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Research Article

A simplistic water body-specific risk assessment model for zebra mussel (*Dreissena polymorpha*) establishment based on physicochemical characteristics

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Abstract

As invasive zebra mussels (*Dreissena polymorpha*) continue to spread through the freshwaters of the United States, efforts have been made to develop mussel invasion risk assessments to focus invasion prevention, monitoring, rapid response, and macrofouling control on at-risk water bodies. Previous invasion risk assessments have been based on broadly applied single factors such as calcium concentration or summer water temperature or on global scale climate variables. While such factors applied on a nationwide basis provide a general overview of regions susceptible to mussel invasion, they do not determine mussel invasion risk for specific water bodies, which can be variable even among those that are closely adjacent. Furthermore, these broad risk assessments may over or underestimate risk due to lack of water body specificity. In order to develop effective mussel prevention and control strategies, managers need mussel invasion risk assessments that can be applied to specific water bodies allowing limited resources to be focused on those most likely to be invaded. This study reports the use of easily determined factors (i.e., calcium concentration, pH, salinity, and summer surface water temperature) to specifically determine mussel invasion risk for 133 Texas water bodies as a case study of simplistic methods with broad geographic applicability. The results indicated that 19.5% of the water bodies had a minimal invasion risk, 9.8% a moderate risk, and 70.7% a high risk. This study demonstrates that these methods provide finer scale risk assessment for Texas water bodies in this case study, finding higher risk in western and southern regions than was predicted by climate-based risk assessments and more nuanced risk levels in the eastern region than predictions based on calcium alone. These methods can provide invaluable information for natural resource managers and water infrastructure operators on a broad geographic scale to guide monitoring and mitigation efforts.

Key words: aquatic invasive species, aquatic ecosystems, dreissenid, Texas, reservoir

Introduction

Zebra mussels (*Dreissena polymorpha*) are native to the Black Sea region of Eurasia (Rosenberg and Ludyanskiy 1994) and were first introduced into North America in the Great Lakes region in 1988 (Hebert et al. 1989) via ballast water of oceangoing ships and have since spread to water bodies throughout much of the central and eastern United States. Zebra mussel infestations result in significant economic costs due to impacts on water infrastructure, such as municipal water delivery and hydroelectric facilities, with mitigation cost at some facilities estimated in the hundreds of millions of dollars (MacIsaac 1996; Park and Hushak 1999; Connelly et al. 2007; IEAB 2010, 2013; Prescott et al. 2013; Robinson et al. 2013). Furthermore, these species are known to have significant deleterious impacts on ecological function and native aquatic species (Higgins and Zanden 2010).

Zebra mussels were first documented in Texas in 2009 in Lake Texoma on the Oklahoma border and, as of July 2023, have spread to 36 water bodies across six river basins. Many other uninfested water bodies in the state remain at risk of invasion yet research suggesting sampling effort required for truly effective early detection monitoring is potentially in excess of 700 samples per water body to achieve ≥ 90% detection (Hoffman et al. 2011; Counihan and Bollens 2017) clearly illustrates that even moderately effective sampling of all water bodies within a state is unattainable for most natural resource managers. Therefore, it is critical—not only in Texas—to prioritize water bodies sampled in order to maximize number of samples per water body. Efforts to evaluate risk at a state level in order to prioritize monitoring have involved gravity modeling of introduction and establishment risk (Robertson et al. 2020) and climate-based establishment risk modeling (Barnes and Patiño 2020).

