GUADALUPE RIVER HABITAT CONSERVATION PLAN

TECHNICAL MEMORANDUM: METHODS/MODELS FOR DETERMINING SPECIES/HABITAT IMPACTS – IMPACT ASSESSMENT FOR COVERED MUSSELS SPECIES

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1.0 Species

False Spike (*Fusconaia mitchelli*)

Guadalupe Fatmucket (*Lampsilis bergmanni*)

Guadalupe Orb (*Cyclonaias necki*)

2.0 Impact Mechanisms

Riverine-adapted freshwater mussels have a complex life history which requires consideration of multiple impact mechanisms. Freshwater mussels have a parasitic larval stage (i.e., glochidia) that must access appropriate host fishes to complete their life cycle (Barnhart et al. 2008). Once transformed into juvenile mussels, they fall off host fish and live in the benthos, feeding on both benthic and suspended food resources (Haag 2012). Due to this complex life history and the dynamic nature of river systems, a variety of mechanisms can influence mussel populations, including the following:

- presence of appropriate host fishes,
- food resources,
- flow conditions, and
- water quality conditions.

A discussion of each potential impact mechanisms is provided below.

2.1 Host Fish

Several host fishes are commonly collected within the lower Guadalupe River and have exhibited stable population trends (Bonner and Perkin 2009)[1]. Given that most of the identified host fishes for the covered mussel species are common to abundant and have stable or increasing population trends, it is unlikely that availability of appropriate host fishes is a limiting factor to populations of the covered mussel species.

2.2 Food Resources

Regarding food resources, adult mussels are generally described as suspension feeders, whereas juveniles regularly ingest benthic organic matter through pedal feeding (Yeager et al. 1994, Haag 2012). However, recent studies on the covered mussels have documented the importance of benthic-derived organic matter to adults as well (Fogelman et al. 2022). In general, feeding ecology of mussels is understudied, and more research is needed to understand environmental influences on

[1] For Guadalupe Orb, Channel Catfish (*Ictalurus punctatus*) and Flathead Catfish (*Pylodictis olivaris*) are commonly collected within the lower Guadalupe River (>2% numerically of all fish collected in aggregate). For False Spike, the likely primary host fishes (Red Shiner [*Cyprinella lutrensis*] and Blacktail Shiner [*Cyprinella venusta*)] are abundant in the Guadalupe River (Dudding et al. 2019, Bonner and Perkin 2009). Although no studies have specifically tested the host fishes of Guadalupe Fatmucket, laboratory trials on congeners suggest that members of the sunfish family are likely primary hosts (Johnson et al. 2012, FMHD 2017, Seagroves 2019). Although not numerically abundant in fisheries surveys, all these species are commonly collected where Guadalupe Fatmucket occur.

food resources. As a result, there is no clear impact mechanism between GRHCP Covered Activities and food resources of the covered mussel species.

2.3 Flow

Flow is considered a master variable within riverine systems due to its influence on other ecologically important variables (e.g., channel morphology, substrate, instream habitat, and water quality) (Poff et al. 1997). Although covered mussels are adapted to a dynamic flow regime, specific flow events can be important structuring mechanisms to mussel populations. Extreme high flows, although ecologically important, can often lead to displacement of mussels and scouring of their habitats (Sotola et al. 2021). However, high flows (i.e., floods) capable of scouring mussel habitats typically result from extreme precipitation events and are not expected to be discernably influenced by Covered Activities.

In contrast, extreme low flows can result in (1) degraded water quality conditions (e.g., high temperatures, low dissolved oxygen) or (2) desiccation of mussel habitats (Randklev et al. 2018) and may be influenced by water diversions. Laboratory studies show that duration thresholds for desiccation tolerance vary among species (Bonner et al. 2018), and some mussel species have developed physiological and behavioral adaptations to deal with stream drying (Gough et al. 2012). However, in the wild, desiccation of mussels results in increased predation risk from terrestrial predators that can result in take. Although low and high flow extremes may have the most direct impact to mussel populations, alteration of base flows can influence available habitat within the typical range of variability for flow conditions. The importance of flow conditions in structuring mussel habitat and the potential influence of Covered Activities on instream flow conditions make streamflow a key impact mechanism for further evaluation.

2.4 Water Quality

Even if flow conditions provide for appropriate habitat, water-quality conditions must be adequate for mussels to complete their life cycle. Covered Activities (e.g., water discharges, water diversions) can influence water quality that may affect mussels. Several water quality parameters have the potential to influence covered mussels (Haag 2012, Augspurger et al. 2003, Mummert et al. 2009, Haney et al. 2019). The most likely of these to be influenced by Covered Activities include water temperature, dissolved oxygen, and ammonia concentrations.

Regarding water temperature and dissolved oxygen, mussel responses to hypoxia (low oxygen) and water temperature are species specific, with responses varying considerably between species and even within a species taken from different drainages (Haney et al. 2019). Multiple studies have also recently examined both sublethal and lethal effects of temperature and hypoxia on the covered mussel species from the Guadalupe drainage[2].

Regarding ammonia, species-specific responses to ammonia concentrations are evident as well (Mummert et al. 2009). Detailed studies of ammonia tolerance for the covered mussels from the Guadalupe basin are being conducted as part of ongoing toxicity testing efforts, including those by GBRA, USFWS, and Texas State University researchers at the San Marcos Aquatic Resource Center

[2] Haney et al. (2019) analyzed the influence of temperature on energy demand and hypoxia tolerance of three central Texas mussel species, including Guadalupe Orb. Khan et al. (2020) evaluated lethal upper thermal tolerances of adult Guadalupe Orb and False Spike from the lower Guadalupe River. Khan et al. (2019) evaluated the lethal upper thermal limits of glochidia for all three of the covered mussel species, among other taxa.

(SMARC), and preliminary data from these studies are available to estimate ammonia thresholds. Results from these studies provide local data to estimate water quality thresholds for take of each of the covered mussel species.

The importance of water-quality thresholds to the persistence of covered mussels and the potential for water discharges and/or diversions to affect water quality necessitates consideration of the key parameters of water temperature, dissolved oxygen, and ammonia.

3.0 Methods for Assessing Take

The focal impact pathways for quantifying mussel take were discussed above. Below, we discuss units and methods for estimating take. The *Habitat Conservation Planning and Incidental Take Permit Processing Handbook* (HCP Handbook, USFWS 2016), states that "quantifying the amount of take provides a key basis for evaluating project impacts." Take can be quantified as numbers of affected individuals. However, other metrics, such as acres of habitat, percent change in habitat quality, or miles of habitat affected, can be used as a surrogate for numbers of individuals. These surrogates are commonly used in HCPs to quantify take.

3.1 Units for Estimating Take

Due to their cryptic nature, estimating occurrence and abundance of freshwater mussels involves time-consuming directed survey efforts. In recent years, several freshwater mussel surveys have occurred within the Plan Area, providing a more complete picture of the current distribution of the covered mussels at a reach-scale (Burlakova and Karatayev 2012, Burlakova et al. 2018, Tsakiris and Randklev 2016, Bonner et al. 2018). These surveys are summarized in the USFWS proposed rule which identifies the occupied reaches for each of the covered mussel species in the Guadalupe River basin (USFWS 2021). In addition, GBRA and USFWS survey efforts in summer 2022 expanded the known distribution of Guadalupe Orb and False Spike within the Guadalupe River basin (BIO-WEST 2022; Matthew Johnson, USFWS, personal communication). Although mussel distributions may change through time and future surveys will continue to enhance our understanding of covered mussel distributions, the information referenced above provides a good baseline for establishing the current distribution of the covered mussels within the Guadalupe River basin.

