relationships are uncertain for *G. angulata*, due to both difficulties in sampling and the mussel's inherent patchy distribution pattern. Since population targets have not been identified for *G. angulata,* the MVP approach was not employed in assessing critical habitat. Instead, a recovery target-independent method was used; the Bounding Box approach (Fisheries and Oceans Canada 2015).

Using the Bounding Box approach, critical habitat is defined by the area of the identified polygon boundaries (Appendix 2), which include biophysical features and attributes that support necessary functions for *G. angulata* (summarized in Table 2). It includes habitats that may be presently degraded and are unoccupied, but are known to have been occupied historically. While current information about *G. angulata* life history has supported identification of some necessary functions, features, and attributes, identified critical habitat may be refined as additional habitat data for *G. angulata* becomes available.

No definitive explanation has been agreed upon to explain the inherent patchiness of mussel beds. Research on freshwater mussels and their habitat requirements draw conclusions varying from geology (Arbuckle and Downing 2002), reach size, hydraulic variability, flow regimes, availability of refuge, predation, abundance of a food base and nutrient concentrations, and host fish presence (Strayer 1999, Morales et al. 2006, Schwalb et al. 2013). These studies incorporate macro (> 100m), meso (10–100 m), and micro scales (< 10 m) and find that the environmental factors that limit *G. angulata* likely depend on different spatial scales and incorporate biotic and abiotic variables.

Additionally, sites within the Okanagan River watershed where juvenile recruitment is known to occur are proposed as critical habitat. These sites have different conservation levels associated with them, depending on their sufficiency in sustaining the population at that mussel bed (Mageroy et al. 2016[3]). The only known study examining juvenile recruitment of *G. angulata (*Mageroy et al. 2016[3]) determined that sufficient juvenile recruitment for maintaining mussel numbers is occurring at five sites in the Okanagan, less than sufficient recruitment at three locations, while insufficient recruitment is reported at one site (Mageroy et al. 2016[3]). The method used in determining this sufficiency was adapted from Young et al. (2001) for the Eastern Pearlshell *(Margaritifera margaritifera)*, to account for the lifespan of *G. angulata,* and is based on an estimated maximum age of 60 years for *G. angulata* in the Okanagan River (Mageroy et al. 2016[3]). Since juvenile recruitment is known to be occurring at these sites, all are proposed as critical habitat within the Okanagan River watershed at this point in time.

3.3 BIOPHYSICAL FUNCTIONS, FEATURES AND ATTRIBUTES OF PROPOSED CRITICAL HABITAT FOR *G. ANGULATA* IN LACUSTRINE HABITAT

3.3.1 Identification of Critical Lacustrine Habitat: Okanagan, Skaha, Vaseux, and Osoyoos Lake

In Canada, Okanagan Lake is the northernmost extent of *G. angulata* distribution. *G. angulata* is also distributed throughout some connected southern lakes: Skaha Lake, Vaseux Lake, and Osoyoos Lake.

Lacustrine critical habitat for *G. angulata* has different features and attributes than riverine critical habitat, while accomplishing the same biophysical functions for supporting *G. angulata* life stages (see Table 2). Juvenile and adult *G. angulata* are present in the same habitat in Okanagan Lake (Mageroy et al. 2016[2]). As a result, creating additional protected sites for juveniles is not necessary to ensure recruitment of this species (Mageroy et al. 2016[2]).

3.3.2 Habitat Suitability Modelling

Ecological modelling is a powerful technique, widely used for mapping species distribution, describing niches, and is used in successful application of management and conservation efforts (Vezza et al. 2012). Classification packages, such as Random Forests, are powerful ensemble (i.e., averaging) methods. Both packages implemented (Random Forest and Party), produce models with robust results, model complex variable interactions, and are not skewed by correlated variables. In particular, the Party package algorithm output includes the measure of correlation between variables, and was therefore necessary to compare to the Random Forests package to eliminate any of these variables. To view complete results of the Random Forests model, see Snook (2015).

Misclassification of the Random Forest package represents the number of times the model incorrectly predicted occurrence sites of *G. angulata* in Okanagan Lake (i.e., 12.75% of the time this model was incorrect). This can also be described as this model correctly predicted the occurrence or absence of *G. angulata* 87.25% of the time.

Table 1. Habitat suitability model results for important habitat variables in classification packages Random Forests and Party.*

Package (implemented in R)	Most important variables, ranked from most to least important	Main tuning parameter (mtry: number of variables used to create the tree)	Results
Random Forest	Embeddedness Fetch Sand Boulder Slope (Snook 2015)	2 (with lowest misclassification rate of 12.75%)	Ranked 5 most important variables for explaining distribution of *G. angulata* in Okanagan Lake, BC.
Party	Sand Embeddedness Fetch Slope (Roxanne Snook, unpub. data 2015[1])	2, 3, 4, 5, 6, 7, 8	Each iteration determined these top 4 predictor variables (with sand and embeddedness switching rank half of the time). Boulder occurrence was determined to be correlated with other variables, and is not in itself explanatory of *G. angulata* distribution.

*Code is available in Appendix 3.

3.3.3 Physical variables

Substrate

Substrate size is not sufficient as the only explanatory variable for mussel distribution (or as critical habitat) (Davis et al. 2013). Substrate size must be combined with other explanatory variables, as described below. The presence of sand at a site increases suitability of habitat for *G. angulata*, as does increasing sand occurrence at a site (> 20%) (Snook 2015). Sand, defined as “granular particles visible to the naked eye”, typically 0.06– 2 mm in size (Schleppe and Mason 2009), is an important component of *G. angulata* habitat as it functions as a suitable substratum for foot anchorage. Gravels and cobbles (fine–coarse grain sizes) were incorporated into preliminary models, but were not found to be explanatory in *G. angulata* distribution (Snook 2015).

Boulders, defined as substrate greater than 256 mm (Schleppe and Mason 2009), provide micro-eddie environments below them, supplying oxygen, organic matter, a deposition environment, and also allowing *G. angulata* anchorage (Davis et al. 2013). Boulders function as refuge from predators, shear stress, and scouring. However, boulders were found to be a highly correlated variable, adding instability to the model in ‘Random Forest’, and were not included in the ‘Party’ output (

Table 1). Although the importance of boulders can be explained for their functionality, their presence is not necessarily part of critical habitat in each site.

Substrate Embeddedness

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). Substrate embeddedness can result from the presence of fine substrates, organic material, sand, and mud. In Okanagan Lake, substrate embeddedness greater than 25% is positively correlated with the occurrence of *G. angulata* (Snook 2015). The degree of substrate embeddedness is a function of energy of a site, as well as terrestrial run-off or sewage treatment output, and can translate to food availability and a medium for mussels to bury in.

Site exposure

Site exposure was assessed using wind potential energy at each site. Wind energy is important for creating turbulent processes within a water body, which result in water movement that promotes distribution of fine sediment, loading and re-suspension of food within a site. Site exposure was measured as total fetch, a proxy for potential wind energy. Fetch is the distance wind can travel over water without being impeded by land. Total fetch was calculated from multiple angles of deviation from the prevailing wind direction, seasonally (see Hakanson 1977 for methodology), within Okanagan Lake (Snook 2015). Thus, fetch provides a proxy of the potential energy to which each site on a lake is exposed (Hakanson 1977, Westerbom and Jattu 2006, Callaghan et al. 2015). Sites with a total fetch of 10–20 km correlate with *G. angulata* occurrence in Okanagan Lake. Less than 10 km and above 20 km appear to limit *G. angulata* distribution. Low site exposure (i.e., < 10 km) may have insufficient loading of food, while high site exposure (> 20 km) may also be devoid of nutrients as high scouring from wave action can remove both juvenile *G. angulata* (Spring Rivers 2007) and fine organic material, and continuously re-suspend fine sediments, making the water devoid of nutrients and starving mussels (Brim Box and Mossa 1999).

Slope

A bench or low (0–20%) inclination functions both as a suitable inclination to anchor in, and the surface of interaction with wind-wave energy. This interaction creates turbulence and makes accumulation of fine sediments possible (Hakanson 1977). Steep slopes have no accumulation of fine sediments (Hakanson 1977).

Depth

G. angulata are usually found within 0.5–5 m depth within the littoral zone, and within 30 m from shore (Stanton et. al. 2012). Surveys have found *G. angulata* in deeper than 7.0 m, such as in Vaseux Lake (Stanton et al. 2012). Recent surveys conducted by deep water divers in Okanagan Lake have not observed *G. angulata* deeper than 5 m (Lora Nield[8], pers. comm). However, lake depths vary greatly along the shoreline in the Okanagan River watershed. In addition, no known bathymetric data are available for GIS implementation for many of the lakes within the Okanagan. Therefore, rather than incorporate depth as an attribute, a fixed width of 80 m from shoreline of elevation 343 m (TRIM) is proposed as polygon dimensions to encompass features and attributes of *G. angulata* critical habitat.

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[8] Lora Nield, BC Forests, Lands, and Natural Resource Operations. 102 Industrial Place Penticton, B.C. V2A 7C8

Chemical parameters

Okanagan Lake is a well circulated lake and drains into the Okanagan River, which feeds into and drains the lakes supporting *G. angulata* throughout its north to south distribution. While chemical parameters have been found to be significant habitat requirements for other freshwater mussels, it can be assumed that the natural ranges of water chemistry in the Okanagan River watershed can support *G. angulata* throughout these lakes (i.e., Okanagan Lake, Skaha Lake, Vaseux Lake, and Osoyoos lake, as well as the Okanagan River) (Figure 1). *G. angulata* are sensitive to chemical pollution, as they are unable to escape adverse conditions. Point and non-point source pollution therefore pose risks to mussel bed die-off, and juvenile and rudimentary life stages are especially sensitive. Outflow from waste water treatment facilities in the Okanagan may contribute to nutrient poor conditions in this system.

Oxygen

Oxygen is vital for survival and basic metabolic functions within this organism, as this species respires through ciliated gills. Since *G. angulata* spend a significant portion of their lives either completely or partially buried, oxygen concentrations described below are required within interstitial substrate and the benthic zone (i.e., not within the water column). Survival, reproduction, and development require near saturated levels of dissolved oxygen for this species (Strayer 1993, Watters 1999). Dissolved oxygen concentrations between 90–110% are optimal for cellular respiration for a sensitive freshwater mussel (*Margaritifera margaritifera*) (Oliver 2000). Dissolved oxygen concentrations less than 3–6 ppm are detrimental to *G. angulata* (Strayer 1993, Watters 1999).

Conductivity/Salinity

Salinity is a measure of dissolved salt content in water, which includes ions such as sodium, potassium, magnesium, calcium, chloride, and sulphate. Extremely low and high salinity concentrations can lead to decreased reproduction and metabolic rate, and possible mortality of mussels (Ercan and Tarkan 2014). Salinity can be estimated by testing the electrical conductivity of water, when corrected for temperature; this yields the measure specific conductance. Mussels transport ions to maintain a steady-state flux for metabolic functions and cellular ion balance (Dietz and Findley 1980, Scheide and Dietz 1982). Low conductivity values may indicate essential ions are not available, for example, for shell formation, or to maintain osmotic pressure in haemocoelic fluid. “Growth, mussel diversity, and survival of Unionoidea are thus related to conductivity (Buddensiek 1995, McRae et al. 2004, Nicklin and Balas 2007)” (Snook 2015).

A habitat suitability study for *G. angulata* in Middle Fork John Day River, Oregon, determined specific conductance values above 140 µS/cm were positively related to mussel presence, while values below this were negatively correlated with their occurrence (Hegeman 2012[9]).

pH

Low pH (< 5.6) is detrimental to Unionoidea populations, and may result in shell dissolution (Fuller 1974, Kat 1984, Buddensiek et al. 1993, Strayer 1993). Acidic waters are also detrimental to fish populations (Harris et al. 2011, Kratzer and Warren 2013) which serve as important hosts for freshwater mussels, thereby negatively affecting mussel recruitment. Higher pH values are less harmful and not as concerning for unionid survival as lower pH (Dr. Ian

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[9] Hegeman, E.E. 2012. Modeling Freshwater Mussel Distribution in Relation to Biotic and Abiotic Habitat Variables in the Middle Fork John Day River, Oregon. *Unpublished thesis, Utah State University,* Utah.

Walker[3], pers. comm.). An optimal pH range of 6.5–7.2 is known for a sensitive Unionoidea species (*M. margartifera*; Oliver 2000). However, the pH range in the Okanagan River watershed can be outside of this range (e.g., Okanagan Lake pH 7.3– 8.5 (Mackie 2010) and Osoyoos Lake pH 9.0–9.5 (Booth 1969). It can be assumed the higher pH range is within *G. angulata* tolerance, given its historic distribution. Therefore, a pH range of 5.6–9.5 is recommended for critical habitat consideration.

Temperature

G. angulata is likely approaching its minimum temperature threshold at its northern distribution, with maximum threshold temperatures a possibility with future climate change scenarios in the Okanagan. Lethal cold water temperatures are specific to each species, but < 4.8°C is known to be below one species' (*Pyrgulopsis bruneauensis*) thermal tolerance (Mladenka and Minshall 2001). Disturbed mussels in water temperatures less than 16°C must use valuable energy resources to rebury (Mackie et al. 2008). Reproduction (i.e., release of conglutinates) has been observed at temperatures above 14°C for *G. angulata* (Roxanne Snook[1], pers. obsv.). The upper lethal temperature for Unionoidea, in watered and dewatered environments (of short durations, e.g., 96 hours) is 31.5–38.8°C (Dimock and Wright 1993, Pandolfo et al. 2010), or > 29°C for longer durations (Fuller 1974). Higher water temperatures can cause premature onset of non-gravid period (as observed in other freshwater mussels).