Gravity modeling (e.g., Robertson et al. 2020; Carillo et al. 2023) can provide highly useful results for prioritizing monitoring efforts as these models can consider both introduction and establishment risk potential, but actual boater movement data is often lacking, requiring simulation (e.g., based on reported travel distances; Robertson et al. 2020; Carillo et al. 2023) with uncertain accuracy that could affect model predictions. Furthermore, although the predictions of Robertson et al. (2020) were instrumental in guiding monitoring, zebra mussels have since invaded a number of water bodies farther south and west than predicted by this model, leading to uncertainty regarding model predictions. Most importantly, the complex methods and time required for gravity modeling, which should be repeated as more water bodies are invaded, are likely not feasible for most natural resource managers. Climate-based models (e.g., Drake and Bossenbroek 2004; Barnes and Patiño 2020) consider only establishment risk (i.e., not introduction risk) but can also provide valuable rough-scale guidance for adaptive monitoring similar to that provided by the methods in this study. The availability (i.e., open source) and relative ease of use of Maxent software used by Barnes and Patiño (2020) could potentially facilitate such modeling by natural resource managers. However, the case of zebra mussel establishment in Texas has shown that this Maxent model that does not incorporate water body specific physicochemical characteristics relevant to zebra mussel establishment into the model itself (Barnes and Patiño 2020) identifies some areas of the state with established zebra mussel populations (TPWD 2023) as low to moderate risk, yielding uncertainty regarding model accuracy. The model of Drake and Bossenbroek

(2004) shows relatively good correlation with established zebra mussel populations but uses sophisticated modeling techniques not feasible for most natural resource managers.

Additionally, establishment risk models based on climatic factors alone (Drake and Bossenbroek 2004; Barnes and Patiño 2020) leave room for uncertainty regarding their accuracy, as they predict high establishment risk for some areas known to have low calcium concentration (Whittier et al. 2008). Calcium is a key limiting factor for dreissenid mussels and some risk and distribution prediction assessments have been conducted based entirely or in large part on calcium availability, with most validated by occurrence data (Ramcharan et al. 1992; Jones and Ricciardi 2005; Whittier et al. 2008; Therriault et al. 2012; Sepulveda et al. 2023). Water temperature has also been explored as a key limiting factor for risk assessment (McMahon and Tsou 1990), although recent work suggests adaptation to higher temperatures in the southern U.S. However, there are a number of factors, including calcium, pH, salinity, and temperature—especially in Texas at the southernmost extent of the zebra mussel's introduced range in North America—that may limit the risk of zebra mussel establishment and the influence of these factors on establishment risk is largely unknown, both for Texas and for other areas lacking water body-specific risk assessments.

Calcium is required by dreissenid mussels for reproduction, survival of all life stages, settlement, and growth and shell development (Sprung 1987; Hincks and Mackie 1997; Cohen and Weinstein 2001; Jones and Ricciardi 2005). Calcium is often considered one of the most significant limiting factors for zebra mussel establishment and is involved in both metabolic functioning and shell building (Whittier et al. 2008). Notably, although zebra mussels in their native range are only found in waters with high calcium concentrations exceeding 25.4–28.3 mg/l (Ramcharan et al. 1992; Karatayev 1995), introduced zebra mussel populations in North America have been documented in waters with calcium concentrations as low as 13 mg/l (Mellina and Rasmussen 1994; Strayer et al. 1996). It is hypothesized that higher calcium thresholds in the native range may be related to other abiotic factors in those environments (Cohen and Weinstein 2001). As a result, calcium requirement thresholds specific to North America (calcium concentrations < 12 mg/l indicating low risk to > 20 mg/l indicating high risk of establishment) have been developed based on further research (McMahon 2015) and are refined for the purposes of this study based on additional literature review (Sprung 1987; Ramcharan et al. 1992; Jones and Ricciardi 2005; Davis et al. 2015; Ruhmann 2014).

The pH tolerance of zebra mussels has not been well studied (Garton et al. 2014, but see summary in Cohen and Weinstein 2001). Evidence exists that interactive effects of pH and calcium levels may be significant (Claudi et al. 2012), with calcium uptake being limited in waters outside the optimal, relatively alkaline, pH range for this species (Hincks and Mackie 1997). Outside of the optimal pH range, zebra mussel shells lose calcium, resulting in adult mortality (Claudi et al. 2012). Furthermore, successful egg development has also been found to occur only within the optimal pH range (Sprung 1987).