Given the targeted surveys required, the clumped nature of mussel distributions, and the complex morphology of riverine channels, evaluating mussel abundance and spatial distribution at an individual or local scale is not feasible over the entire Plan Area. However, the surveys summarized in the USFWS proposed rule and described above allow for estimation of occurrence at a reach scale. Since quantification of individual or local scale take is not feasible over the entire Plan Area, the proposed unit for evaluating take for freshwater mussels related to both flow and water quality is occupied habitat, measured in stream miles. This assumes a direct positive relationship between occupied stream miles and mussel population size. This is consistent with USFWS methodologies for quantifying impacts to freshwater mussels in the Species Status Assessment (SSA) for the central Texas mussels (USFWS 2018) and the Proposed Rule to list central Texas mussels (USFWS 2021). It is also consistent with other recent Section 10 permits quantifying take of freshwater mussels such as the Brazos River Authority Candidate Conservation Agreement with Assurances. It is recognized that covered mussel abundance and density varies across the Guadalupe River basin, generally being higher in the lower basin than the upper basin. While our approach simplifies these nuances, it presents a consistent metric for evaluating impacts and assessing the influence of conservation activities given the spatial resolution of the available data.

3.2 Methodology for Estimating Take

Stream flow and water quality, given these two impact mechanisms are the most clearly understood and quantifiable in consideration of best available data, are proposed as the means of quantifying incidental take of mussel species resulting from Covered Activities. A discussion of the methodology for estimating take for each key mechanism is described below.

3.2.1 Stream Flow

As discussed in Section 2.1, Covered Activities may cause base flow alterations or increase the frequency or duration of low flow conditions that reduce habitat quality for mussels, including desiccation of habitats.

Currently, models documenting the relationship between mussel habitat (specifically) and flow along the Guadalupe River are not available. However, recent environmental flow studies within the Guadalupe River basin have been conducted to examine conditions necessary to maintain a sound ecological environment, with a focus on fish habitat (GSA BBEST 2011, BIO-WEST 2017). These studies modeled changes in availability of fish habitat guilds under various flow scenarios to generate environmental flow recommendations.

One of the underlying assumptions of these flow-specific habitat models is that fishes can move between habitat patches to locate appropriate hydraulic habitat conditions (depth, velocity, substrate) as flow conditions change. Most mussel species are relatively sessile and exhibit minimal movement compared to fish (Schwalb and Pusch 2007, Gough et al. 2012, Newton et al. 2015). As a result, mussel habitats must be hydraulically appropriate across the entire range of flow conditions experienced.

Some have suggested that modeling based on habitat utilization data using simple hydraulic variables such as depth and velocity is of little use in determining appropriate flows for mussels and that complex hydraulic parameters such as shear stress modeled over a range of flow conditions to identify "persistent habitat" are better predictors of mussel abundance (Layzer and Madison 1995, Maloney et al. 2012). However, some of the same authors recognized that mussels did show a preference for particular hydraulic conditions and that depth and velocity were important factors limiting their distribution under base flow conditions (Layzer and Madison 1995). Recent studies have integrated shear stress across a range of flow conditions to identify persistent habitat patches with traditional habitat suitability criteria based on simple hydraulic parameters (i.e., depth, velocity, Froude number, Reynolds number) to successfully model mussel habitat (Littrell et al. 2018). While this approach accounts for the requirement of persistent habitat across a broad range of flow conditions, as well as patterns in mussel habitat utilization under base flow conditions, the complex morphology of rivers necessitates detailed hydraulic models to evaluate shear stress. On a reach scale, creation of such models for miles of riverine habitat is not feasible.

In addition, the influence of shear stress on mussel habitats is most prominent under high flow conditions. As discussed above, most high flow or flood events are not expected to be impacted by Covered Activities nor are they likely to drive take of the species. Base flows and subsistence flows are more likely to be influenced and will be the focus of impact analyses. Therefore, persistent habitat patches will be assumed constant, and changes in depth and velocity will assess availability of mussel habitat under two scenarios: a reference scenario which assesses the regulatory baseline for covered mussels and a covered activities scenario, which assesses future conditions from the implementation of all activities covered by the HCP.

Although some studies have established habitat suitability criteria for mussels in other Texas rivers (Randklev et al. 2014, Littrell et al. 2018), no habitat suitability criteria for the covered mussels are available in the Guadalupe River. However, based on known habitat associations, the covered mussels can be associated with existing fish habitat guilds for which currently available discharge to habitat curves exist (see example in Figure 1) at multiple Guadalupe basin instream flow control points (GSA BBEST 2011, BIO-WEST 2017). Figure 1 demonstrates the percent of maximum habitat available for several habitat guilds at the Guadalupe River at Cuero under various discharge levels. The underlying assumption in utilizing this data is that habitat to discharge relationships quantified at the control point represent those throughout the nearby reach of river, and that they stay consistent through time.

Similar discharge to habitat relationships for each guild are available at nine instream flow control points within the Guadalupe River basin (GSA BBEST 2011, BIO-WEST 2017). However, not all of the reaches represented by the control points are occupied by the covered mussels. Analysis will focus on instream flow control points where the covered mussel species are known to occur, and will be expanded to one additional control point (Guadalupe River at Lake Wood) to assess the middle Guadalupe River between Canyon Dam and the San Marcos River confluence:

1. Guadalupe River at Comfort, TX (USGS Gage #08167000)
2. Guadalupe River near Spring Branch, TX (USGS Gage #081675000)
3. Guadalupe River at Lake Wood[3]
4. Blanco River at Wimberley, TX (USGS Gage #08171000)
5. San Marcos River at Luling, TX (USGS Gage #08172000)
6. Guadalupe River at Gonzales, TX (USGS Gage #08173900)
7. Guadalupe River at Cuero, TX (USGS Gage #08175800)
8. Guadalupe River at Victoria, TX (USGS Gage #08176500)

[3] New control point added given that Covered Species were recently documented in this stretch. Flows in this stretch will be different from Spring Branch because Canyon Reservoir is in between. Flows in this stretch will be different from Gonzales because the San Marcos River confluence is in between. Existing habitat to discharge relationships do not exist, so habitat to discharge relationships from the Gonzales control point will be utilized here.