3.3.4 Biotic parameters

Riparian Habitat

Riparian habitat plays many critical roles in freshwater ecology (Gregory et al. 1991). Although no studies have validated the role of riparian habitat for *G. angulata,* future studies should be undertaken to determine the importance and requisite amount of riparian habitat. Okanagan River and Okanagan Lakes have minimal riparian habitat in locations *G. angulata* are found.

Host fish

Availability of host fish, within the identified critical habitat boundaries, is a feature of critical habitat for *G. angulata*. As obligate parasites the presence and abundance of its host fish is critical to its survival. The function of the host fish is to provide a "surface" during metamorphosis of larvae to juvenile. Encystment of the glochidia is mandatory for successful development on the host fish (O'Brien et al. 2013). After metamorphosis is complete, the new juvenile drops off the host fish and burrows in the sediment. In this way the host fish acts as a vector for larval dispersion. While potential host fish could be various species, the following are attributes of host fish availability: they need to perform functions of foraging while *G. angulata* spawning is occurring, at the same locations (i.e., same depths), must come into contact with the larvae, and must have gills of sufficient width for glochidia to attach.

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 (*R. falcatus* Eigenmann and Eigenmann, 1893), and Northern Pikeminnow (*Ptychocheilus oregonensis* Richardson, 1836) may also serve as hosts (Stanton et al. 2012, Mageroy 2015). Field data illustrating successful encystment, both prevalence (i.e., of a fish species) and intensity (i.e., number of encysted glochidia on gills), of glochidia are highest on sculpin (Mageroy 2015). Successful encystment was also observed on Longnose Dace and Leopard Dace with much lower prevalence and intensity (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). If the habitat and conditions are suitable, recruitment can be successful at this new location.

A host fish infection experiment is scheduled to occur in 2017 to confirm laboratory infection of various species of potential fish hosts. However, field observations and model predictions of sculpin occurrence suggest Okanagan Lake is saturated with sculpin, and therefore availability of host fish is not a limiting factor for *G. angulata* recruitment in that lake system. There were fewer sculpin observed in other lakes and rivers as compared to Okanagan Lake (Dr. Jon Mageroy, unpub. data, 2015). This observation may be tied to the presence of introduced fish species (especially Smallmouth Bass (*Micropterus dolumieu*)) (Dr. Jon Mageroy, pers. comm.). The observation of fewer sculpin south of Okanagan Lake has the implication that less recruitment may be occurring in these lakes and the Okanagan River.

3.4 BIOPHYSICAL FUNCTIONS, FEATURES AND ATTRIBUTES OF PROPOSED CRITICAL HABITAT FOR *G. ANGULATA* IN RIVERS

3.4.1 Physical Variables

The same characteristics as discussed for lacustrine habitat include: chemical parameters, oxygen, conductivity, pH, and temperature. Characteristics unique to *G. angulata* riverine habitat are discussed below.

River Habitat – uniform flow with low hydraulic variability

The majority of *G. angulata* are found outside of the thalweg (i.e., lowest point of the river) in channelized river sections, along both edges of the river bank in Okanagan River. River bank edges are characterized as stable substrate with slow, calm moving water (Roxanne Snook[1], pers. obsv.). *G. angulata* inhabit sections of high substrate embeddedness, up to 100% cover with fine sediments with only their siphons visible at times, as well as buried in substratum to 40 cm depth (Dr. Jon Mageroy[2], unpub. data). The embeddedness measure includes a combination of sand (0.6–2 mm), organics, silt, and mud. Although the exact water velocity parameters cannot be given at this time, river mesohabitat is characterized as ‘glide’, which by definition is usually fine sediment at the bottom and a glassy water surface (i.e., not a riffle, run, or pool). The majority of sections of Okanagan River inhabited by *G. angulata* are channelized, having low hydraulic variability, with less scouring force than meandering river sections (Roxanne Snook[1], pers. obsv.).

Habitat immediately below weir structures also contains high *G. angulata* density. These structures may help to create the habitat below them, creating turbulent water flow and nearly uniform water depth year-round. In these locations, *G. angulata* are found in flow refuges: wedged below boulders and coarse cobbles in fine sediments.

While the channelizing and dredging of Okanagan River was thought to degrade preferable habitat for *G. angulata* (Strayer 2008, DFO 2011), with a 93% loss of the natural river channel (Lauzier and Stanton 2012), diking and the creation of low flow variability vicariously (and accidentally) created preferable habitat for *G. angulata*. However, very few *G. angulata* have been found in natural and restored sections of Okanagan River, where similar bank features to those of channelized sections occur.

Depth

Mussels must be at sufficient depth to have continuous submersion year-round. Seasonal variation in Okanagan River water levels occur for various reasons, such as drought or freshets. *G. angulata* are generally observed along the river bank edges from 0.5 m to the edge of the thalweg (i.e., lowest point of the river) (Roxanne Snook[1], pers. obsv., Dr. Jon Mageroy[2], pers.

obsv.). The thalweg is an area of high shear stress and scouring energy depression, making it unsuitable for anchorage for mussels.

Dams and weirs

Below weirs there are high numbers of *G. angulata* observed in the Okanagan River. The turbulent waters below them are likely oxygen-rich and provide mechanisms for ideal re-suspension of food sources. *G. angulata* are observed in sheltered locations in these turbulent waters (i.e., flow refuges below boulders (> 256 mm) and coarse cobbles (128–256 mm).

Substrate

Stable substrate provides refuge for mussels in high flow situations (Morales et al. 2006, Davis et al. 2013). Boulders (> 256 mm) and coarse cobbles (128–256 mm) not only provide relief from scouring and shear stress from water movement, shearing action from small substrates, but also from predators. In addition, micro-eddies exist under boulders and cobbles (Davis et al. 2013), thus creating an environment of dissolved oxygen and organic matter circulation (i.e., food availability), and deposition of organics and fine sediments (i.e., embeddedness of substrates), which creates a medium for mussels to bury. This availability of refuge is especially important below weir structures, where high densities of *G. angulata* are observed below larger substrates embedded in sand (0.6–2 mm) and organics. Rip rap is rock armour, designed for river bank protection. Rip rap creates micro habitats for *G. angulata* along channelized river sections.

3.4.2 Biotic Parameters

Riparian Habitat

Riparian habitat is critical for many species of aquatic organisms (McRae et al. 2004, Pearson 2007, DFO 2011). While no known study has been conducted on *G. angulata* in relation to riparian habitat, it can be assumed riparian vegetation has critical functions relating to ecosystem health that will directly affect *G. angulata*. For example, a decrease in riparian vegetation (i.e., shade) can lead to increased water temperatures, while also decreasing detritus (i.e., food) which is filtered out of the water column by mussels. The width of the riparian reserves required to protect potentially key habitat attributes for *G. angulata* are unknown. Projects on riparian habitat requirements are recommended for future studies.

Host fish

Same as lacustrine habitat attributes and features.

3.5 AMOUNT OF CRITICAL HABITAT REQUIRED

A minimum viable population (MVP) size is required for a species to persist over X generations, based on recovery targets and modeling (The Alberta Westslope Cutthroat Trout Recovery Team 2013, Pearson 2007). As discussed previously, the MVP approach is not applicable for *G. angulata* at this time. Using the best available information, critical habitat has been identified using a Bounding Box approach for extant populations of *G. angulata* in Okanagan Lake, Skaha Lake, Vaseux Lake, Osoyoos Lake, and Okanagan River.

This approach requires the use of essential functions, features, and attributes for each life stage of this species to identify patches of critical habitat within the 'bounding box', which is defined by occupancy (2005–2015) data for the species. Life stage habitat information was summarized in chart form using available data and studies referred to in Sections 1.3 (Key life stages and general description of habitat needs). The 'Bounding Box' approach was the most appropriate, given the limited information available for this species and the lack of detailed habitat mapping for these areas. This approach and the methods used to identify reaches of critical habitat are consistent with the approaches recommended by DFO (2011) for freshwater mussels.

G. angulata are generally found within 30 m of shore with some exceptions in Okanagan Lake (Stanton et al. 2012). As a precautionary width for proposed critical habitat, a fixed-distance of 80 m has been recommended based on these observations, to encompass the majority of water depths to which *G. angulata* are found within the Okanagan (Sean MacConnachie, Fisheries and Oceans Canada, Nanaimo, BC, pers. comm.). When bathymetric data becomes available, these can be used to adjust the proposed critical habitat to the appropriate depths (e.g., 5–7 m) rather than a fixed distance from shoreline. This exercise is recommended in section five as a project that would increase the accuracy of the proposed critical habitat for *G. angulata*.

The geographical extent of habitat recommended in this report, in combination with insufficient recruitment occurring in some of the Okanagan River watershed (Mageroy et al. 2016[3]), suggests insufficient habitat is presently occupied to maintain this population. The total geographic extent of proposed critical habitat using the Bounding Box approach is 3.35 km^2 (264,6552 m^2 lake habitat Table 3; and 708,770 m^2 river habitat; Table 4), which includes only sites with confirmed *G. angulata* occurrence since 2005 (Table 5). The extent of critical habitat required for this population cannot be provided at this time because recovery targets have not yet been identified. In addition, many details of the species life history and ecology are unknown, such as threats to this species recovery, and the roles associated with host fish juvenile recruitment and habitat connectivity. While a recent study suggests sufficient juvenile recruitment is occurring in a few sites within Okanagan Lake, these results have uncertainties associated with aging *G. angulata* (Mageroy et al. 2016[3]). For sites south of Okanagan Lake, it is even less certain whether juvenile recruitment is sufficient to maintain mussel populations (Dr. Jon Mageroy[2], pers. comm.).

Table 2. Essential functions, features and attributes of critical habitat for each life-stage of G. angulata*, in the Okanagan River watershed (i.e., lacustrine and riverine habitats).

Life Stage	Function	Feature(s)	Attribute(s)	Shared Attribute(s) of Features
Adult	Spawning and brooding	Lacustrine habitat	• Site exposure (i.e., effective fetch) 6–20 km • Bench or low (0–20%) slope/site inclination • Availability of boulders (> 256 mm) and coarse cobbles (128–256 mm) (Stanton et al. 2012) • Polygon width of 80 m from shoreline elevation of 343 m (TRIM)	• Availability of food supply • Availability of high sand (0.6–2 mm) occurrence (> 20%), medium-high substrate embeddedness (> 25%) which may contain a mixture of sand, silt, mud, and organics (Stanton et al. 2012, Snook 2015) • Water quality parameters (oxygen > 3–6 ppm and pH 5.6–9.5) within the natural range of variation • Water temperatures > 14°C for conglutinate release period • Availability of appropriate host fish (both species and abundance); sculpin (*Cottus* sp.) and possibly additional species
	Reproduction (Glochidia released as conglutinates from May-July)			
	Spawning and brooding	Riverine Habitat	• Stable banks of depths 0.5–5 m river bottom • Low hydraulic variability (Davis et al. 2013), i.e., channelized river, glide • Free flowing water available year-round • Flow refuge (in the form of boulders (> 256 mm) or coarse cobbles (128–256 mm) in stable substrate), especially below weir structures	
	Reproduction (Glochidia released as conglutinates from May-July)			

Life Stage	Function	Feature(s)	Attribute(s)	Shared Attribute(s) of Features
Juvenile (post excystment/ detachment from host)	Growth to reproductive stage (6–7 years in Okanagan)	Lacustrine habitat	• Site exposure (i.e., effective fetch) 6–20 km • Bench or low (0–20%) slope/site inclination • Availability of boulders (> 256 mm) and coarse cobbles (128–256 mm) (Stanton et al. 2012) • Polygon width of 80 m from shoreline elevation of 343 m (TRIM)	• Availability of food supply • Availability of sand (0.6–2 mm) occurrence (> 20%), medium-high substrate embeddedness (> 25%) which may contain a mixture of sand, silt, mud, and organics (Stanton et al. 2012, Snook 2015) • Water quality parameters (oxygen > 3–6 ppm and pH 5.6–9.5) within the natural range of variation • Availability of appropriate host fish (both species and abundance) i.e., sculpin (*Cottus* sp.) and possibly additional species
		River Habitat	• Flow refuge (in the form of boulders (> 256 mm) or coarse cobbles (128–256 mm) in stable substrate), especially below weir structures • Low hydraulic variability (Davis et al. 2013), i.e., channelized river, glide • Free flowing water available year-round • Stable banks of depths 0.5– 5 m river bottom	

Life Stage	Function	Feature(s)	Attribute(s)	Shared Attribute(s) of Features
Juvenile-Adult	Foraging	Lacustrine habitat	• Site exposure (i.e., effective fetch) 6–20 km • Bench or low (0–20%) slope/site inclination (Snook 2015) • Availability of high sand (0.6–2 mm) occurrence (> 20%), medium-high substrate embeddedness (> 25%) which may contain a mixture of sand, silt, mud, and organics (Stanton et al. 2012, Snook 2015) • Availability of boulders (> 256 mm) and coarse cobbles (128–256 mm) (Stanton et al. 2012) • Polygon width of 80 m from shoreline elevation of 343 m (TRIM)	• Availability of food supply • Availability of sand (0.6–2 mm) occurrence (> 20%), medium-high substrate embeddedness (> 25%) which may contain a mixture of sand, silt, mud, and organics (Stanton et al. 2012, Snook 2015) • Water quality parameters (oxygen > 3–6 ppm and pH 5.6–9.5) within the natural range of variation
		River Habitat	• Stable banks of depths 0.5–5 m river bottom • Free flowing water available year-round • Flow refuge (in the form of boulders (> 256 mm) or coarse cobbles (128–256 mm) in stable substrate) where fine sediments accumulate, especially below weir structures • Low hydraulic variability (Davis et al. 2013), i.e., channelized river, glide	

**where known or supported by existing data*

Studies to further refine knowledge on the essential functions, features and attributes for various life-stages of the *G. angulata* are described in Section 5 (Schedule of studies to identify critical habitat).