Salinity tolerance of zebra mussels has been found to be lower than that of most other freshwater bivalves (Horohov et al. 1992). Zebra mussels have been found to have relatively low capacity for hyperosmotic regulation and high epithelial ion permeability which may reduce capacity for excretion and filtration in high salinities (Dietz and Byrne 1997). Survival of zebra mussel veligers at salinities higher than 4 ppt is low (Wright et al. 1996) and adults exposed to 5 ppt were found to experience 100% mortality in 18 days (Spidle et al. 1995) with the incipient lethal limit for adults estimated to be between 2–4 ppt (Kilgour et al. 1994).

There are examples of comprehensive risk assessments incorporating multiple water body physicochemical factors along with introduction risk factors that likely provide highly accurate results (e.g., Wu et al. 2010); however, these models also use sophisticated modeling approaches that may not be feasible for natural resource managers. This study sought to present a more simplistic water body-specific establishment risk assessment for zebra mussels, using Texas as a case study. By basing this assessment on water body physicochemical factors that are limiting to zebra mussel establishment (i.e., calcium, pH, salinity, and temperature), the accuracy of such predictions can be significantly increased over previous assessments based on climate or calcium alone. Developing a better understanding of the risk of zebra mussel establishment can aid state and local agencies to better understand the potential risks of economic impacts to infrastructure, mitigation planning needs, and prioritization of early detection and prevention efforts. For natural resource managers to effectively develop monitoring programs that make the best possible use of limited time and resources, there is a need for simple yet accurate methods of establishment risk assessment which can be coupled with knowledge of water body attractiveness and boater use to prioritize monitoring and implement adaptive management.

Materials and methods

Data collection

The Texas Commission on Environmental Quality (TCEQ) oversees the statewide Surface Water Quality Monitoring (SWQM) program, which compiles data collected by numerous partners across the state. For this assessment, ten years (2010–2019) of SWQM data were obtained from TCEQ for temperature, pH, salinity, specific conductance, calcium, and water hardness (TCEQ *unpublished data*). Data were obtained for a total of

Table 1. Zebra mussel establishment risk thresholds for key water body physicochemical characteristics.

Physical Risk Factor	Minimal Risk	Moderate Risk	High Risk	References
Calcium	< 12 mg/l	12–20 mg/l	> 20 mg/l	Davis et al. 2015; Jones and Ricciardi 2005; Ramcharan et al. 1992; Ruhmann 2014; Sprung 1987
pH	< 7.0 or > 9.6	7.0–7.3 or 9.4–9.6	> 7.3 or < 9.4	Arterburn and McMahon 2022; Claudi et al. 2012; Sprung 1987
Salinity	> 5 ppt	4–5 ppt	< 4 ppt	Kilgour et al. 1994; Spidle et al. 1995; Wolff 1969; Wright et al. 1996
Summer Water Temperature	> 32 °C	31–32 °C	< 31°C	Koplyay 2020; McMahon *unpublished data*; Morse 2009; Spidle 1995

Table 2. Criteria for determining zebra mussel establishment risk levels based on August water temperature at 2–4 m depths.

Risk Level	Criteria
High Risk	H1. All temperatures < 32 °C; and/or H2. Some temperatures ≥ 32 °C but only isolated events; and/or H3. ≥ 50% of temperatures/year ≥ 32 °C for < 50% of years, with < 3 consecutive
Moderate Risk	M1. ≥ 50% of temperatures/year ≥ 32 °C for 3 consecutive years at least once; and/or M2. ≥ 50% of temperatures/year ≥ 32 °C for ≥ 50% of years
Minimal Risk	L1. ≥ 90% of temperatures/year ≥ 32 °C for ≥ 50% of years; and/or L2. ≥ 75% of temperatures/year ≥ 32 °C for 3 consecutive years more than once

156 water bodies; after removing water bodies with no boating access or other sources of possible introduction of zebra mussels and one water body no longer in existence following 2015 dam failure, data were analyzed for a total of 133 Texas water bodies. A total of 236 large public water bodies were identified in Texas; this analysis includes 56% of these reservoirs. Calcium/hardness data were not available from TCEQ for many water bodies and were augmented by calcium data collected by the University of Texas at Arlington (2011–2017) and Texas Parks and Wildlife Department (TPWD; 2014–2022) to provide data for additional water bodies for analysis.