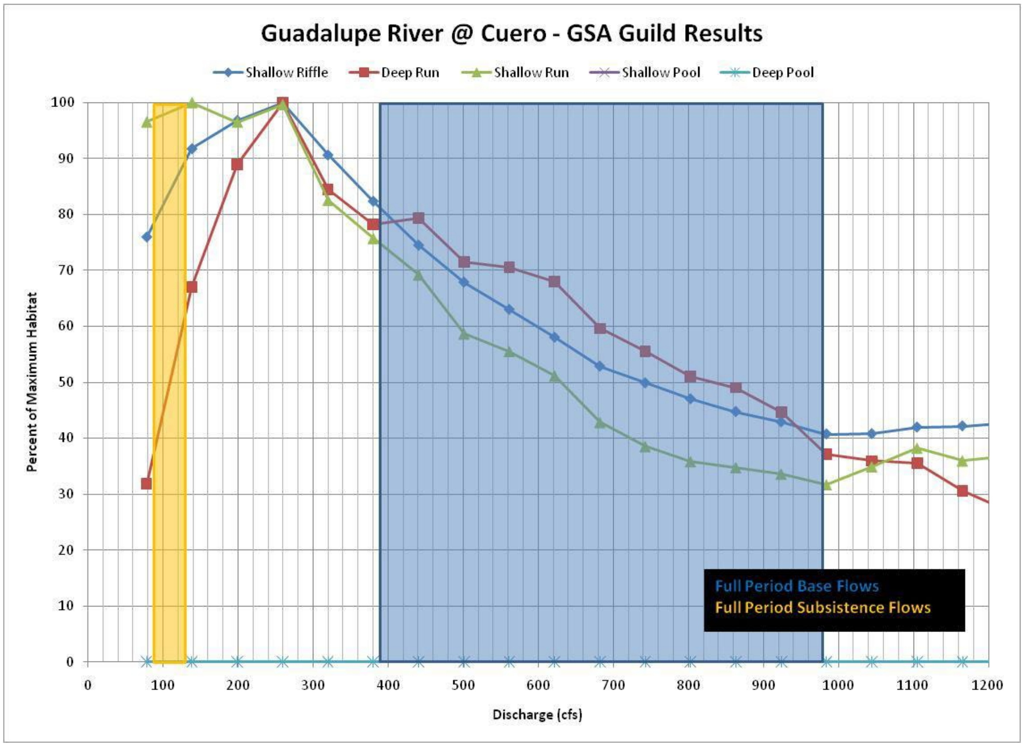


Figure 1. Example of existing discharge to habitat guild relationships for the Guadalupe River at Cuero.

At each of these control points, Water Availability Model (WAM) outputs will be combined with existing habitat to discharge relationships to evaluate available mussel habitat under reference conditions. To quantify impacts, this analysis will also be conducted for future scenarios including Covered Activities. The difference in available habitat between the reference condition and the covered activities scenario will be utilized to quantify impacts from stream flow alteration due to Covered Activities (Figure 2). This analysis will be conducted at each control point for each covered mussel species known to occur there.

The stepwise process for assessing flow impacts is as follows:

1) Determine occupied stream miles associated with each specified instream flow control point.
2) Generate WAM hydrology for both reference and Covered Activity scenarios.
3) Associate each covered mussel species with existing fish habitat guilds.
4) Use habitat-to-discharge relationships available from existing studies at specified control points combined with WAM hydrology to determine available habitat for a given guild under reference and (separately) Covered Activity scenarios.
5) Calculate the percent difference between available habitat in the two scenarios to estimate changes due to Covered Activities.
6) If predicted available habitat declines under Covered Activities, take will be assigned proportionally in river miles of habitat.

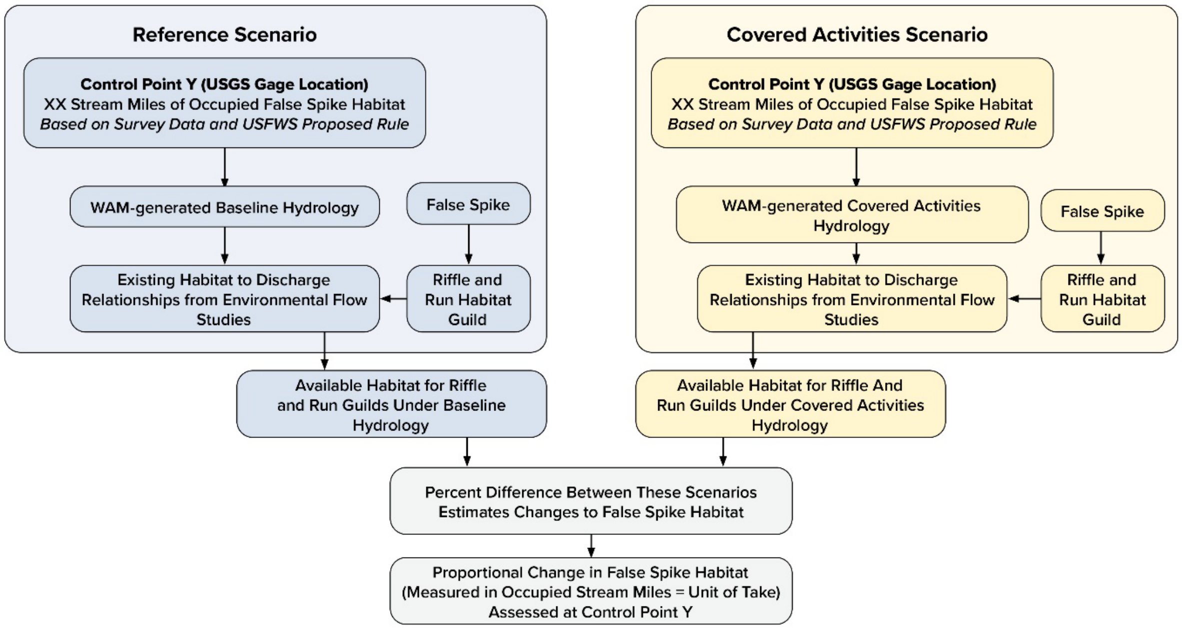


Figure 2. Flow chart illustrating mussel take methodology for flow.

Based on known distributional information from the literature and the USFWS proposed rule (USFWS 2021), a currently occupied reach length in occupied stream miles will be assigned for each of the covered mussel species at each control point where they occur, covering all known mussel distribution in the permit area. This will serve as the reference available habitat condition. Based on habitat modeling described above, the percent change in available habitat between reference conditions and future conditions with Covered Activities will be estimated. If available habitat increases or stays the same under the Covered Activity scenarios, then no take will be estimated for that species within that reach. If available habitat decreases, a proportional percentage of take will be allotted in river miles of habitat.

The following sections summarize the current understanding of habitat utilization for each of the covered mussel species and identify appropriate guild associations.

Guadalupe Orb

Within the upper Guadalupe River, the Guadalupe Orb was observed most frequently within fluvial habitats (78% relative abundance) where water depth ranged from 0.7 to 1.3 feet (ft) and current velocity ranged from 0.3 to 0.9 feet per second (ft/s). Dominant substrates were bedrock, gravel, or a mixture of gravel, sand, and silt (Bonner et al. 2018). In the lower Guadalupe River, Species Indicator Analysis suggested that the Guadalupe Orb is strongly associated with riffles, although in the same study Canonical Correspondence Analysis suggested no strong association with specific microhabitat variables such as water depth or current velocity (Tsakiris and Randklev 2016). The Guadalupe Orb was also previously observed in riffle habitats in the San Marcos River (Burlakova and Karatayev 2012). Lastly, observations in the Blanco River were within habitats with variable velocities and mostly cobble and gravel substrates (Horne and McIntosh 1979, Sullivan 2020).

Based on available habitat information, Guadalupe Orb is assigned to the "riffle" and "shallow run" habitat guilds as defined in the GSA BBEST report (See Appendix; GSA BBEST 2011).

False Spike

The False Spike was previously observed in the lower Guadalupe River within run habitat containing gravel and sand substrates, at shallow depths (<3.3 ft) with current velocities ranging from 2.0 to 3.2 ft/s (Mabe and Kennedy 2014). Species Indicator Analysis suggested that the False Spike is strongly associated with riffles (Tsakiris and Randklev 2016). Similarly, Canonical Correspondence Analysis demonstrated that the False Spike is positively associated with microhabitats comprising higher current velocity and coarse substrates and negatively associated with embedded areas containing higher amounts of algae and fine particulate organic matter (Tsakiris and Randklev 2016).