4 GEOGRAPHIC IDENTIFICATION

The following brief descriptions include each water body in which *G. angulata* are present in the Okanagan. As additional areas are explored, these may be recommended as critical habitat.

Okanagan Lake

An estimated shoreline and littoral zone alteration of 80% where "mussels are present has likely had a major impact" on their habitat (DFO 2011). Model predictions from a recent study suggest sites of optimal habitat exist in the Mission area of Kelowna (in addition to the 25 presence sites already known in this lake). *G. angulata* are distributed throughout this lake, but have higher densities and occupy more sites in the southern portion near Summerland and Penticton.

Skaha Lake

"Most of the Skaha Lake shoreline has been altered by road, railway or residential development." (DFO 2011). Very low numbers of *G. angulata* are located along Eastside Road. This area has extremely high silt content.

Vaseux Lake

This lake is protected as a bird sanctuary, however *G. angulata* have been poached from here (Roxanne Snook[1], pers. obs. 2014; Park Ranger, Vaseux Lake Provincial Park Campground pers. comm. 2015). Low abundance of *G. angulata* were observed in 2015 at one location in this lake that was previously identified as an area of high abundance (Sean MacConnachie, unpub. data 2015). Smallmouth Bass have become well established and very few sculpin have been observed here. Other host fish may be present, but it is possible that this mussel population is now a relic group, with potentially little recruitment occurring. This lake is nearing the upper thermal limit (~30°C) for *G. angulata.* Surveys have been conducted in Vaseux Lake at 27°C (Roxanne Snook[1], unpub. data 2013). This lake is arguably an extension of Okanagan River, with hydrodynamics more similar to a river than a lake (i.e., contains steady laminar flow).

Osoyoos Lake

Historic records exist of *G. angulata* within Osoyoos Lake (north of the Canadian border). This is a productive (mesotrophic) lake with extensive algal growth (Rae 2005 as cited in DFO 2011) and warm temperatures in the summer months. No additional mussels were found in surveys conducted in 2013 and 2014.

Park Rill Creek

G. angulata are no longer found in this creek. Historic records are likely from when the Okanagan River was originally where Park Rill Creek runs. The redirection of the river and existing beaver dam has left this creek a slow moving water system. In combination with upstream agricultural run-off, livestock access to the creek, and increased aquatic vegetation, it should now be considered unsuitable habitat for G. angulata (Dr. Jon Mageroy[2] and Roxanne Snook[1], pers. obs. 2015).

Okanagan River

G. angulata occur throughout Okanagan River, which flows from the southern end of Okanagan Lake and connects all of the Okanagan Lakes. There are three segments of Okanagan River in BC;

1. south of Okanagan Lake to the north of Skaha Lake (through Penticton),
2. south of Skaha Lake to the north of Vaseux Lake (through Okanagan Falls), and

3. from the south of Vaseux Lake to the north of Osoyoos Lake (through Oliver) (Figure 1, Table 4).

G. angulata has noticeably higher density locations along channelized sections and are nearly absent from natural sections of Okanagan River. There are very few *G. angulata* found along the first portion of Okanagan River. In the second portion of the river, *G. angulata* inhabit the mouth of the river emerging from Vaseux Lake in the highest density. The highest river densities of *G. angulata* occur along the third section, from Oliver to the river mouth into Osoyoos Lake. 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 2011) with numerous weirs existing along Okanagan River.

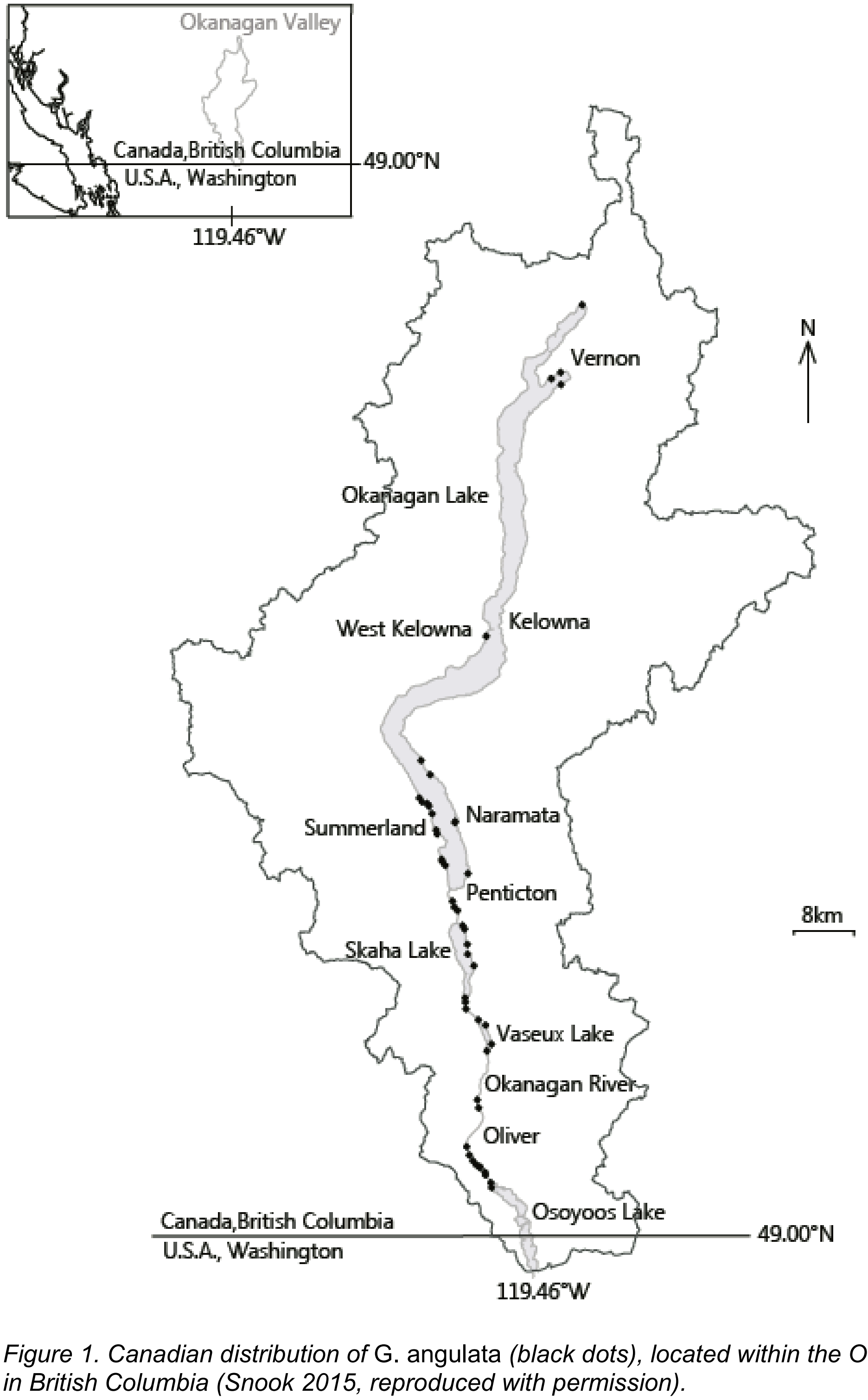

Figure 1. Canadian distribution of G. angulata *(black dots), located within the Okanagan River watershed in British Columbia (Snook 2015, reproduced with permission).*

The following locations of the potential critical habitat for *G. angulata* have been identified using the Bounding Box approach. This approach requires the use of essential functions, features, and attributes for each life stage of this species to identify patches of critical habitat within the 'Bounding Box', which is defined by occupancy (2005–2015) data for the species. The areas within which critical habitat for *G. angulata* occurs are identified in Figure 6–15 and correspond with the list of coordinates in Tables 3 and 4. The edges of these coordinates represent distinct land marks and are not representative of the start and end points of mussel beds. Distinct land marks were based on Foreshore, Inventory, and Mapping data for Okanagan Lake, and researcher's descriptions while in the field. Identifying distinct landmarks was done for mapping purposes (e.g., recording coordinates in Google Earth) and describing sites for returning researchers. While this data is the best current available data, ground truth with accurate G.P.S. is recommended for future mapping. A mapping exercise from Snook (2015) thesis predicted additional potential critical habitat, and is recommended for surveying to confirm or disregard these sites (see Appendix 2).

Table 3. Coordinate positions of G. angulata *polygon edges within Okanagan Lake, Skaha Lake, Vaseux Lake, and Osoyoos Lake. Universal Transverse Mercator (UTM) 11. Date of recorded occurrence are in categories: present (2005–2015), recent (1990's–2004), and historic (pre-1990s). Data from multiple sources: Dr. Jon Mageroy et al 2016[3], Snook, R., unpub. data. Data, Ecocat accessed December 2015.*

Section	**Start UTM**	**End UTM**	**Length (m) between landmarks**	**Approx. area (m^2) (all section widths are 80m from 348m TRIM shoreline elevation)**	**Occurrence (present, recent, historic)**
Okanagan Lake 20	307163 5500612	307625 5500340	907.4	72592	Present
Okanagan Lake 21	307625 5500340	308013 5499679	829.4	66352	Present
Okanagan Lake 22	308013 5499679	308297 5498817	1047.8	83824	Present
Okanagan Lake 23	308297 5498817	308351 5498748	109.9	8792	Present
Okanagan Lake 24	308351 5498748	308387 5497952	1064.7	85176	Present
Okanagan Lake 25	308389 5497950	308381 5497763	239.6	19168	Present
Okanagan Lake 26	308381 5497763	308336 5497681	154.0	12320	Present
Okanagan Lake 27	308336 5497681	308627 5496874	1048.9	83912	Present
Okanagan Lake 28	308627 5496874	308859 5495744	1170.6	93648	Present

Section	Start UTM	End UTM	Length (m) between landmarks	Approx. area (m^2) (all section widths are 80m from 348m TRIM shoreline elevation)	Occurrence (present, recent, historic)
Okanagan Lake 29	308859 5495744	308992 5495702	145.8	11664	Present
Okanagan Lake 30	308992 5495702	308855 5495742	714.1	57128	Present
Okanagan Lake 39	309728 5491310	309875 5491102	339.5	27160	Present
Okanagan Lake 40	313844 5489084	313119 5486973	289.3	23144	Present
Okanagan Lake 41	310024 5490855	310092 5490621	310.9	24872	Present
Okanagan Lake 42	310636 5487124	310777 5486763	417.8	33424	Present
Okanagan Lake 43	310988 5486687	310777 5486763	556.1	44488	Present
Okanagan Lake 44	312057 5486772	310988 5486687	1419.5	113560	Unknown year recorded
Okanagan Lake 50	313919 5490235	314106 5489680	618.0	49440	Present
Okanagan Lake 51	313752 5490666	313919 5490235	642.4	51392	Present
Okanagan Lake 63	310342 5503223	312088 5498968	5139.9	411192	Present
Okanagan Lake 70	309151 5504567	308676 5504946	656.4	52512	Present
Okanagan Lake 235	317925 5526817	317557 5525607	1522.1	121768	Present
Okanagan Lake 266	332126 5567545	331764 5567481	409.4	32752	Present

Section	Start UTM	End UTM	Length (m) between landmarks	Approx. area (m^2) (all section widths are 80m from 348m TRIM shoreline elevation)	Occurrence (present, recent, historic)
Okanagan Lake 273	330131 5568359	332260 5569014	2419.4	193552	Present
Okanagan Lake 274	328980 5567189	330131 5568359	1740.3	139224	Present
Okanagan Lake 305	334171 5578614	335362 5579968	6255.2	500416	Present
Skaha Lake Polygon 1	313325 5477944	313186 5478246	330	26400	Present
Skaha Lake Polygon 2	313732 5475712	313724 5475903	192	15360	Present
Skaha Lake Polygon 3	313843 5475228	313873 5474997	244	19520	Present
Skaha Lake Polygon 4	313193 5469321	313363 5469604	350	28000	Present
Skaha Lake Polygon 5	312955 5469306	312784 5469245	180	14400	Present
Skaha Lake Polygon 6	312589 5471206	312567 5471111	97	7760	Present
Skaha Lake Polygon 7	312677 5470672	312613 5470848	197	15760	Present
Skaha Lake Polygon 8	313719 5472562	313579 5472462	170	13600	Present
Skaha Lake Polygon 9	313869 5474813	313859 5474937	130	10400	Present
Skaha Lake Polygon 10	312898 5479728	312898 5479728	0	0	Historic
Vaseux Lake Polygon 1	315958 5463856	316102 5463504	380	30400	Present

Section	Start UTM	End UTM	Length (m) between landmarks	Approx. area (m^2) (all section widths are 80m from 348m TRIM shoreline elevation)	Occurrence (present, recent, historic)
Vaseux Lake Polygon 2 (to mouth of Okanagan River)	316324 5460937	316067 5460802	310	24800	Present
Vaseux Lake 3	316499 5462451	316747 5461602	905	72400	Present
Osoyoos Lake Polygon 1	315444 5438748	315771 5438185	638	51040	Present
Osoyoos Lake Polygon 2	316022 5437983	316128 5437802	210	16800	Present
Osoyoos Lake Polygon 3	321398 5432509	320969 5432246	1355 (170m width recommended)	230350	Historic

Table 4. Coordinate positions of G. angulata within Okanagan River segments. Length, width, and approximate area are polygon dimensions, in which one or more mussel beds are found. All records are current (2005–2015) observations (Dr. Jon Mageroy[2], unpub. data). Universal Transverse Mercator (UTM) 11.