Establishment risk categorization thresholds

Thresholds for risk of establishment of zebra mussels for calcium, pH, salinity, and temperature were modified from McMahon (2015) based on literature review to create minimal, moderate, and high-risk categorizations for each parameter (Table 1). Specifically, the parameters of McMahon (2015) were modified by McMahon as follows: calcium threshold between moderate and high risk was modified based on additional and more recent literature (Sprung 1987; Ramcharan et al. 1992; Jones and Ricciardi 2005; Ruhmann 2014; Davis et al. 2015), pH thresholds were modified based on more recent literature (Arterburn and McMahon 2022), and salinity thresholds were added based on literature review (Wolff 1969; Kilgour et al. 1994; Spidle et al. 1995; Wright et al. 1996). Separate risk thresholds for summer surface water temperature were established as described below based on factors contributing to poor establishment success (Table 2) to accommodate lack of average continuous summer water temperatures in data available for this study—and likely available to most natural resource managers.

Calcium

When available, measured calcium concentration data were used for this assessment (i.e., 51 water bodies). If calcium concentration data were not available, calcium concentration was calculated from water hardness (i.e., 19 water bodies) based on molecular weight (i.e., $CaCO_3$ mg/l * 0.04) to facilitate assessment as opposed to including water hardness as an additional parameter as has been done in some studies (e.g., Robertson et al. 2020). Calcium data were lacking for 14 water bodies within the interpolated area identified by Whittier et al. (2008) as likely to have calcium levels ≤ 12 mg/l for which overall risk level was uncertain without calcium data; we conducted site visits to these water bodies to collect samples for calcium analysis to augment data for this study and facilitate their overall risk assessment. Calcium concentration data were available for a total of 85 water bodies included in this study (i.e., 64%). Mean calcium concentration (mg/l) was calculated for each water body using measurements from all dates and depths and risk category was determined for each water body based on the thresholds defined in Table 1.

pH

Data on pH were available for all water bodies included in this study. Mean pH was calculated for each water body using measurements from all sites, dates, and depths, as recommended by Prisciandaro (2022) to account for temporal and spatial variation. Risk category was determined for each water body based on the thresholds defined in Table 1.

Salinity

Salinity data from TCEQ-SWQM were unavailable for most water bodies included in this study. Therefore, salinity was calculated from specific conductance as practical salinity units (PSU; roughly equivalent to ppt) following the methods of Wagner et al. (2006). Specific conductance data were available for all water bodies included in this study. Mean salinity (PSU) was calculated for each water body using measurements from all dates and depths and risk category was determined for each water body based on the thresholds defined in Table 1. Detailed salinity trends in four water bodies with maximum salinity greater than or equal to 4 PSU were explored, with water bodies having prolonged periods (i.e., several years) of salinity levels in the minimal to moderate-risk range being assigned moderate risk status.

Summer water temperature

To evaluate the impacts of summer water temperature on risk of zebra mussel establishment, August (i.e., hottest month) temperatures in the two-to-four meter depth range were used. These depths were selected to avoid extremely shallow waters where solar radiation may increase water temperature on any given date/time above normal August temperatures as well as to avoid depths that may fall below the summer thermocline. Temperature data in this depth range were available for 126 (95%) of the water bodies included in this study. Temperature data were lacking entirely for one water body and insufficient (i.e., depths < 2 m) for six water bodies.