Based on this, the False Spike is assigned to the "riffle" and "shallow run" habitat guilds as defined in the GSA BBEST report (See Appendix; GSA BBEST 2011).

Guadalupe Fatmucket

Previous mussel surveys in the upper Guadalupe River observed the Guadalupe Fatmucket in riffle (n = 1 site), run (n = 4 sites), and pool (n = 1 site) mesohabitats. At occupied sites, dominant substrates (median percent composition) included 30% bedrock, 30% gravel, and 15% cobble. Water depths ranged from 0.5 to 2.8 ft and mean-column velocity ranged from 0.3 to 1.8 ft/s (BIO-WEST unpublished data). The Guadalupe Fatmucket in the Blanco River was previously observed in habitats containing mostly gravel with current velocities ranging from 1.6 to 3.3 ft/s (Horne and McIntosh 1979). The Guadalupe Fatmucket has been previously observed within reservoirs in Kerrville, suggesting they can occupy lentic habitats (Randklev et al. 2020). This aligns with similar observations of the congener Texas Fatmucket (*Lampsilis bracteata*) in small reservoirs of the Llano River basin (Sullivan and Littrell 2020). Occurrence within swift flowing fluvial habitats as well as small reservoirs suggests Guadalupe Fatmucket to be a habitat generalist.

Therefore, Guadalupe Fatmucket will be assigned to all available GSA BBEST habitat guilds (Deep Pool, Shallow Pool, Deep Run, Shallow Run, Riffle) and aggregate trends will be examined.

3.2.2 Water Quality

The method for assessing impacts to mussel habitat from altered flow conditions is described above. However, an additional method is needed to quantify potential water quality impacts. Therefore, exceedances of water temperature, dissolved oxygen, and ammonia thresholds which potentially impact resident mussels will also be quantified to estimate take. These three thresholds will be established for each species, or group of species, based on the existing data from literature and ongoing toxicity studies reviewed in Section 2.0.

Modeling will then be conducted to evaluate exceedance of water quality thresholds under pertinent scenarios. Given the resolution of the available data and existing models, temperature will be assessed by evaluating flow and water temperature relationships at each instream flow control point, whereas dissolved oxygen and ammonia will be assessed at specific discharge points using existing QUAL-TX models. Details on each methodology are provided below.

Water Temperature

Available water temperature data in the area of each instream flow control point will be used along with existing hydrology data to establish a relationship between water temperature and discharge during summer months (May – September) as presented in the Hydrologic Modeling Needs Memorandum (Figure 3). These regression relationships will then be used with WAM model output to estimate daily water temperature and evaluate the percentage of time each established threshold is exceeded at each control point under the proposed WAM modeling scenarios. If the percentage of days with exceedances increases under the Covered Activities scenario, then a proportional amount of take will be assessed in river miles at that control point (Figure 4).

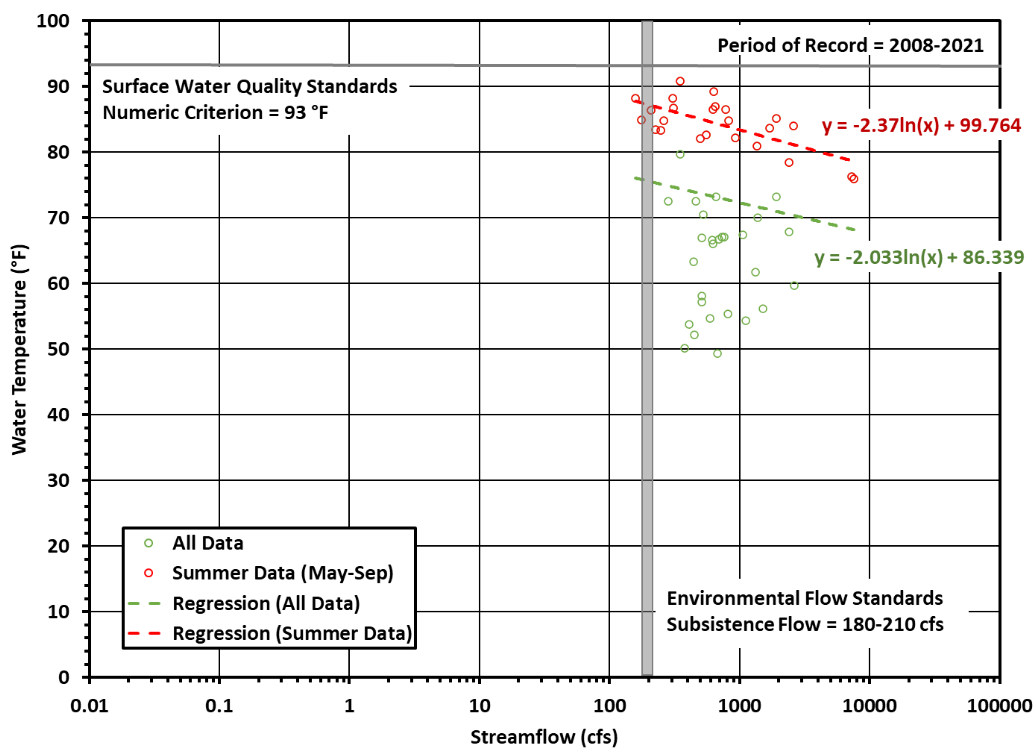


Figure 3. Water temperature to flow relationships at the Guadalupe River at Gonzales.

To summarize, the stepwise process for assessing impacts from water temperature is as follows:

1) Determine occupied stream miles associated with each specified instream flow control point.
2) Determine water temperature thresholds for each species or group of species from existing literature.
3) Generate regressions for water temperature and discharge at each control point using existing data.
4) Use regressions and WAM hydrology to estimate daily water temperature under both reference and Covered Activity scenarios.

5) Calculate the percentage difference between frequency of water temperature threshold exceedances in the two scenarios to estimate changes between reference conditions and Covered Activities scenarios.

6) If temperature exceedance increases under Covered Activities scenarios, convert this percent difference in frequency of temperature exceedance to take by allotting a proportional percent difference in river miles of habitat.

These steps are illustrated in Figure 4. Temperature data calculated from the above regressions will also be utilized as input to QUALTX models to assess dissolved oxygen and ammonia concentrations below specific discharge points, as discussed below.