Section	Start UTM	End UTM	Length (m) between landmarks	width avg.	approx. area (M2)	River type	*G. angulata* (# observed)
Okanagan River, Lower lagoon below Vaseux Lake to McIntyre Dam	315893 5460233	316031 5459087	1190	45	53550	Channelized	32
Okanagan River, Development to Hwy bridge	315862 5457345	314959 5456085	1720	31	53320	Natural	1

Section	**Start UTM**	**End UTM**	**Length (m) between landmarks**	**width avg.**	**approx. area (M2)**	**River type**	***G. angulata* (# observed)**
Penticton channel, former bridge to bend	311331 5484584	311630 5484294	420	24	10080	Channelized	2
Okanagan River, Spawning channel to first restored oxbow	314343 5453315	314050 5452836	520	23	11960	Channelized	5
Okanagan River, Oliver bridge to 1st weir	314361 5451058	314880 5449987	1110	27	29970	Channelized	46
Okanagan River, 1st weir to 2nd weir	314880 5449987	314729 5448978	1070	27	28890	Channelized	63
Okanagan River, 2nd weir to Thorp Rd. Bridge	314729 5448978	314292 5448306	800	28	22400	Channelized	71
Okanagan River, Thorp Rd. To 3rd weir	314292 5448306	313525 5447532	1090	30	32700	Channelized	162
Okanagan River, 3rd weir to 4th weir	313525 5447532	312777 5446789	1060	28	29680	Channelized	83
Okanagan River, 4th weir to # 9 Rd. Bridge	312777 5446789	312509 5446515	380	27	10260	Channelized	12
Okanagan River, # 18 Rd. Bridge to 1st weir	312742 5443345	313501 5442262	1320	29	38280	Channelized	150

Section	**Start UTM**	**End UTM**	**Length (m) between landmarks**	**width avg.**	**approx. area (M2)**	**River type**	***G. angulata* (# observed)**
Okanagan River, 1st weir to # 22 Rd. Bridge	313501 5442262	314903 5440465	2280	34	77520	Channelized	160
Okanagan River, # 22 Rd. Bridge to 2nd weir	314903 5440465	315243 5440058	530	25	13250	Channelized	111
Okanagan River, 2nd weir to Osoyoos Lake	315243 5440058	316119 5438962	1410	40	56400	Channelized	99
OK River-Oliver 1st Weir to Pedestrian Bridge	314115 5452194	314232 5451627	580	24	13920	Channelized	84
OK River-Oliver Pedestrian Bridge to Kinsmen Park (255 Fairview Rd. Bridge)	314232 5451627	314361 5451058	580	23	13340	Channelized	369
OK River-Rd9 weir/bridge to Rd15 weir	312509 5446515	312361 5444522	2220	28.5	63270	Channelized	252
OK River-Rd15-next weir	312361 5444522	312511 5443763	780	26	20280	Channelized	297
OK River-weir to Rd18	312511 5443763	312742 5443345	490	26	12740	Channelized	46
Okanagan River, Weir # 15 to Weir # 14	312810 5467482	313330 5466680	960	44	42240	Channelized	1

Section	Start UTM	End UTM	Length (m) between landmarks	width avg.	approx. area (M2)	River type	*G. angulata* (# observed)
Okanagan River, Weir # 14 to start of first bend	313330 5466680	314012 5466140	880	44	38720	Channelized	2
Okanagan River, Power line to 2nd bend	314100 5465968	314552 5465500	800	45	36000	Channelized	1

Table 5. Summary of polygon areas from Tables 3 and 4 with proposed 80 m width. Polygons contain only sites in which G. angulata is presently recorded (i.e., 2005–2015) in the Okanagan River watershed. Data from multiple sources: Dr. Jon Mageroy[3], unpub. data, Snook, R. unpub. data[1], Ecocat accessed December 2015.

Location	Section length (m)	Approximate width (m)	Approximate Area (m²)	Approximate Area (km^2)
Penticton channel:	420	24	10080	0.01008
between Skaha and Vaseux:	2640	between 44 and 45	116960	0.11696
directly below Vaseux before Oliver township	2910	between 45 and 31	106870	0.10687
Oliver to Osoyoos:	16220	between 23 and 40	474860	0.47486
TOTAL River	**22190**	-	**708770**	**0.70877**
Okanagan Lake	28748.9	80	2299912	2.299912
Skaha Lake	1890	80	151200	0.1512
Vaseux Lake	1595	80	127600	0.1276
Osoyoos Lake	2203	80	67840	0.06784
TOTAL Lake	**33081.9**	**-**	**2646552**	**2.646552**
SUM Lake & River	**55271.9**	**-**	**3355322**	**3.355322**

Most recent surveys in 2013, 2014, and 2015 have discovered many new *G. angulata* sites within the Okanagan River watershed. These additional sites are from increased survey efforts, and are not considered new populations of *G. angulata* since 2009 surveys.

5 ACTIVITIES LIKELY TO DESTROY CRITICAL HABITAT (ALTD CH)

The definition of destruction of habitat is defined as:

"Destruction of critical habitat would result if any part of the critical habitat were degraded, either permanently or temporarily, such that it would not serve its functions when needed by the species. Destruction may result from single or multiple activities at one point in time or cumulative effects of one or more activities over time." (Fisheries and Oceans Canada 2015).

Activities that are likely to permanently or temporarily destroy critical habitat for *G. angulata* are described in Table 6. These include land development for resource extraction or private homes, which alters sediment input into nearby water sources. Enhancement of habitat for other species (e.g., salmonids) can alter the features with which *G. angulata* are established or assocated. Tourism pressures in the Okanagan result in removal of invasive aquatic macrophytes via root extraction from rototilling. This procedure involves altering substrate, increasing turbidity, and crushing benthic dwelling organisms. Cumulative impacts of dock construction within mussel beds may now have a significant effect on their habitat. Dredging of locations with heavy sediment, detritus, or sewage output can remove substrate, and mussels. Water level changes can be drastic in the Okanagan, for reasons including, but not limited to, low snow pack accumulation, drought, high water extraction, and energy demand. Invasive species can alter food web structure, such as Smallmouth Bass and *Dreissena sp.* (Mackie 1991). Deleterious substance release and other point source pollution scenarios can cause immediate die-off of mussels, whereas impacts from non-point source pollution may take years to become evident if less recruitment is occurring.

Table 6. Activities likely to result in the destruction of critical habitat of the G. angulata*. The pathway of effect for each activity is provided as well as the potential links to the biophysical functions, features and attributes of critical habitat reviewed in Table 2.*

Threat	**Activity**	**Effect -Pathway**	**Function Affected**	**Feature Affected**	**Attribute Affected**
Activities that generate significant sediment inputs	Work in or around critical habitat with improper sediment and erosion control (e.g., installation of bridges, culverts), run-off from urban, residential, agricultural and industrial land use, use of industrial equipment, cleaning or maintenance of bridges, drains or other structures without proper mitigation.	Improper sediment and erosion control or mitigation can cause increased turbidity and sediment deposition. Significant sediment influx into the river or lake could impair the osmoregulatory capacity of *G. angulata* and obstruct host fish from coming into contact with conglutinates.	Spawning and Brooding,	River & Lacustrine Habitat	• Water quality parameters (oxygen and pH) within the natural range of variation • Sedimentation within natural range of variation • Availability of high sand (0.6–2 mm) occurrence (> 20%), medium-high substrate embeddedness (> 25%) which may contain a mixture of sand, silt, mud, and organics (Stanton et al. 2012, Snook 2015) • Stable banks of depths 0.5-5 m (River only) • Suitable habitat for host fish
Alteration of habitat for human use	Disturbance or loss of littoral and riverine habitat (e.g., rototilling of Eurasian watermilfoil). Installation and maintenance of docks, pilings, groynes, piers.	Disrupts and may cover preferred habitat. Can bury and crush mussels. Cutting or trimming is recommended as an alternative method in sites with *G. angulata*. Dock construction	Spawning and brooding Reproduction Growth Foraging	River & Lacustrine Habitat	• Water quality parameters (oxygen, temperature and pH) within the natural range of variation • Sedimentation within natural range of variation • Availability of high sand (0.6–2 mm) occurrence (> 20%), medium-high substrate embeddedness (> 25%) which may contain a mixture of sand, silt, mud, and organics

Threat	Activity	Effect -Pathway	Function Affected	Feature Affected	Attribute Affected
	Dredging, grading, excavation, structure removal and construction of dams and/or barriers. Alteration of river bed composition and shape for salmon enhancement.	can crush or bury mussels with piling placement. Groynes can alter water movement and disturb or cover preferable substrate. River alterations for salmon habitat resulting in reduction of available suitable habitat for *G. angulata.*			(Stanton et al. 2012, Snook 20015) • Bench or low (0–20%) slope/site inclination Water depths 0.5 m – 5 m along littoral zone (Lacustrine Habitat) • Availability of food supply • Availability of appropriate host fish (both species and abundance), sculpin (*Cottus* sp.) and potentially other species • Host fish foraging synchronized with conglutinate release, within hours-days • Suitable habitat for host fish • Flow refuge (in the form of boulders (> 256 mm) or coarse cobbles (128–256 mm) in stable substrate), especially below weir structures (River only) • Stable banks of depths 0.5-5 m (River only) • Low hydraulic variability (Davies et al. 2013), i.e., channelized river, glide (River only)

Threat	Activity	Effect -Pathway	Function Affected	Feature Affected	Attribute Affected
Water withdrawals and/or impoundment	Water-level management (e.g., through dam operation) or water extraction activities (e.g., for irrigation), that causes dewatering of habitat.	Water fluctuations greater than natural variability could alter water flow in the Okanagan River and Okanagan Lakes. Reduced water levels can isolate and strand mussels above water level (Stanton et al. 2012) or in a highly exposed position, vulnerable to wave action, weathering, desiccation, or predation. Changes to river flow can affect sediment deposits (altering preferred substrates), and change water temperature. Juveniles are especially vulnerable to scouring.	Spawning and brooding Reproduction Growth Foraging	River & Lacustrine Habitat	• Water quality parameters (oxygen, temperature and pH) within the natural range of variation • Flow refuge (in the form of boulders (> 256 mm) or coarse cobbles (128–256 mm) in stable substrate), especially below weir structures (River only) • Stable banks of depths 0.5–5 m (River only) • Low hydraulic variability (Davis et al. 2013), i.e., channelized river, glide (River only) • Water depths 0.5—5 m along littoral zone (Lacustrine only) • Availability of food supply • Availability of appropriate host fish (both species and abundance), sculpin (*Cottus* sp.) and potentially other species • Suitable habitat for host fish

Threat	Activity	Effect -Pathway	Function Affected	Feature Affected	Attribute Affected
Introduction of invasive species through human activities	Inadvertent or deliberate introduction of non-native species (e.g., *Dreissena* sp); opening of dams and fish ladders that allow species transfers (e.g., Smallmouth Bass).	Modification of predator/prey relationships.	Spawning and brooding Reproduction Growth Foraging	River & Lacustrine Habitat	• Availability of appropriate host fish (both species and abundance), sculpin (*Cottus* sp.) and possibly additional species • Suitable habitat for host fish • Host fish foraging synchronized with conglutinate release, within hours-days • Availability of food supply • Destruction of substrate; *Dreissena* sp. can create own substrate and suffocate native freshwater mussels

Threat	**Activity**	**Effect -Pathway**	**Function Affected**	**Feature Affected**	**Attribute Affected**
Release of deleterious substances and excessive nutrient input through groundwater and/or surface flows from point or non-point sources	Release of urban and industrial pollution into habitat including: storm-water runoff from existing and new developments, residential septic seepage, over-application of fertilizer (commercial or residential) and improper nutrient management (e.g., organic debris, wastewater, animal waste, septic system and municipal sewage).	Polycyclic Aromatic Hydrocarbons (PAHs) do not readily dissolve in water but will bind with organic material and can be deposited in the sediment. This could affect adult feeding and metamorphosis, as well as larvae development and host fish availability and habitat. Eutrophication resulting in algal blooms reducing light penetration and water clarity, changing water chemistry, increasing sedimentation rates and altering food web structure.	Spawning and brooding Reproduction Growth Foraging	River & Lacustrine Habitat	• Water quality parameters (oxygen and pH) within the natural range of variation • Few or no added pollutant • Availability of appropriate host fish (both species and abundance) i.e., sculpin (*Cottus* sp.) and possibly additional species • Availability of food supply

6 STUDIES TO INFORM THE IDENTICATION OF CRITICAL HABITAT FOR *G. ANGULATA*

Host fish migration studies (i.e., how far do sculpin travel) would determine a projected temporal and spatial framework for mussel distribution. In addition, determination of additional host fish species and their ecological roles in terms of mussel recruitment, dispersal, bed connectivity and genetic variability in the population would address questions pertaining to population genetics and dispersal mechanisms.

Additional or refined critical habitat recommendations can be made from a projection of a Random Forests model across Okanagan Lake. This may predict sites where *G. angulata* occur, but have not yet been surveyed, or locate sites with optimal habitat for this species where it hasn't yet dispersed. A refined model can be applied across the lakes in the Okanagan River watershed when bathymetric data becomes available. This will adjust the proposed critical habitat polygons to appropriate depths (e.g., 5–7 m) rather than a fixed distance from shoreline (i.e., 80–343 m elevation (TRIM)). Likewise, increasing accuracy of proposed critical habitat can be done by ground truthing of actual edges of mussel beds with G.P.S. in the Okanagan.