The temperature risk thresholds in Table 1 are based on mean August surface water temperature; however, measurements were available for no more than one date per water body for August each year and, thus, monthly average data were not available. Mean August water temperatures across the entire ten-year study period (i.e., all years, sites, and depths in the 2–4 m range) were below the 32 °C upper threshold for zebra mussel survival. Therefore, we calculated maximum temperature for each water body and carefully evaluated temperature trends for each water body with maximum temperature ≥ 32 °C. Because temperatures were found to vary within these water bodies both within and among years, we developed a set of risk level criteria based on the proportion of temperatures exceeding this threshold and whether periods of multiple years (i.e., ≥ 3) of high temperatures occurred that would preclude zebra mussel establishment (Table 2). When August temperatures were not available for a given year, temperature was presumed to have reached or exceeded 32 °C in August for a given site/depth if July or September temperatures were ≥ 31.0 °C (measurements to nearest 0.1 °C).

Overall establishment risk

Overall establishment risk for each water body was determined to be the lowest risk level for any of the evaluated parameters – calcium, pH, salinity, or temperature. Given the results of temperature assessment, temperature-based risk was assumed to be high for the purposes of overall risk assessment for the seven water bodies for which temperature data were unavailable or insufficient, given that none of these were power plant water bodies where temperature may have been a limiting factor. Similarly, calcium-based risk was assumed to be high for the purposes of overall risk assessment for all water bodies for which calcium data were not available as they were located within the zone predicted by Whittier et al. (2008) to be high risk based on calcium availability and calcium results in this study showed high agreement with the predictions of that study. Due to the goal of providing a method of utility to natural resource managers without modeling expertise, we did not attempt to conduct calcium interpolation as has been done in some other studies (e.g., Wells et al. 2011).

Assessment validation

In order to validate the results of this assessment, overall establishment risk for each water body was compared to actual zebra mussel presence/establishment in Texas (i.e., water bodies with repeated detections and/or clear evidence of an established, reproducing population). This assessment was based on 28 water bodies with zebra mussels present and 33 additional water bodies included in this assessment that are monitored for early detection by a partnership including state, federal, and local agencies and one university. Eight additional water bodies with zebra mussels, primarily very small water

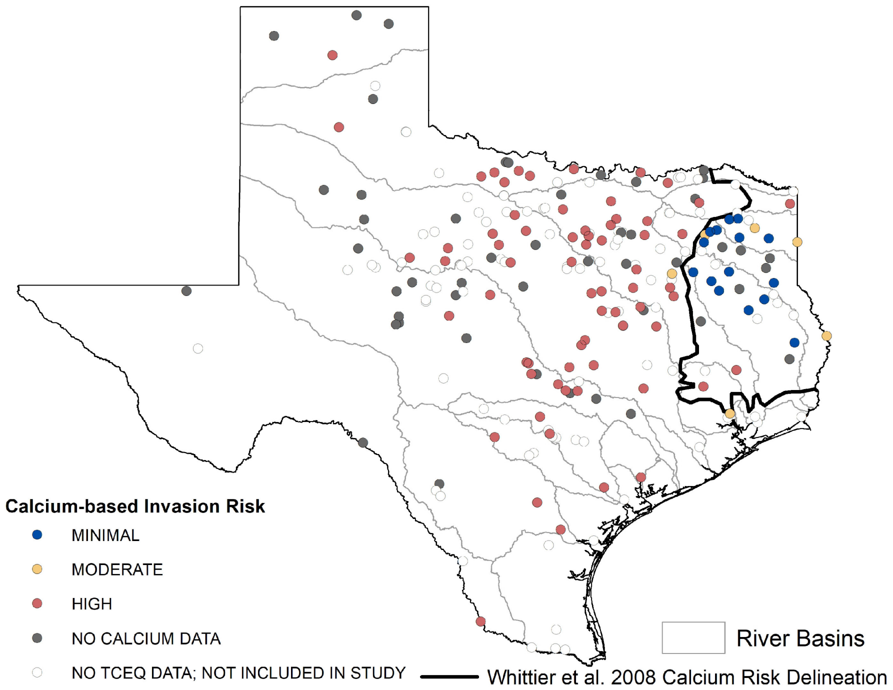

Figure 1. Calcium-based zebra mussel establishment risk categorization of 85 Texas water bodies. Areas to the east of the Whittier et al. (2008) calcium risk delineation were predicted by that study to have ≤ 12 mg/l calcium (i.e., minimal establishment risk); this delineation is shown to demonstrate level of agreement with that study. Major water bodies not included in this study due to lack of TCEQ water quality data are shown for context of the study extent. The Cypress, Sabine, and Neches River basins referenced in the text are the three East Texas basins with predominantly minimal risk water body categorizations.