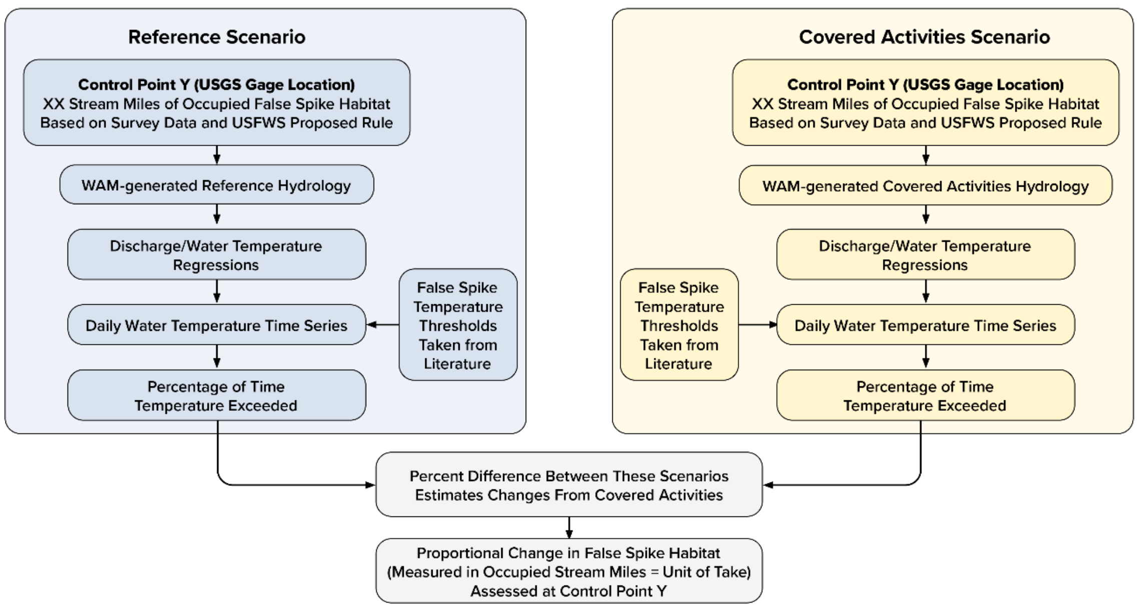


Figure 4. Flow chart illustrating mussel take methodology for temperature.

Dissolved Oxygen and Ammonia

The temperature regression analysis described above will provide temperature inputs for use in QUAL-TX modeling to evaluate ammonia and dissolved oxygen at specific discharge locations. QUAL-TX is a steady-state model that evaluates water quality under critical conditions that are characterized by 1) high summer critical temperatures, 2) critical low flow (7Q2), and 3) full permitted loads. Based on these flow and temperature inputs, along with effluent data, QUAL-TX produces spatial outputs that capture water quality over the modeled stream segment under critical conditions (Figure 5). The example in Figure 5 shows the predicted flow, dissolved oxygen (DO), 5-day carbonaceous oxygen demand (CBOD5), and ammonia as nitrogen (NH_3-N) at different river kilometers along a modeled stream reach under critical conditions.

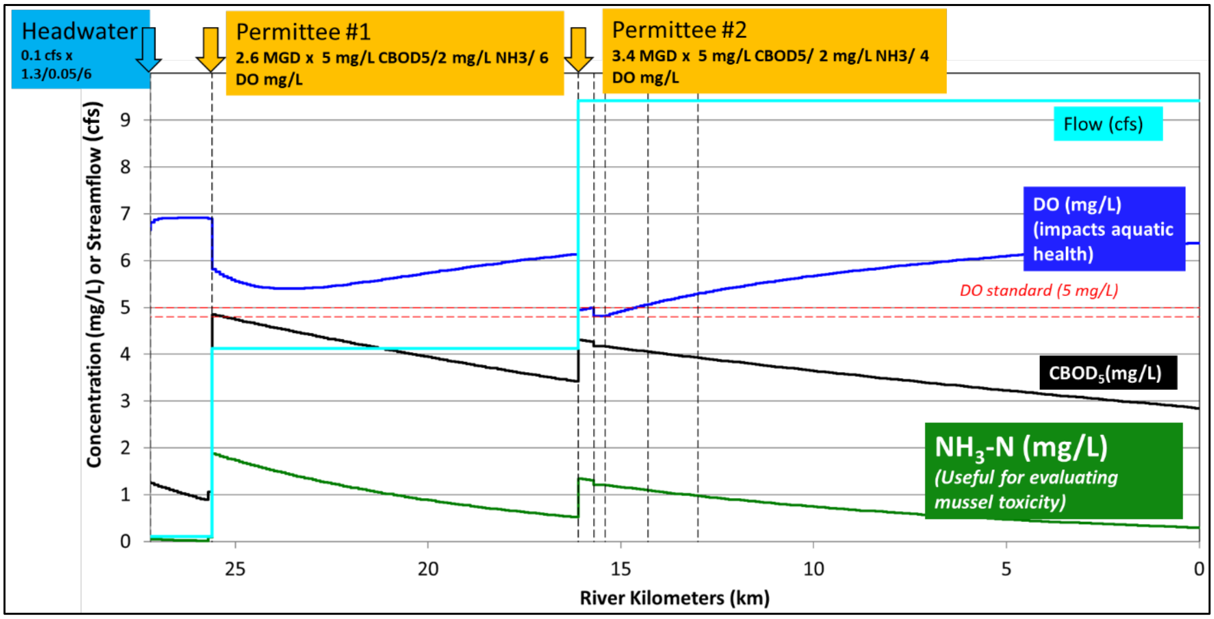


Figure 5. Example water quality outputs from QUAL-TX model.

For ammonia and dissolved oxygen, the amount of take in stream miles of habitat can be assessed from the QUAL-TX model outputs by identifying the lengths of stream reaches where the predicted dissolved oxygen or ammonia threshold is exceeded (Figure 6). The ammonia concentration output is indicated by the green line in Figure 6. If a hypothetical ammonia threshold of 1mg/L NH_3-N is assumed, the green line can be compared with the threshold to identify stream intervals with exceedances. Two intervals, 5 km and 3 km long, are identified and are shaded in grey. This results in 8 km, or approximately 5 stream miles, of affected distance, assuming that all the affected areas are within occupied mussel habitat. In similar fashion, dissolved oxygen can be compared against a given threshold to estimate take in stream miles for dissolved oxygen. If either or both criteria (dissolved oxygen and ammonia) are exceeded within an area, then that area will be presumed impacted (Figure 7).

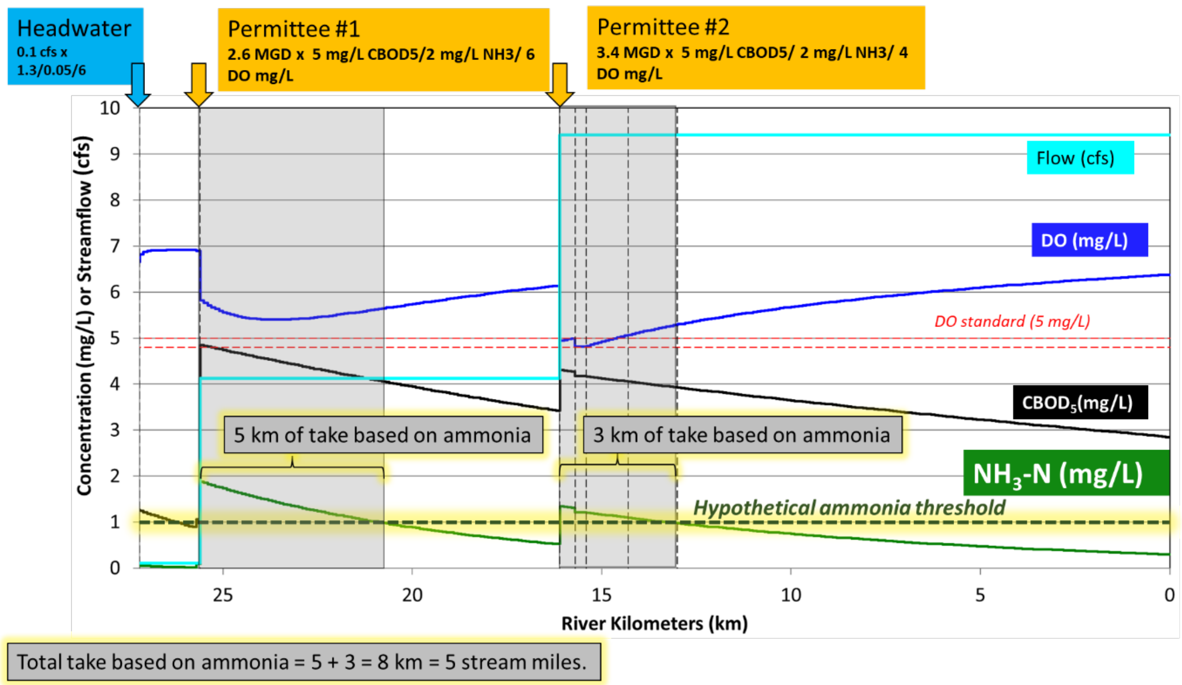


Figure 6. Illustration of using QUAL-TX results to evaluate take in stream miles.