The ecological role of riparian habitat is unknown for *G. angulata,* in terms of quantity and quality necessary in lakes and rivers. Presumably, riparian habitat has multiple vital functions for *G. angulata*. Since *G. angulata* are passive filter feeders, specific ranges of quantity and quality of detritus and riparian habitat are likely important attributes for this species.

7 KNOWLEDGE GAPS IN *G. ANGULATA* BIOLOGY

A minimum viable population size is an unknown element in the management of this species (DFO 2011). Determining if the amount of proposed critical habitat is sufficient to maintain this population may become plausible as more information becomes available on recovery targets, and population ecology. Details such as whether *G. angulata* are short-term (tachytictic) brooders, with spawning and glochidial release occurring in the same season or if they are long-term (bradytictic) brooders (Spring Rivers 2007) are unknown elements in the species life history. This information may be important for determining minimum or maximum temperatures required during climate change or years of adverse environmental conditions.

Habitat ranges or limitations associated with sedimentation and interstitial oxygen requirements are unknown for this species. These may be of importance due to the potential for increased erosion in the Okanagan River watershed from foreshore development and increased water treatment output with increasing human population pressures.

Limitations in the ability to accurately estimate the age of *G. angulata* result in uncertainties in estimates of juvenile recruitment. Aging mussels by their external growth rings is difficult, and can pose a risk of underestimating the age of the mussel by 100% (Downing et al. 1991). For example, if the true age for *G. angulata* is 45 years old, the number of estimated locations supporting sufficient recruitment is reduced (Mageroy et al. 2016[3]).

The critical number of host fish and necessary fish species composition (within the region/watershed/mussel bed) to sustain a population of *G. angulata* is unknown, as is the ecological role of different host fish in terms of habitat connectivity.

There is uncertainty related to habitat requirements of water flow and movement at sites with *G. angulata.* Since *G. angulata* are passive filter feeders, feeding and respiration are accomplished from loading of the sites with food in well circulated waters. Minimum, maximum, and optimal water flow at and movement at sites are unknown habitat parameters for this species.

8 CONCLUSIONS AND RECOMMENDATIONS

Potential lacustrine and riverine critical habitat sites have been identified and spatially described by polygons using the Bounding Box approach. Should this species be listed as Endangered, sites with recently (2005–2015) confirmed occurrences are recommended for critical habitat designation. A total area of 708,770 m^2 (0.70877 km^2) of river habitat is recommended as critical habitat for *G. angulata*, while a total area of 2,646,552 m^2 (2.646552 km^2) is recommended for lake habitat. Total proposed critical habitat is 3,355,322 m^2 (3.355322 km^2), which includes only sites with confirmed *G. angulata* occurrence since 2005. Advice on the extent of critical habitat required for this population cannot be provided because no recovery targets have been identified.

Recommendations for further study include studying the ecology of *G. angulata* host fish species, to improve understanding of their roles associated with juvenile recruitment, habitat connectivity, and threats to population's recovery. It is recommended to apply a Random Forest habitat model to the entire Okanagan Lake. It is also recommended that sites which lack *G. angulata* occurrence, but have suitable habitat features be considered by management in association with objectives linked to distribution, survival, and recovery goals. These sites may be appropriate for critical habitat designation once more information becomes available on the recovery targets, and on the population(s) ecology.

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10 REFERENCES

Arbuckle, K.E., and Downing, J.A.. 2002. Freshwater mussel abundance and species richness: GIS relationships with watershed land use and geology. Can. J. Fish Aquat. Sci. 59: 310–316.

BC Conservation Data Centre. 2015a. Conservation Status Report: *Gonidea angulata*. BC Ministry. of Environment. (Accessed June 4, 2018).

BC Conservation Data Centre. 2015b. Species Summary: *Gonidea angulata*. BC Ministry. of Environment. (Accessed June 4, 2018).

Bogan, A.E. 1993. Freshwater Bivalve Extinctions (Mollusca: Unionoida): A search for causes. Amer. Zool 33: 599–609.

Booth, D.M. 1969. Water Quality Studies in Osoyoos Lake, British Columbia. Thesis (M.Sc.) University of British Columbia. 180 p. (Accessed June 4, 2018).

Breiman, L. 2001. Random Forests. Machine Learning 45: 5–32. doi:10.1023/A:1010933404324.

Brim Box, J., and Mossa, J. 1999. Sediment, land use, and freshwater mussels: Prospects and problems. J. N. Am. Benthol. Soc. 18: 99–117. (Accessed June 4, 2018).

Buddensiek, V. 1995. The culture of juvenile freshwater pearl mussels *Margaritifera margaritifera* L. in cages: A contribution to conservation programmes and the knowledge of habitat requirements. Biol. Cons. 74: 33–40. doi:10.1016/0006-3207(95)00012-S.

Buddensiek, V., Engel, H., Fleischauer-Rossing, S., and Wachtler, K. 1993. Studies on the chemistry of interstitial water taken from defined horizons in the fine sediments of bivalve habitats in several northern German lowland waters. 1: Sampling techniques. Arch. Hydrobiol. 119: 55–64.

Callaghan, D.P., Leon, J.X., and Saunders, M.I. 2015. Wave modelling as a proxy for seagrass ecological modelling: Comparing fetch and process-based predictions for a bay and reef lagoon. Estuar. Coast. Shelf Sci. 153: 108–120. doi:10.1016/j.ecss.2014.12.016.

COSEWIC. 2003. COSEWIC assessment and status report on the Rocky Mountain Ridged Mussel *Gonidea angulata* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vi + 29 pp. (Accessed June 4, 2018).

COSEWIC. 2010. COSEWIC assessment and status report on the Rocky Mountain Ridged Mussel *Gonidea angulata* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. x + 56 pp. (Accessed June 4, 2018).

Davis, E.A., David, A.T., Norgaard, K.M., Parker, T.H., McKay, K., Tennant, C., Soto, T., Rowe, K., and Reed, R. 2013. Distribution and abundance of freshwater mussels in the Mid Klamath Subbasin, California. Northwest Sci. 87: 189–206.

DFO. 2010. Recovery Potential Assessment of Wavy-Rayed Lampmussel (*Lampsilis fasciola*) in Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/045.

DFO. 2011. Recovery Potential Assessment for Rocky Mountain ridged mussel (*Gonidea angulata*) in British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/053.

Dietz, T.H., and Findley., A.M. 1980. Ion-stimulated ATPase activity and NaCl uptake in the gills of freshwater mussels. Can. J. Zool. 58: 917–923. doi:10.1139/z80-126.

Dimock, R.V., and Wright, A.H.. 1993. Sensitivity of juvenile freshwater mussels to hypoxic, thermal, and acid stress. J. Elisha Mitchell Sci. Soc. 109: 183–192.

Downing, W.L., Shostel, J., and Downing, J.A. 1991. Non-annual external annuli in the freshwater mussels *Anadonta grandis grandis* and *Lampsilis radiata siliquoidea*. Freshwater Biol. 28: 309–317.

Downing, J.A., Meter, P.V., and Woolnough D.A. 2010. Suspects and evidence: a review of the causes of extirpation and decline in freshwater mussels. Anim. Biodivers. Conserv. 33.2: 151–185.

Ecocat. Ecological Reports Catalogue. *Gonidea angulata*. (Accessed June 4, 2018).

Ercan, E., and Tarkan, A.S. 2014. Effect of salinity on the growth and survival of the freshwater mussel, *Unio crassus*, in an environmentally disturbed river. Pakistan J. Zool. 46: 1399–1406.

Fisheries and Oceans Canada. 2011. Management plan for the Rocky Mountain ridged mussel (*Gonidea angulata*) in Canada [Final]. Species at Risk Act Management Plan Series. Fisheries and Oceans Canada, Vancouver, British Columbia.

Fisheries and Oceans Canada. 2015. *Species at Risk Act.* Guidelines for the Identification of Critical Habitat for Aquatic Species at Risk.

Fuller, S.L.H. 1974. Clams and mussels (Mollusca: Bivalvia)., *In* Hart, C.W., and Fuller, S.L.H. (eds.). Pollution ecology of freshwater invertebrates. Academic Press, New York. 215–273 p.

Geist, J. 2005. Conservation Genetics and Ecology of European Freshwater Pearl Mussels (*Margaritifera margaritifera* L .). Dissertation (Ph.D.) Technischen Universität München eingereicht und durch die Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt, Munich, Germany. 120 p.

Gregory S., Swanson, F.J., McKee, W.A., and Cummins, K.W. 1991. An ecosystem perspective of riparian zones. Biosci. 41(8): 540–541.

Haag, W.R. 2012. North American Freshwater Mussels: Natural History, Ecology and Conservation. Cambridge Press. 535 p.

Hakanson, L. 1977. The influence of wind, fetch, and water depth on the distribution of sediments in Lake Vanern, Sweden. Can. J. Earth Sci. 14: 397–412.

Harris, A., Daelyn, T. Woolnough A., and Zanatta, D.T. 2011. Insular lake island biogeography: Using lake metrics to predict diversity in littoral zone mollusk communities. J. N. Am. Benthol. Soc. 30: 997–1008. doi:10.1899/11-020.1.

Hothorn, T., Hornik, K., and Zeileis, A. 2006. Party: A laboratory for recursive partitioning.

Jepsen, S., LaBar, C., and Zarnoch, J. 2010. Species Profile: Western Ridged Mussel (*Gonidea angulata*). The Xerces Society. (Accessed June 4, 2018).

Kat, P.W. 1984. Parasitism and the Unionacea (Bivalvia). Biol. Rev. Camb. Philos. 59: 189–207.

Kratzer, J.F., and Warren, D.R. 2013. Factors limiting brook trout biomass in Northeastern Vermont streams. N. Am. J. Fish Manage. 33: 130–139. doi:10.1080/02755947.2012.743934.

Lauzier, R.B., and Stanton, L.M. 2012. Recovery Potential Assessment for Rocky Mountain ridged mussel (*Gonidea angulata*). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/109. vi + 37p.

Lydeard, C., Cowie, R.H., Ponder, W.F., Bogan, A.E., Bouchet, P., Clark, S.A., and Cummings, K.S.. 2004. The global decline of nonmarine mollusks. Biosci. 54: 321–330.

Mackie, G.L. 1991. Biology of the exotic zebra mussel, *Dreissena polymorpha*, in relation to native bivalves and its potential impact in Lake St. Claiar. Hydrobiologia 219: 251–268.

Mackie, G., Morris, T.J., and Ming, D. 2008. Protocols for the detection and relocation of freshwater mussels species at risk in Ontario-Great Lakes Area (OGLA). Can. Manusc. Rep. Fish. Aquat. Sci. 2790: vi+50 pp.

Mackie, G. 2010. Risk assessment of water quality in Okanagan Lake, British Columbia, to Zebra/Quagga mussel infestations. Report submitted by Water Systems Analysts Ltd. for the COSEWIC Mollusc Species Subcommittee. September 2010. 6 pp.

Dr. Jon Mageroy 2015. Rocky Mountain ridged mussel (*Gonidea angulata*) in the Okanagan Valley, BC: Final report on juvenile recruitment, host fish field sampling, and the impact of rototilling against Eurasian watermilfoil (*Myriophyllum spicatum*). Report. University of British Columbia, Kelowna, British Columbia.

McRae, S.E., Allan, J.D., and Burch, J.B. 2004. Reach and catchment-scale determinants of the distribution of freshwater mussels (Bivalvia: Unionidae) in south-eastern Michigan, U.S.A. Freshwater Biol. 49: 127–142.

Mladenka, G.C., and Minshall, G.W. 2001. Variation in the life history and abundance of three populations of Bruneau hot spring snails (*Pyrgulopsis bruneauensis*). West. N. Am. Nat. 61: 204–212.

Morales, Y., Weber, L.J., Mynett, A.E., and Newton, T.J. 2006. Effects of substrate and hydrodynamic conditions on the formation of mussel beds in a large river. J. N. Am. Benthol. Soc. 25: 664–676. doi:10.1899/0887-3593(2006)25[664:EOSAHC]2.0.CO;2.

Mouton, A.M., De Baets B., and Goethals, P.L.M. 2010. Ecological relevance of performance criteria for species distribution models. Ecol. Model. 221: 1995–2002.

Nedeau, E.J., Smith, A.K., Stone J., and Jepsen, S. 2009. Freshwater mussels of the Pacific Northwest. 2nd ed. The Xerces Society for Invertebrate Conservation. Portland, Oregon, U.S.A.

Nicklin, L., and Balas, M.T. 2007. Correlation between unionid mussel density and EPA habitat-assessment parameters. Northeast. Nat. 14: 225–234. (Accessed December 18, 2017).

O'Brien, C., Nez, D., Wolf, D., and Brim Box, J. 2013. Reproductive biology of *Anodonta californiensis, Gonidea angulata,* and *Margaritifera falcata* (Bivalvia: Unionoida) in the Middle Fork John Day River, Oregon. Northwest Sci. 87: 59–72.

Oliver, G. 2000. Conservation objectives for the freshwater pearl mussel (*Margaritifera margaritifera*). Report to English Nature, Peterborough.

Pandolfo, T.J., Cope, W.G., Arellano, C., Bringolf, R.B., Barnhart, M.C., and Hammer, E. 2010. Upper thermal tolerances of early life stages of freshwater mussels. J. N. Am. Benthol. Soc. 29: 959–969.