bodies, lacked water quality data for inclusion in this assessment and so are not represented in the assessment validation. Single detections (i.e., veliger or adult) were also considered. Six additional water bodies being monitored where zebra mussels have not been detected lacked water quality data for inclusion in this assessment and so are not represented in the assessment validation.

Results

Calcium

Of the 84 water bodies (i.e., 63%) for which calcium data were available, 15 were determined to be minimal risk for zebra mussel establishment based on the criteria shown in Table 1 (mean Ca range 3.7–10.8 mg/l). All minimal-risk water bodies were located within the very low-risk zone identified by Whittier et al. (2008) (Figure 1). Six water bodies were determined to be of moderate risk (mean Ca range 12.0–15.9 mg/l) (Figure 1). With the exception of Cedar Creek Reservoir (Trinity River Basin) and Lake Houston (San Jacinto River Basin), all of these were located within the very low-risk zone identified by Whittier et al. (2008); these two water bodies were located in close proximity to that zone. Three water bodies within the very low-risk zone identified by Whittier et al. (2008) based on calcium concentrations were determined to be high risk – Lake Wright Patman (Sulphur River Basin), Lake Livingston (Trinity River Basin, infested with zebra mussels), and Lake Conroe (San Jacinto

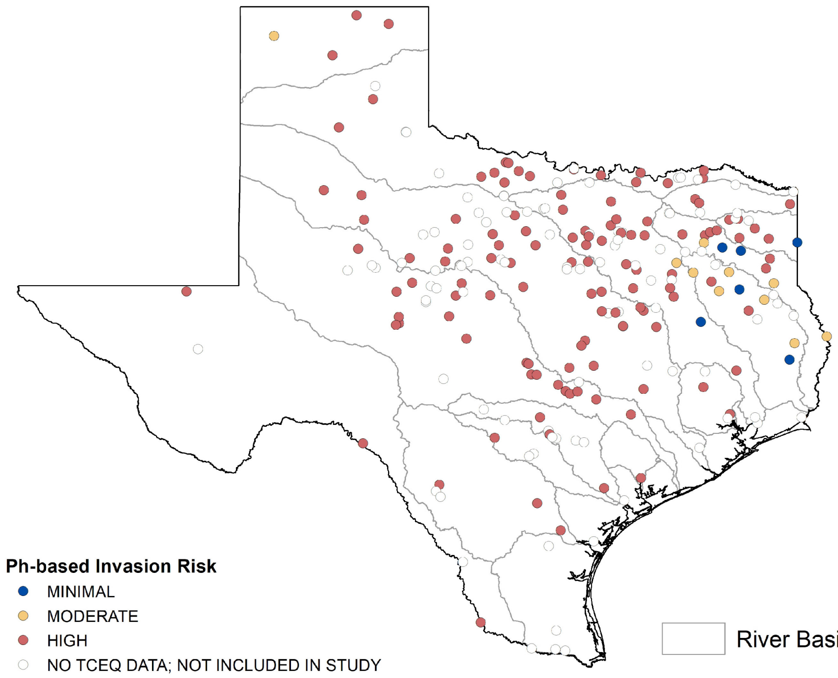

Figure 2. pH-based zebra mussel establishment risk categorization of 133 Texas water bodies. Major water bodies not included in this study due to lack of TCEQ water quality data are shown for context of the study extent.