To summarize, the stepwise process for assessing dissolved oxygen and ammonia impacts are as follows:

1. For each covered mussel species, define occupied reach length in stream miles within each QUAL-TX model extent.
2. Establish dissolved oxygen and ammonia thresholds for take of each of the covered mussel species based on the laboratory studies discussed in Section 2.0 above.
3. Conduct QUAL-TX modeling to estimate the location and linear extent of stream that exceeds dissolved oxygen or ammonia thresholds under reference and Covered Activities scenarios.
4. Assess the difference between the two scenarios to evaluate impacts from Covered Activities.
5. If length of impacted habitat increases under Covered Activities, a proportional amount of take (measured in stream miles) will be allotted for each covered mussel species due to dissolved oxygen and ammonia.

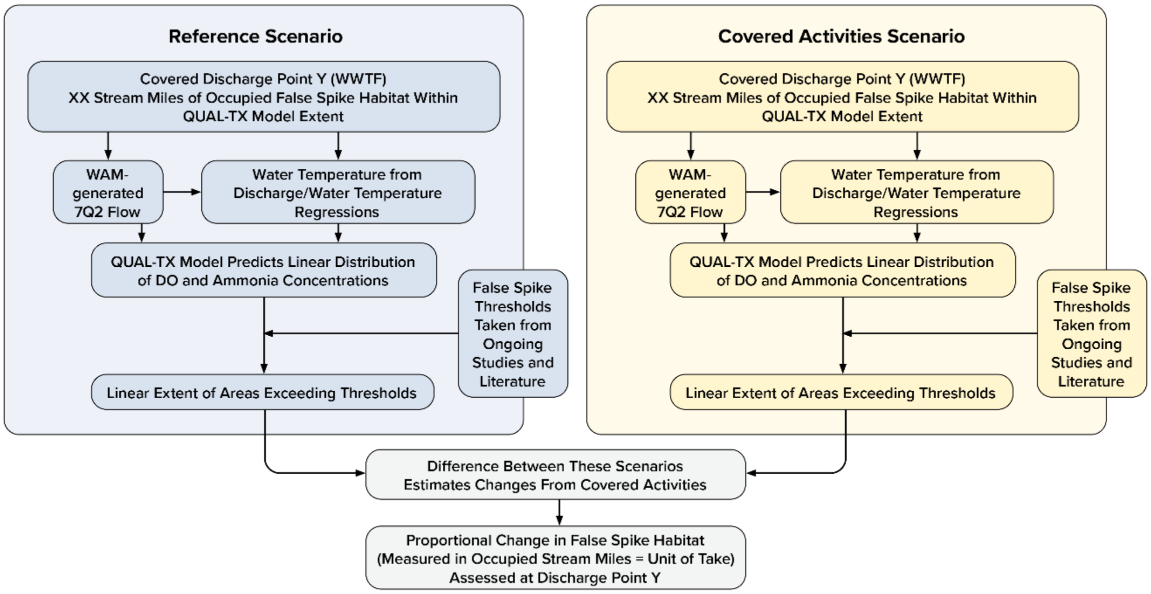


Figure 7. Flow chart illustrating mussel take methodology for dissolved oxygen and ammonia.

4.0 References

Augspurger, T., A. E. Keller, M. C. Black, W. G. Cope, and F. J. Dwyer. 2003. Water quality guidance for protection of freshwater mussels (Unionidae) from ammonia exposure. Environ. Toxicol. Chem. 22(2003): 2569-2575.

Barnhart, M. C., W. R. Haag, and R. N. Williams. 2008. Adaptations to host infection and larval parasitism in Unionidae. Journal of the North American Benthological Society. 27:370-394.

BIO-WEST, Inc. 2017. Comprehensive Instream Flow Study for the Gonzales Reach of the Lower Guadalupe River. Final Report to Guadalupe-Blanco River Authority, June 2017.

BIO-WEST, Inc. 2022. 2022 GBRA Mussel Surveys Final Report. Final Report submitted to Guadalupe-Blanco River Authority, November 2022.

Bonner, T. H., and J. S. Perkin. 2009. Historical zoogeography and abundance of fishes in two Texas river basins with an annotated species list. Final Report November 17, 2009.

Bonner, T. H., E. L. Oborny, B. M. Littrell, J. A. Stoeckel, B. S. Helms, K. G. Ostrand, P. L. Duncan and J. Conway. 2018. Multiple freshwater mussel species of the Brazos River, Colorado River, and Guadalupe River basins. Final Report to the Texas Comptroller of Public Accounts. 653 pp.

Burlakova, L. E., and A. Y. Karatayev. 2012. State-Wide Assessment of Unionid Diversity in Texas. Texas Parks and Wildlife State Grants Program, Austin, Texas, 42 pp.

Burlakova, L., A. Karatayev, E. Froufe, A. E. Bogan, and M. Lopes-Lima. 2018. A new freshwater bivalve species of the genus *Cyclonaias* from Texas (Unionidae: Ambleminae: Quadrulini). The Nautilus 132:45-50.

Dudding, J., M. Hart, J. Khan, C. R. Robertson, R. Lopez, and C. R. Randklev. 2019. Host fish associations for two highly imperiled mussel species from the southwestern United States: *Cyclonaias necki* (Guadalupe Orb) and *Fusconaia mitchelli* (False Spike). Freshwater Mollusk Biology and Conservation 22: 12-19.

Fogelman, K. J, J. A. Stoeckel, H. A. Abdelrahman, and B. S. Helms. 2022. The relative importance of suspended versus benthic food sources to freshwater mussels in central Texas, U.S.A. Freshwater Biology DOI: 10.1111/fwb.13901.

Freshwater Mussel Host Database (FMHD). 2017. The freshwater mussel host database, Illinois Natural History Survey & Ohio State University Museum of Biological Diversity, 2017. http://wwx.inhs.illinois.edu/collections/mollusk/data/freshwater-mussel-host-database. (December 2022).

Gough, H. M., A. M. Gascho Landis, J. A. Stoeckel. 2012. Behaviour and physiology are linked in the responses of freshwater mussels to drought. Freshwater Biology 57(11): 2356-2366.

Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays Basin and Bay Expert Science Team (GSA BBEST). 2011. Environmental Flows Recommendations Report. March 2011.

Haag, W. R. 2012. North American Freshwater Mussels: Natural History, Ecology, and Conservation. Cambridge University Press, New York.

Haney, H., H. Abdelrahman, and J. A. Stoeckel. 2019. Effects of thermal and hypoxic stress on respiratory patterns of three unionid species: implications for management and conservation. Hydrobiologia (2020) 847:787-802.