Pearson, M. 2007. An Assessment of Potential Critical Habitat for Nooksack Dace (*Rhinichthys cataractae* ssp.) and Salish Sucker (*Catostomus* sp.). DFO Can. Sci. Advis. Sec. Res. Doc. 2007/058. viii + 71 p.

Scheide, J.I., and Dietz, T.H. 1982. The effects of independent sodium and chloride depletion on ion balance in freshwater mussels. Can. J. Zool. 60: 1676–1682.

Schleppe, J., and Mason, B. 2009. Standard methods for completion of foreshore inventory and mapping projects. Prepared by: Ecoscape Environmental Consultants Ltd. and The Community Mapping Network doi:10.1016/B978-012373624-6/50008-4.

Schwalb, A.N., Morris, T.J., Mandrak, N.E., and Cottenie, K. 2013. Distribution of unionid freshwater mussels depends on the distribution of host fishes on a regional scale. Divers. Distrib. 19: 446–454.

Shaffer, M.L. 1981. Minimum population sizes for species conservation. Biosci. 31: 131–134

Snook, R. 2015. Modeling Habitat Suitability for the Rocky Mountain ridged mussel (*Gonidea angulata*), in Okanagan Lake, British Columbia, Canada. Thesis (M.Sc.) University of British Columbia, BC. 96 p. (Accessed June 4, 2018)

Spring Rivers. 2007. Reproductive timing of freshwater mussels and potential impacts of pulsed flows on reproductive success. California Energy Commission. PIER Energy-Related Environmental Research Program. CEC-500-2007-097.

Stanton, L., Lauzier, R., Macconnachie, S.,. Nield, L., Pollard, S., Heron, J., and Davies, S. 2012. Exploratory surveys and directed studies of Rocky Mountain Ridged Mussel (*Gonidea angulata* Lea, 1839) in British Columbia. Can. Man. Rep. of Aquat Sci. No. 3003.

Strayer, D.L. 1993. Macrohabitats of freshwater mussels (Bivalvia : Unionacea) in streams of the Northern Atlantic Slope. . J. N. Am. Benthol. Soc.12: 236–246.

Strayer, D.L. 1999. Use of flow refuges by unionid mussels in rivers. .J. N. Am. Benthol. Soc. 18: 468–476.

Strayer, D.L. 2008. Freshwater Mussel Ecology: A multifactor approach to distribution and abundance. University of California Press, Berkeley, California. 216 p.

The Alberta Westslope Cutthroat Trout Recovery Team. 2013. Alberta Westslope Cutthroat Trout Recovery Plan: 2012–2017. Alberta Environment and Sustainable Resource Development, Alberta Species at Risk Recovery Plan No. 28. Edmonton, AB. 77 p.

Vannote, R.L., and Minshall, G.W. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proc. Natl. Acad. Sci. U.S.A. 79: 4103– 4107.

Vaughn, C.C., Nichols, S.J., and Spooner D.E. 2008. Community and foodweb ecology of freshwater mussels. J. N. Am. Benthol. Soc.27: 409–423. doi:10.1899/07-058.1.

Vezza, P., Paranimf, C. De Gandia, G., España, V., Martinez-capel, F., Muñoz-mas, R., and Alcaraz-hernandez, J.D. 2012. Habitat suitability modeling with random forest as a tool for fish conservation in Mediterranean rivers. *In* Eds: Mader, H., and Kraml, J., 9th International Symposium on Ecohydraulics 2012 Proceedings, Vienna, Austria. ISBN: 978-3-200-02862-3.

Watters, T.G. 1999. Freshwater mussels and water quality: A review of the effects of hydrologic and instream habitat alterations, 261–274. *In* Proceedings of the First Freshwater Mollusk Conservation Society Symposium.

Westerbom, M., and Jattu, S. 2006. Effects of wave exposure on the sublittoral distribution of blue mussels *Mytilus edulis* in a heterogeneous archipelago. Mar. Ecol. Prog. Ser. 306: 191–200.

Young, M.R., Hastie, L.C., and al-Mousawi, B. 2001. What represents an “ideal” population profile for *Margaritifera margaritifera*? *In* Die Flussperlmuschel in Europa: Bestandssituation und Schutzmassnahmen. Wasserwirtschaftsamt Hof & Albert-Ludwigs Universität Freiburg. 35–44 p.

APPENDIX 1. IMAGES OF *G. ANGULATA* HABITAT

Figure 2. G. angulata in lacustrine habitat with a substrate mixture of sand, silt, and mud. This site also has a bench slope and site exposure of 12 km (Summerland, Okanagan Lake) (Photo: Roxanne Snook).

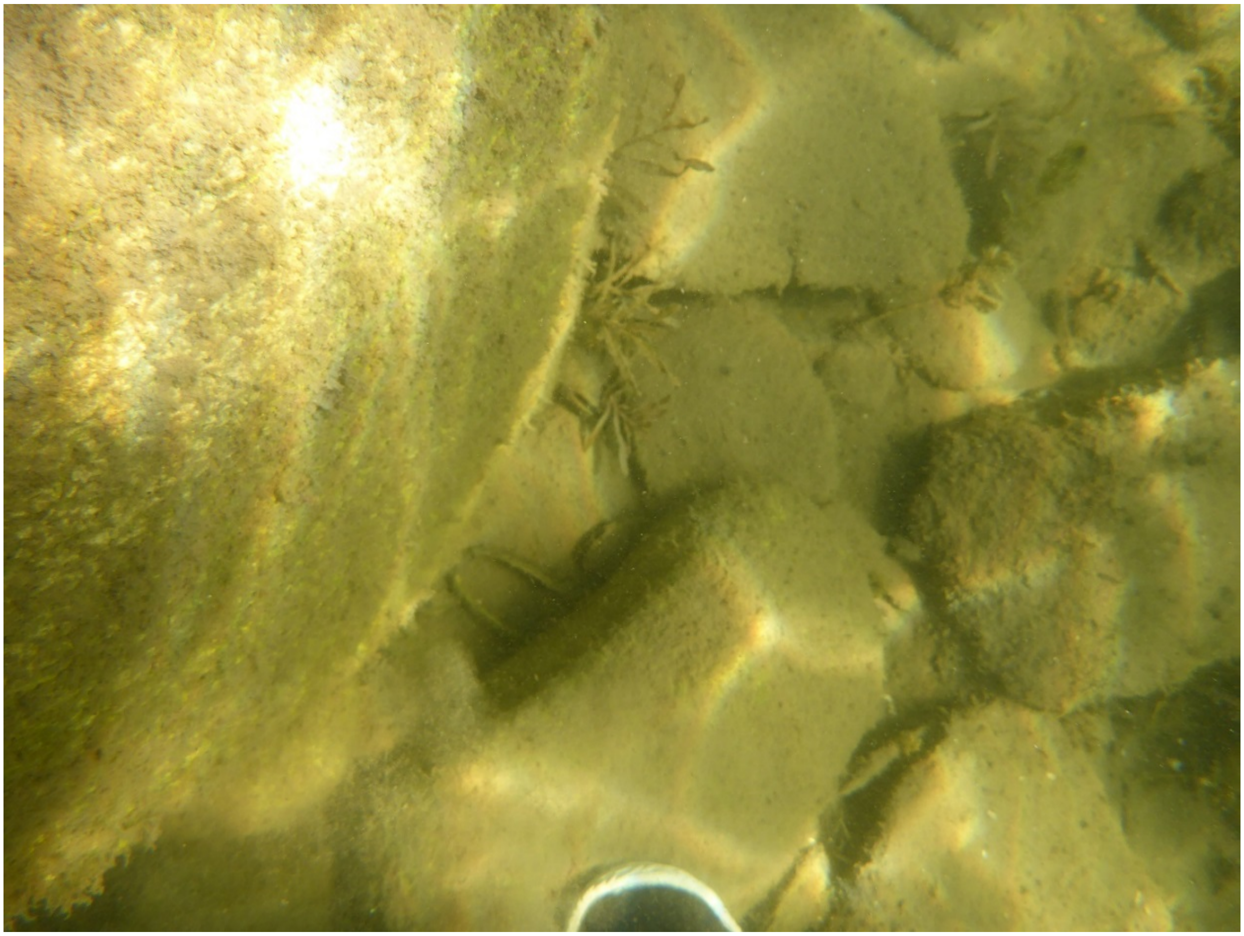

Figure 3. G. angulata are wedged between boulders and coarse cobble in sand and fine sediment deposits, Dog Beach, Summerland, Okanagan Lake (Photo: Roxanne Snook).

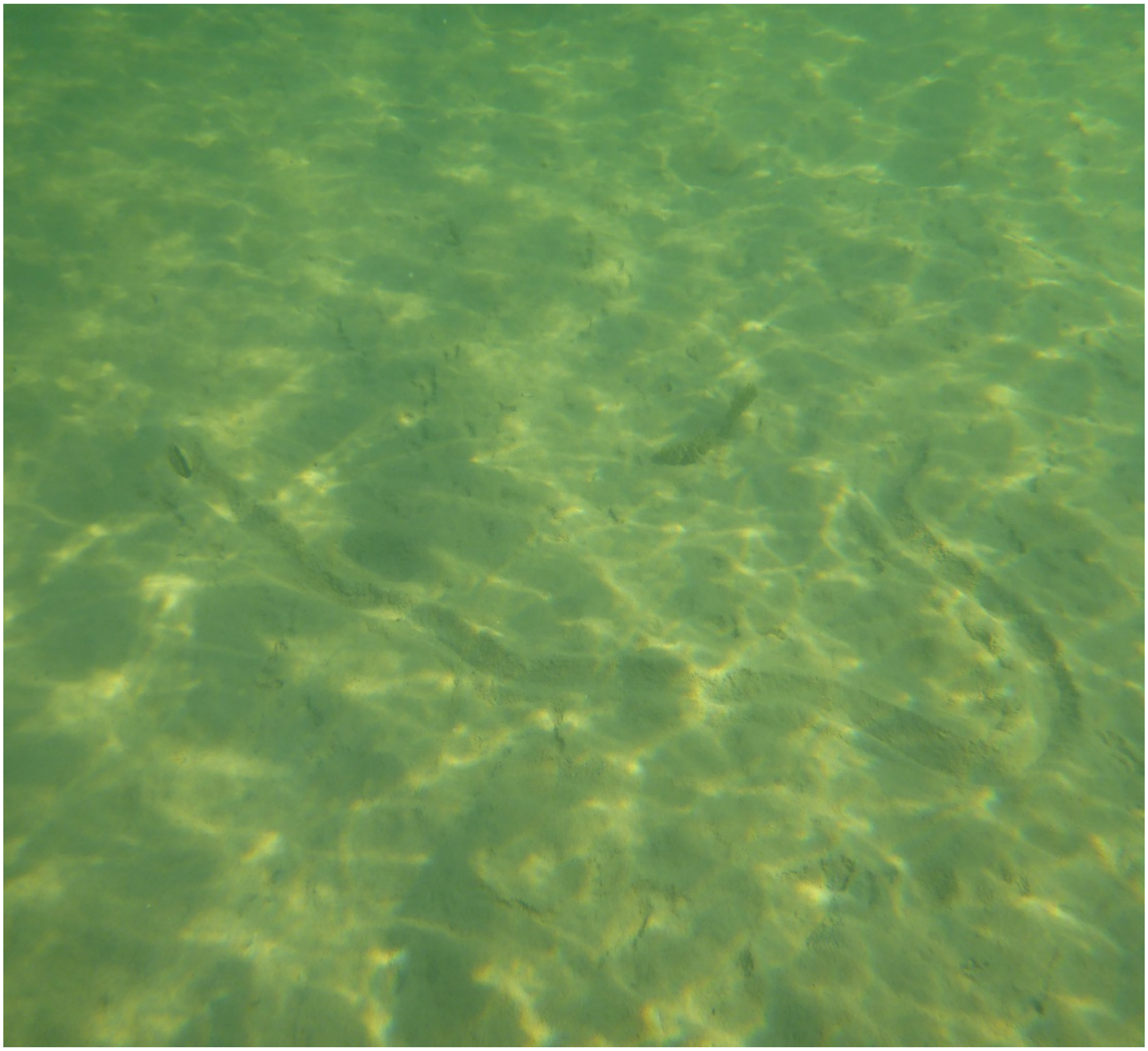

Figure 4. G. angulata trail in a site with high (100%) substrate embeddedness, with high sand content and silt and organics. This site also has a site exposure of 13 km and a bench slope (Photo: Steven Brownlee).

Figure 5. In waters with more turbulence and shear stress (e.g., below weir structures), G. angulata are found wedged below boulders and coarse (large) cobbles (Photo: Roxanne Snook).