River Basin). All other water bodies were determined to be high risk. With the exception of the two moderate-risk water bodies outside of the Whittier et al. (2008) very low-risk zone noted above, all minimal to moderate risk water bodies based on low calcium were located within the Cypress, Sabine, and Neches river basins. Results of calcium data analysis are shown in Figure 1 and Supplementary material Table S1.

pH

Six water bodies were determined to be minimal risk for zebra mussel establishment based on pH using the criteria shown in Table 1 (mean pH range 6.5–6.9). Ten water bodies were determined to be moderate risk – nine due to moderately low pH (mean pH range 7.0–7.3) and one due to high pH (mean pH 9.5). All other water bodies were determined to be high risk. Results of pH data analysis are shown in Figure 2 and Table S1.

Salinity

Only one water body – Red Bluff Lake (Pecos River impoundment, Rio Grande River Basin) was determined to be minimal risk for zebra mussel establishment based on high salinity (mean salinity 5.97 PSU). Although average salinity levels for all other water bodies were in the high-risk range, detailed salinity trends in water bodies with maximum salinity greater than or equal to 4 PSU were explored. Trends indicated periods, often prolonged, of high salinity in four water bodies—Lake E.V. Spence (Colorado River

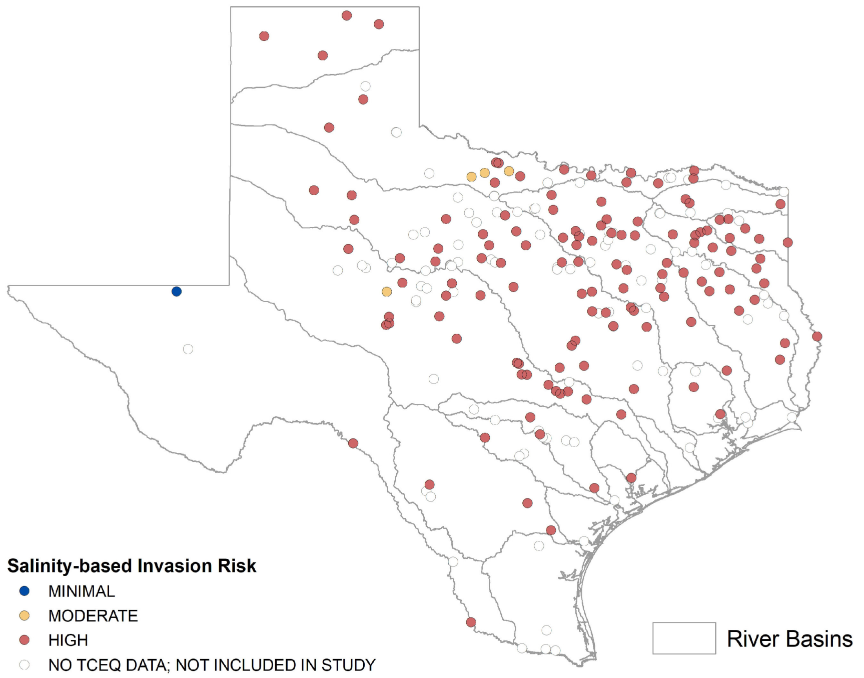

Figure 3. Salinity-based zebra mussel establishment risk categorization of 133 Texas water bodies. Major water bodies not included in this study due to lack of TCEQ water quality data are shown for context of the study extent.

Basin) and Diversion Lake, Lake Kemp, and Lake Wichita (Red River Basin) —that would likely eliminate zebra mussel populations should they become established during low salinity periods; these water bodies were designated as moderate risk. Results of salinity data analysis are shown in Figure 3 and Table S1.

Summer water temperature

Of the 126 water bodies for which temperature data at 2–4 m depths were available, five—Lake Bastrop, Brandy Branch Reservoir, Coleto Creek Reservoir, Fayette Lake, and Martin Creek Lake—were determined to be minimal risk for zebra mussel establishment, with four of these meeting both criteria L1 and L2 (Table 2) and Coleto Creek meeting criterion L1. Two water bodies were determined to be moderate risk for zebra mussel establishment – Lake Arlington, meeting criteria M1 and M2 (Table 2), and Fairfield Lake, meeting criterion M1. All of the minimal to moderate risk water bodies are power plant cooling reservoirs, which experience higher temperatures due to heated power plant effluent. This finding that temperature is, in general, not a limiting factor in Texas is noteworthy, as this is the southernmost extent of the contiguous U.S. All other water bodies for which data were available were determined to be high risk. Results of temperature risk analysis are shown in Figure 4 and Table S1.