Horne, F. R., and S. McIntosh. 1979. Factors influencing distribution of mussels in the Blanco River of central Texas. The Nautilus 94:119-133.

Johnson, M. S., P. D., Caccavale, C. R. Randklev, and J. R. Gibson. 2012. New and confirmed fish hosts for the threatened freshwater mussel *Lampsilis bracteata* (Gould, 1855), the Texas Fatmucket (Bivalvia:Unionidae). The Nautilus 126:148-149.

Khan, J. M., M. Hart, J. Dudding, C. R. Robertson, R. Lopez, and C. R. Randklev. 2019. Evaluating the upper thermal limits of glochidia for selected freshwater mussel species (Bivalvia: Unionidae) in central and east Texas, and the implications for their conservation. Aquatic Conservation - Marine and Freshwater Ecosystems 2019:1-14.

Khan, J. M., J. Dudding, M. Hart, C. R. Robertson, R. Lopez, and C. R. Randklev. 2020. Linking flow and upper thermal limits of freshwater mussels to inform environmental flow benchmarks. Freshwater Biology 2020(00): 1-16.

Layzer, J. B., and L. M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. Regulated Rivers: Research and Management 10:329-345.

Littrell, B. M., K. Sullivan, and E. Oborny. 2018. Task 3 Environmental Flow Analysis. Pages 136-190 *in* Bonner, T.H., E.L. Oborny, B.M. Littrell, J.A. Stoeckel, B.S. Helms, K.G. Ostrand, P.L. Duncan and J. Conway. 2018. Multiple freshwater mussel species of the Brazos River, Colorado River, and Guadalupe River basins. Supplemental Report to the Texas Comptroller of Public Accounts, August 31, 2018.

Mabe, J. S., and J. Kennedy. 2014. Habitat conditions associated with a reproducing population of the critically endangered freshwater mussel *Quadrula mitchelli* in central Texas. The Southwestern Naturalist 59:297-300.

Maloney, K. O., W. A. Lewis, R. M. Bennett, and T. J. Waddle. 2012. Habitat persistence for sedentary organisms in managed rivers: the case for the federally endangered dwarf wedgemussel (*Alasmidonta heterodon*) in the Delaware River. Freshwater Biology 57:1315-1327.

Mummert, A. K., R. J. Neves, T. J. Newcomb, and D. S. Cherry. 2009. Sensitivity of juvenile freshwater mussels (*Lampsilis fasciola*, *Villosa iris*) to total and un-ionized ammonia. Environmental Toxicology and Chemistry 22(11): 2545-2553.

Newton, T. J., S. J. Ziglerand, and B. R. Gray. 2015. Mortality, movement and behavior of native mussels during a planned water-level drawdown in the Upper Mississippi River. Freshwater Biology 60. DOI: 10.1111/fwb.12461.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The Natural Flow Regime: A paradigm for river conservation and restoration. BioScience 47:769-784.

Randklev, C. R., M. Cordova, J. Groce, E. Tsakiris, and B. Sowards. 2014. Freshwater mussel (Family: Unionidae) data collection in the middle and lower Brazos River. Report submitted to Texas Parks and Wildlife (TPWD) as part of TPWD Contract No. 424520.

Randklev, C. R., E. T. Tsakiris, M. S. Johnson, T. Popejoy, M. A. Hart, J. Khan, D. Geeslin, and C. R. Robertson. 2018. The effect of dewatering on freshwater mussel (Unionidae) community structure and the implications for conservation and water policy: A case study from a spring-fed stream in the southwestern United States. Global Ecology and Conservation 16 (2018): e00456. https://doi.org/10.1016/j.gecco.2018.e00456.

Randklev, C. R., N. B. Ford, M. Fisher, R. Anderson, C. R. Robertson, M. Hart, J. Khan, and R. Lopez. 2020. Mussels of Texas Project Database, Version 1.0.

Schwalb, A. N., and M. T. Pusch. 2007. Horizontal and vertical movement of unionid mussels in a lowland river. The North American Benthological Society 26:261-272.

Seagroves, L. A., M. C. Barnhart, T. Hardy, and A. N. Schwalb. 2019. Reproductive ecology of the threatened and endemic freshwater mussel *Lampsilis bracteata*. Aquatic Convervation: Marine and Freshwater Ecosystems 29:1216-1226.

Sotola, V. A., K. T. Sullivan, B. M. Littrell, N. H. Martin, D. S. Stich, and T. H. Bonner. 2021. Short-term responses of freshwater mussels to floods in a southwestern U.S.A. river estimated using mark–recapture sampling. Freshwater Biology 66:349-361.

Sullivan, K. T. 2020. Persistence of *Cyclonaias necki* (Bivalvia: Unionidae) in the Blanco River, Texas: first live record in over 40 years. Texas Journal of Science 72: General Note 2.

Sullivan, K. T., and B. M. Littrell. 2020. Freshwater mussel assemblage structure in a small Edwards Plateau impoundment with comments on conservation implications for Texas Fatmucket, *Lampsilis bracteata* (Gould 1855). Freshwater Mollusk Biology and Conservation 23:36-41.

Tsakiris, E. T., and C. R. Randklev. 2016. Distribution and habitat associations of freshwater mussels (Bivalvia: Unionidae) in the lower Guadalupe River, Texas. Texas A&M Institute of Renewable Natural Resources, College Station, Texas, 32 pp.

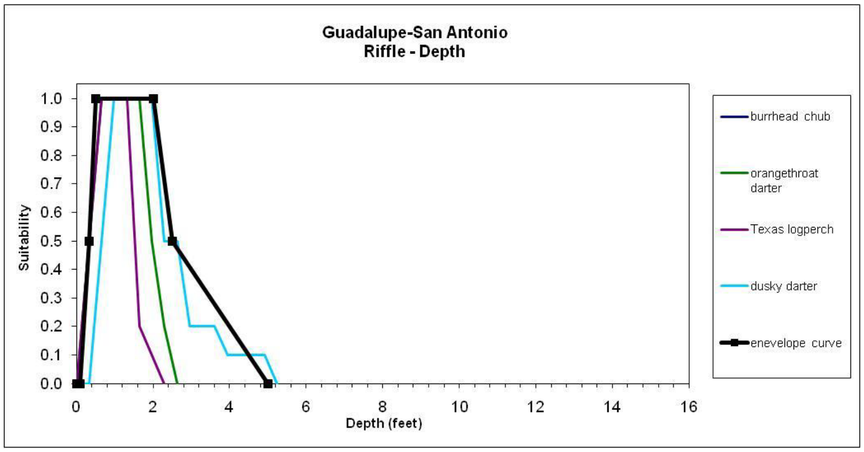
U.S. Fish and Wildlife Service (USFWS). 2016. Habitat Conservation Planning and Incidental Take Permit Processing Handbook, U.S. Fish and Wildlife Service, and National Marine Fisheries Service, December 21, 2016.