APPENDIX 2. CRITICAL HABITAT MAPS IN OKANAGAN VALLEY

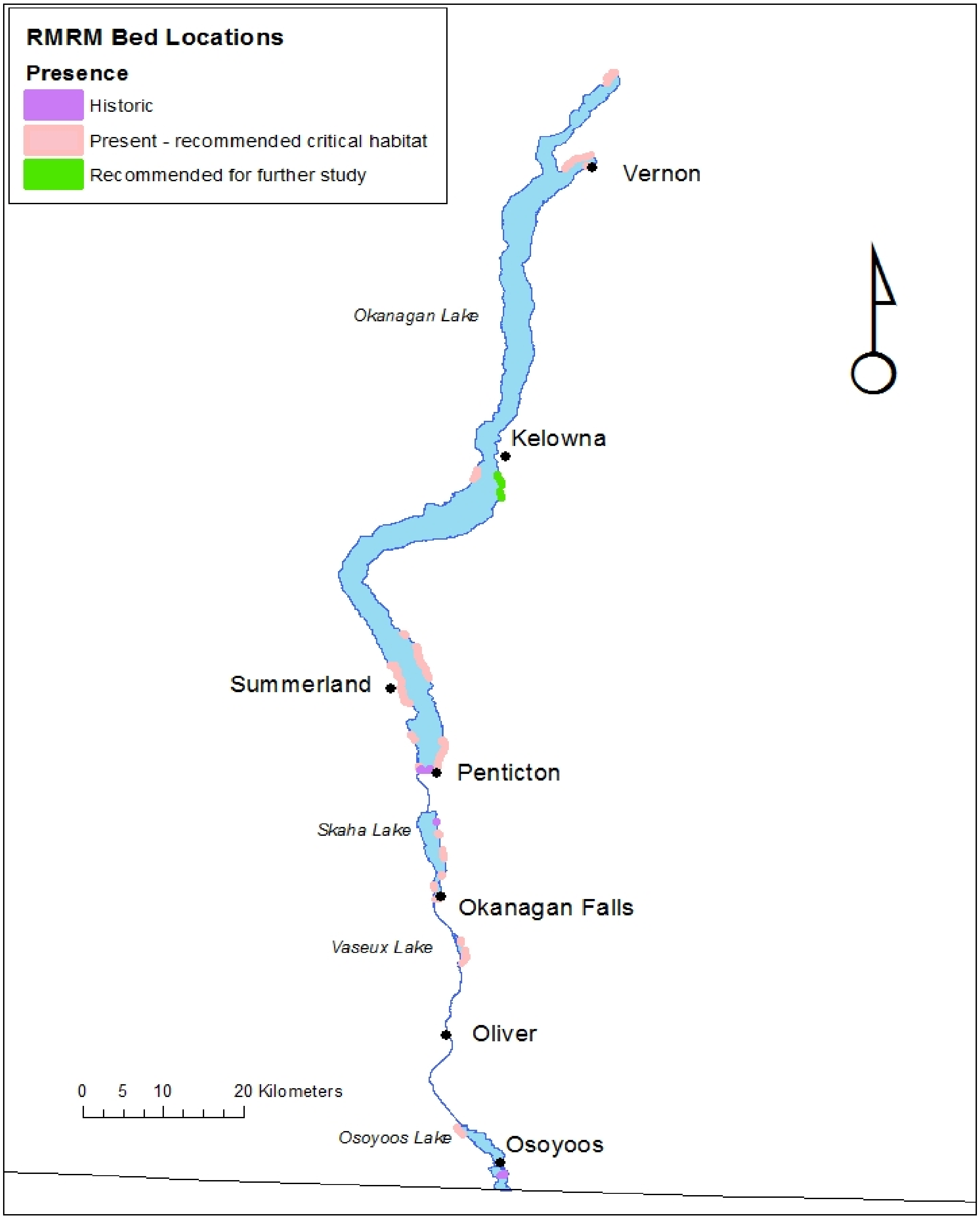

Figure 6. G. angulata bed location within Okanagan Valley lakes. Coloured polygons represent historic (purple) present (pink since 2005) and recommended for further surveys. Pink segments are recommended as critical habitat.

A mapping exercise was conducted by Snook (2015) from a Random Forest model in Okanagan Lake. The effective fetch was calculated by hand, and variables included were only top predictors from the model output. Therefore, many additional sites may be present in Okanagan Lake. Sites in Table 7 are therefore additional potential sites recommended for surveying for *G. angulata*, and potentially provide suitable habitat for this species.

Table 7. Recommended sites for future surveying as potential suitable habitat (and not as critical habitat) for G. angulata, based on Snook (2015).

FIM segment	**Length (m) between landmarks**	**Starting Northing**	**Starting Easting**	**Ending Northing**	**Ending Easting**
Okanagan Lake* 92	919.4	5523932	320809	5523094	321088
Okanagan Lake* 96	277.6	5524955	321168	5524722	321195
Okanagan Lake* 97	455.7	5525359	320975	5524958	321166
Okanagan Lake* 98	273.3	5525574	320826	5525356	320975
Okanagan Lake* 99	235.6	5525773	320701	5525575	320825
Okanagan Lake* 100	483.7	5526095	320576	5525772	320701

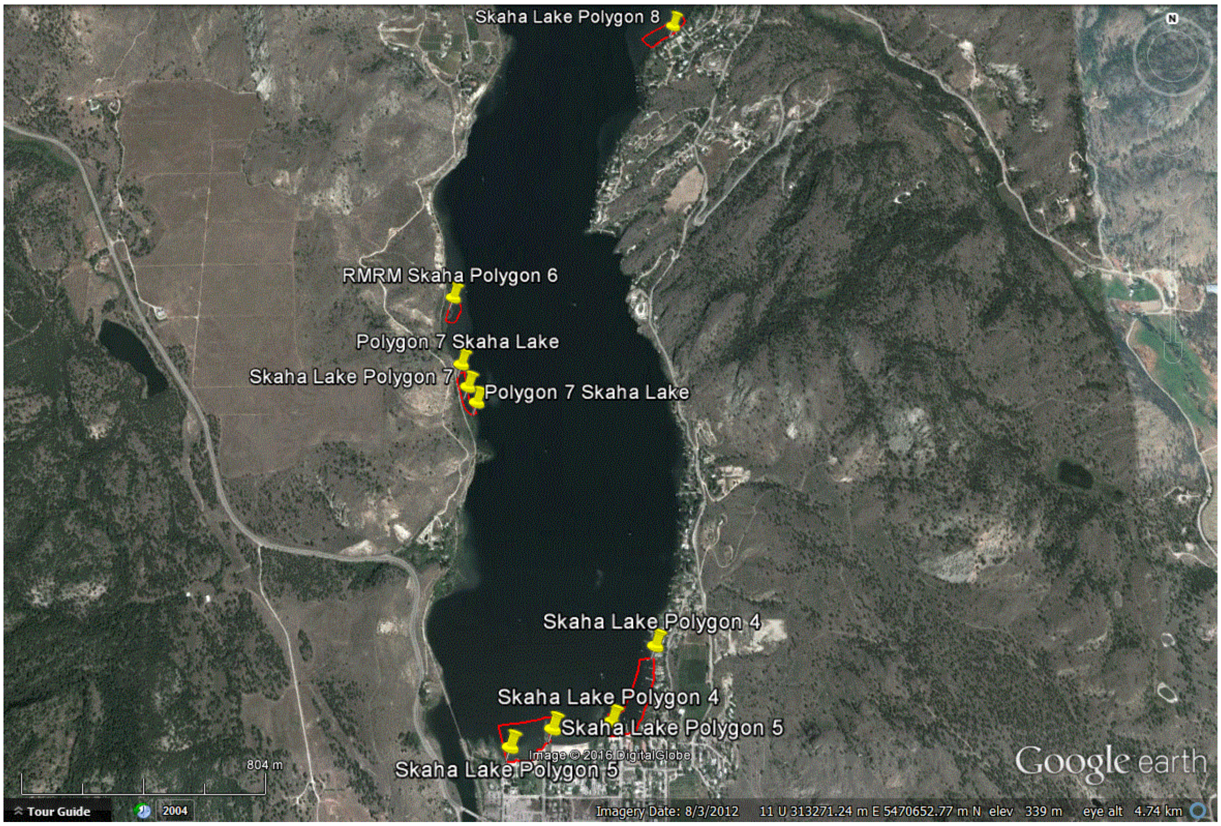

Figure 7. Okanagan Falls, Skaha Lake south polygons 4, 5, 6, 7, and 8.Sites which have confirmed occurrences of G. angulata between 2005–2015 are recommended as critical habitat polygons (Table 3).

Figure 8. Osoyoos Lake current and historic locations of G. angulata. *Historic records around Haynes point (polygon 3) are from 2010 (Ecocat accessed December 15, 2015). Sites which have confirmed occurrences of G. angulata between 2005–2015 are recommended as critical habitat polygons (Table 3).*

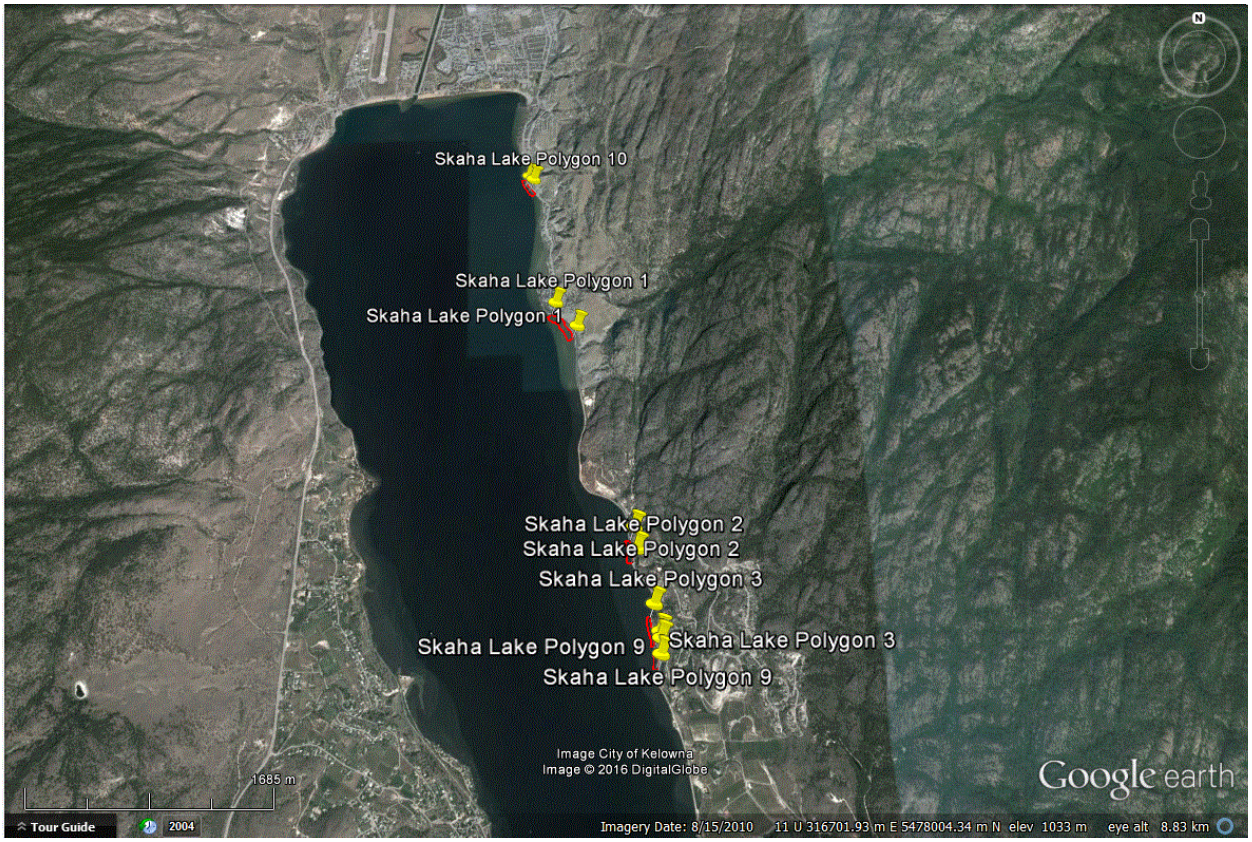

Figure 9. Skaha Lake North polygons, 1, 2, 3, 9, and 10. Sites which have confirmed occurrences of G. angulata between 2005–2015 are recommended as critical habitat polygons (Table 3).

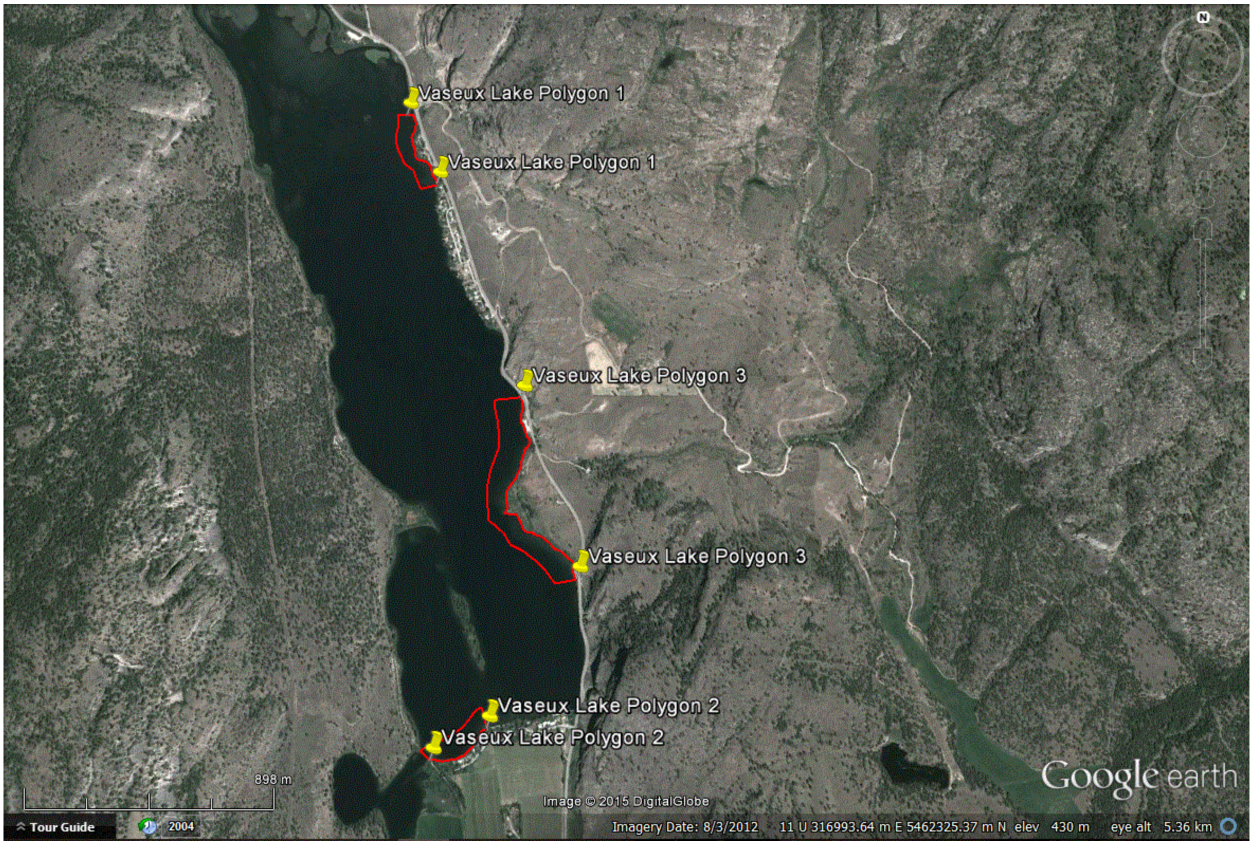

Figure 10. Vaseux Lake three polygons of G. angulata critical habitat. Sites which have confirmed occurrences of G. angulata between 2005–2015 are recommended as critical habitat polygons (Table 3).

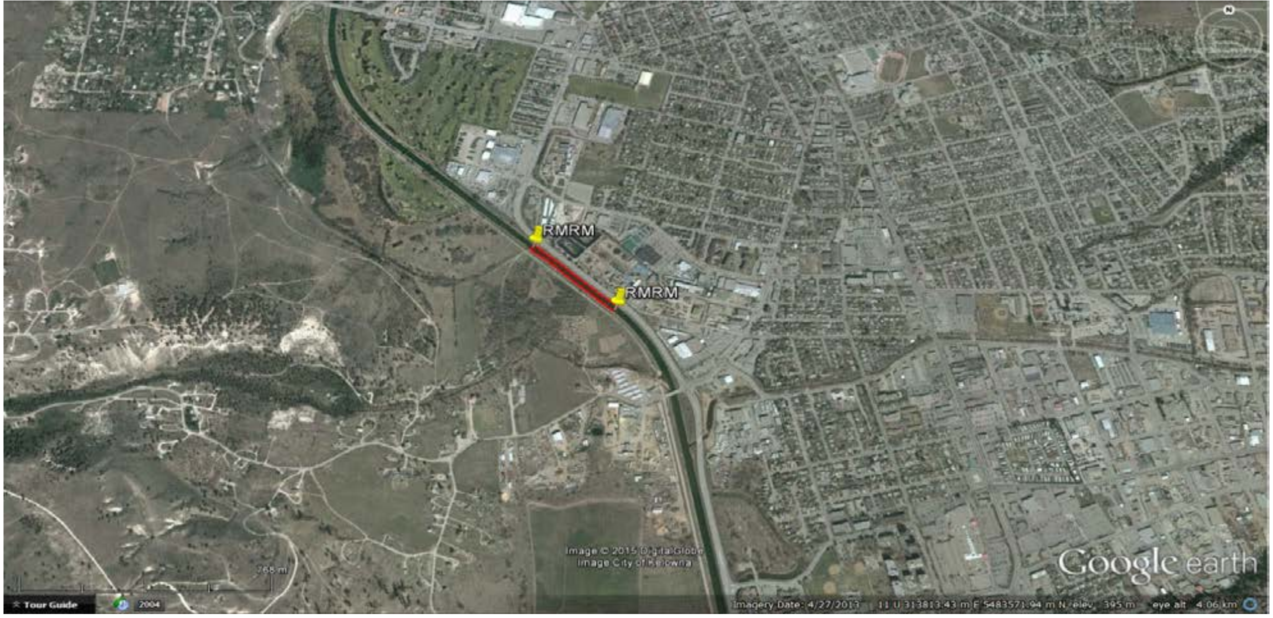

Figure 11. Penticton Channel critical habitat, with two G. angulata specimens observed in 2015 (Dr. Jon Mageroy[2], unpub. data). This polygon is recommended as critical habitat.

Figure 12. Directly below Vaseux Lake is a channelized section (northern polygon) and natural section of Okanagan River (i.e., not channelized), from a development to a highway bridge (1.72 km long southern polygon). Gallager Lake is to the east. These polygons are recommended as critical habitat.

Figure 13. Okanagan River spawning channel to first restored oxbow.This is a channelized section of the river (Dr. Jon Mageroy[2], unpub. data 2015). This polygon is recommended as critical habitat.

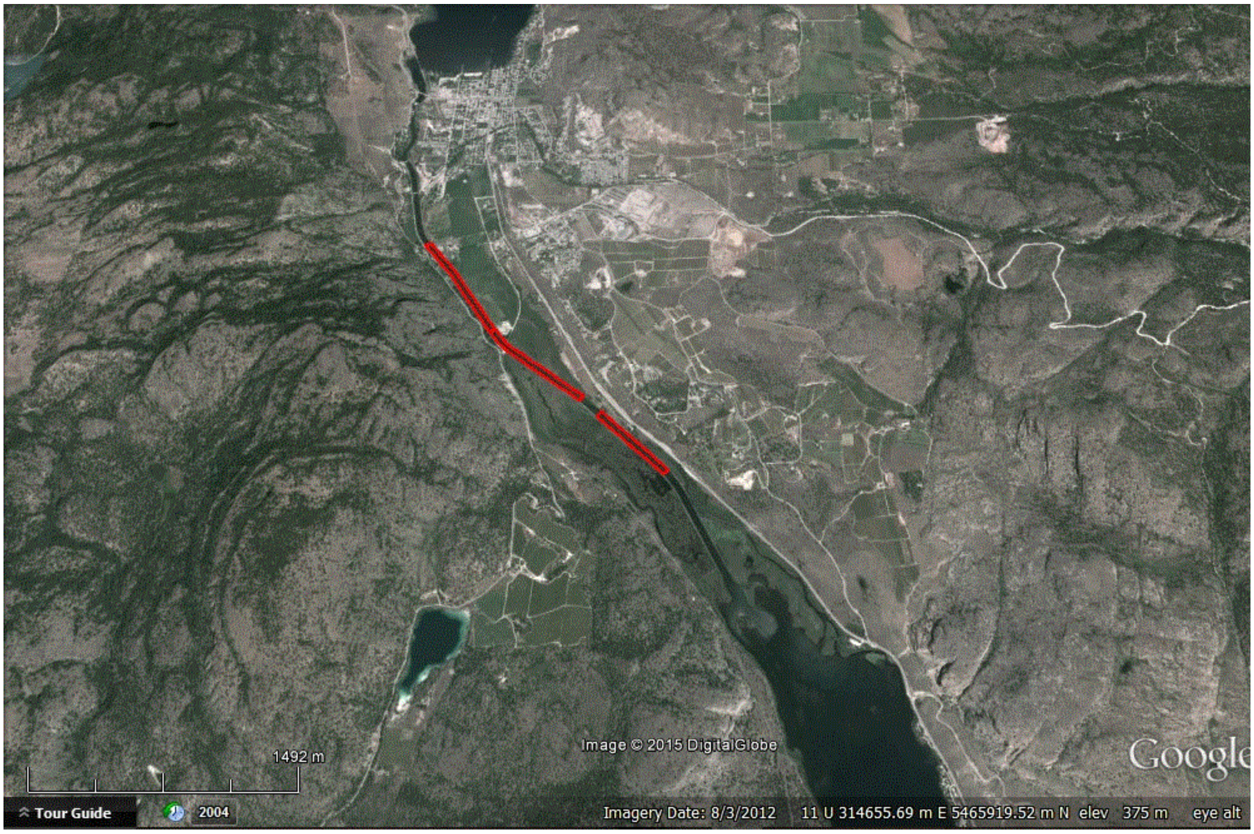

Figure 14. Critical habitat below Skaha Lake and above Vaseux Lake. These polygons are recommended as critical habitat.

Figure 15. Okanagan River, Oliver Township to Osoyoos Lake. These polygons are recommended as critical habitat.

APPENDIX 3. STATISTICAL CLASSIFICATION CODES IMPLEMENTED IN R

CODE FOR PARTY PACKAGE:

```
library (party)
FIM<-read.csv("Datacollection_RS2014d.csv", header=TRUE, stringsAsFactors=T)
set.seed(1000)
FIM <- na.omit(FIM)
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)"))

mycontrols <- cforest_control(ntree=1000,mtry=3, minsplit=5)
rf.model <- cforest(RMRM_live ~ Total_Fetch+ Sand_ord+ Boulder_ord+ Embeddedne+ Slope, data=FIM, controls=mycontrols)
varimp(rf.model, conditional = TRUE)
```

CODE FOR RANDOM FOREST PACKAGE:

```
library(randomForest)
file.choose()
FIM<-read.csv("Datacollection_RS2014.csv", header=TRUE, stringsAsFactors=T)
FIM <- na.omit(FIM)
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)"))
```

```
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)

FIM_rf


###		Partial dependence plots:

partialPlot(FIM_rf, FIM, Total_Fetch, "yes", xlab="Total Fetch", ylab="Probability of RMRM Presence")

partialPlot(FIM_rf, FIM, Slope, "yes", xlab="Slope", ylab="Probability of RMRM Presence")

partialPlot(FIM_rf, FIM, Boulder_ord, "yes", xlab="Boulders", ylab="Probability of RMRM Presence")

partialPlot(FIM_rf, FIM, Sand_ord, "yes", xlab="Sand", ylab="Probability of RMRM Presence")
```

For all data on sensitivity analysis, contact the author.

APPENDIX 4. PARTIAL DEPENDENCE PLOTS FOR RANDOM FORESTS

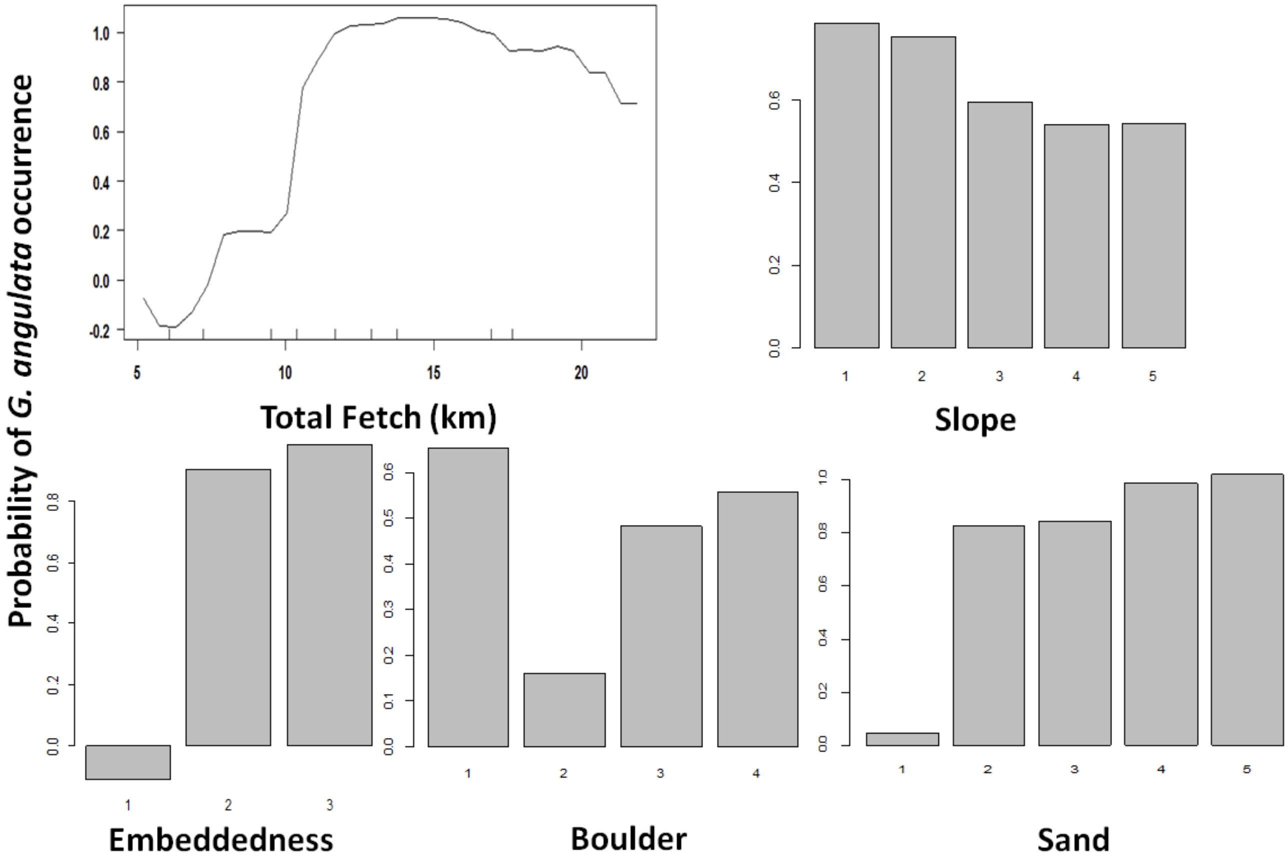

Figure 16. Partial dependence plots of each variable. Plots indicate probability of G. angulata occurrence based on each predictor variable in the best models after averaging out the effects of all other predictor variables in the model. Embeddedness is an ordinal variable including low (0–25%), medium (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+).