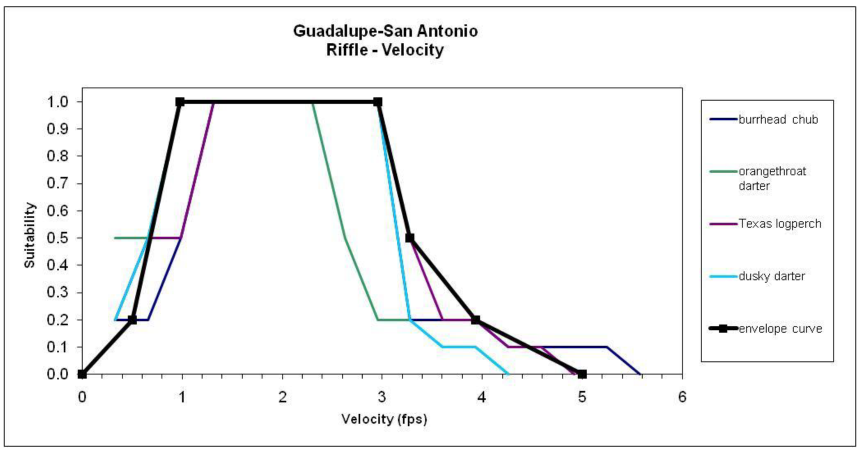
U.S. Fish and Wildlife Service (USFWS). 2018. Species Status Assessment Report for the Central Texas Mussels: False Spike (*Fusconaia mitchelli*), Texas Fatmucket (*Lampsilis bracteata*), Texas Fawnsfoot (*Truncilla macrodon*), Texas Pimpleback (*Cyclonaias petrina*), Guadalupe Fatmucket (*Lampsilis sp. cf. bracteata*), and Guadalupe Orb (*Cyclonaias necki*). Version 1.3, October 2018. USFWS Region 2 Albuquerque, NM.

U.S. Fish and Wildlife Service (USFWS). 2021. Endangered Species Status with Critical Habitat for Guadalupe Fatmucket, Texas Fatmucket, Guadalupe Orb, Texas Pimpleback, and False Spike, and Threated Species Status with Section 4(d) Rule and Critical Habitat for Texas Fawnsfoot. Federal Register 86:47916-48011.

Yeager, M. M., D. S. Cherry, and R. J. Neves, 1994. Feeding and burrowing behaviors of juvenile Rainbow Mussels, *Villosa iris* (Bivalvia: Unionidae). Journal of the North American Benthological Society 13: 217–222.

Appendix





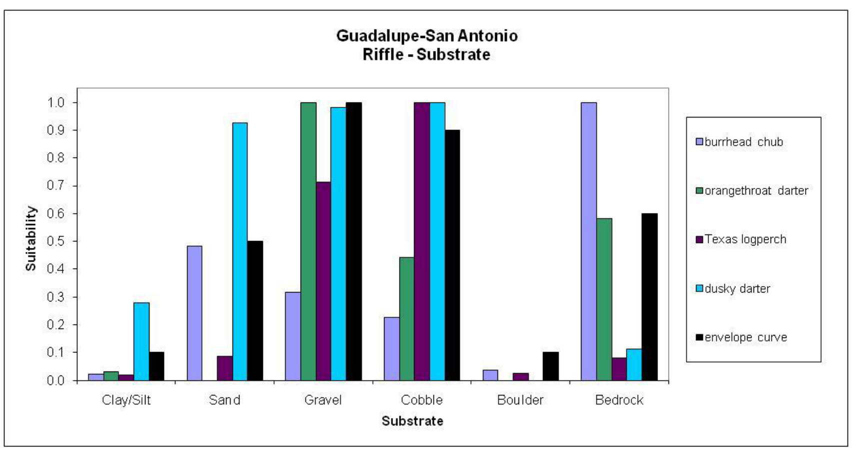


Figure A1. Envelope and species-specific habitat suitability curves for the Guadalupe-San Antonio Riffle habitat guild related to depth (top), velocity (middle), and substrate (bottom).

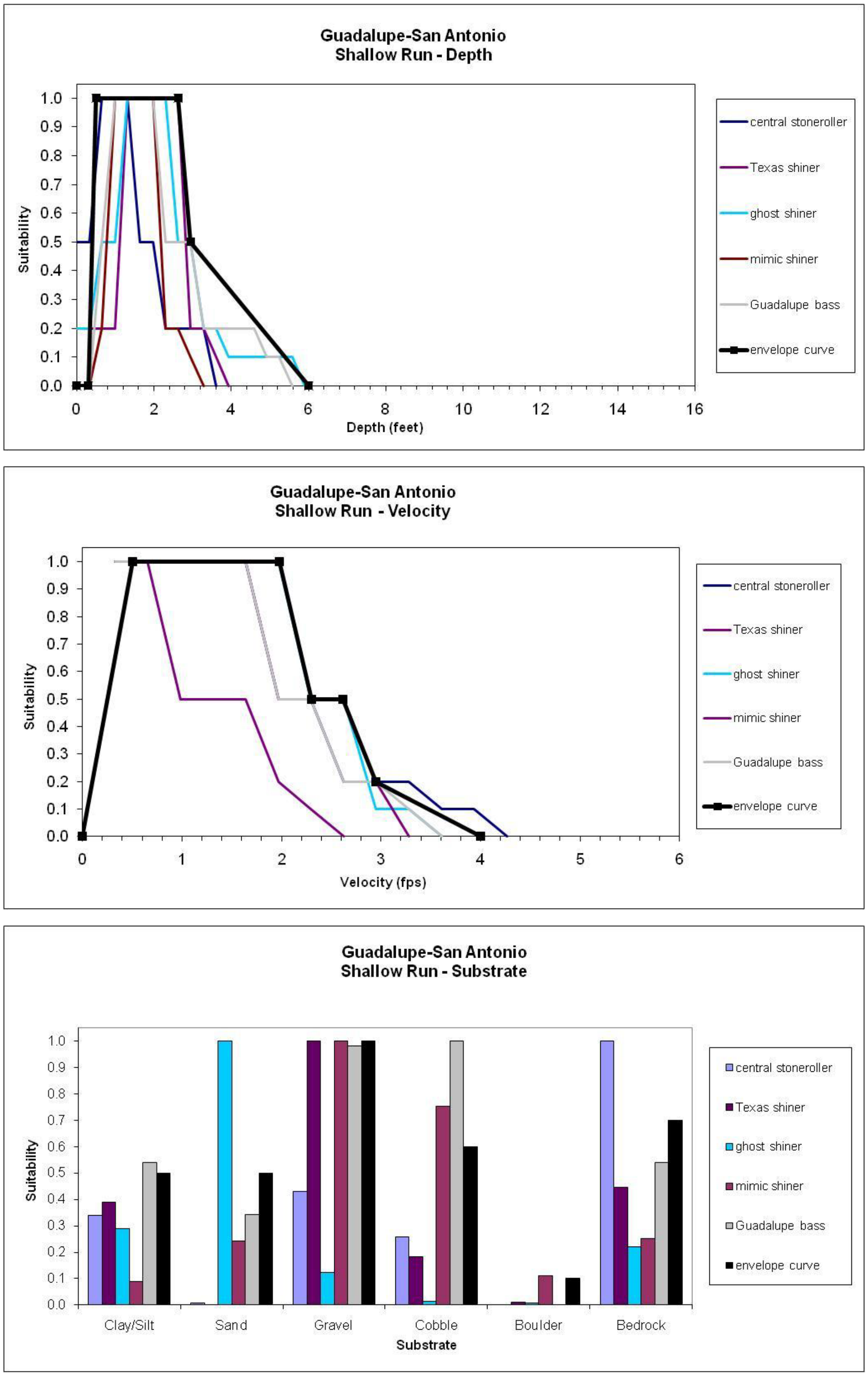


Figure A2. Envelope and species-specific habitat suitability curves for the Guadalupe-San Antonio Shallow Run habitat guild related to depth (top), velocity (middle), and substrate (bottom).