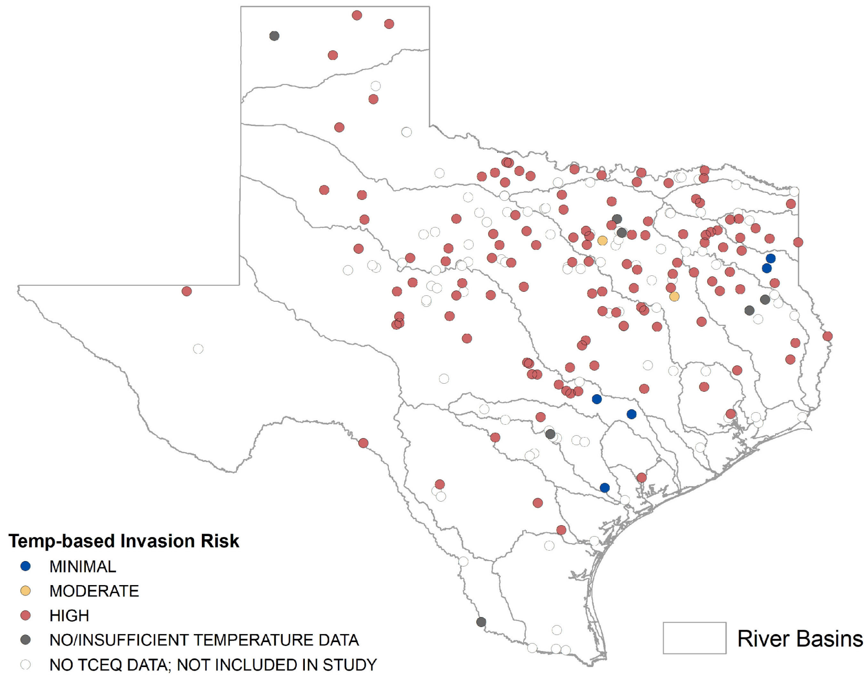

Figure 4. Temperature-based zebra mussel establishment risk categorization of 126 Texas water bodies. Major water bodies not included in this study due to lack of TCEQ water quality data are shown for context of the study extent.

Overall water body risk assessment

A total of 26 of the 133 water bodies (i.e., 19.5%) were determined to be minimal risk for zebra mussel establishment due to calcium (n = 15; 7 of these were also of moderate risk for pH – which may be related to calcium), pH (n = 6; 1 of these was also of moderate risk for calcium – which may be related to pH), salinity (n = 1), or temperature (n = 4). A total of 13 water bodies (i.e., 9.8%) were determined to be moderate risk due to calcium (n = 4), pH (n = 2); both calcium and pH (n = 1), salinity (n = 4), or temperature (n = 2). All remaining water bodies (70.7%) were determined to be high risk. Results of overall risk analysis are shown in Figure 5 and Table S1.

Assessment validation

All 28 water bodies included in this study where zebra mussels have been repeatedly detected or are known to be fully established were predicted to be high risk for establishment by this assessment. Additionally, one water body, Lake Waco, where a localized introduction of zebra mussels was discovered in 2014 and subsequently eradicated (TPWD 2021) was also determined to be high risk. Zebra mussels were detected a single time (one adult) in 2011 in one high risk water body, Lake Ray Hubbard, with no subsequent detections or population development. Of the water bodies included in this assessment being monitored for early detection, 22 were found by this study to be high risk, 4 to be moderate risk, and 7 to be minimal risk. With the exception of one moderate risk water body, Lake Fork, where a single veliger was detected in 2015 with no subsequent

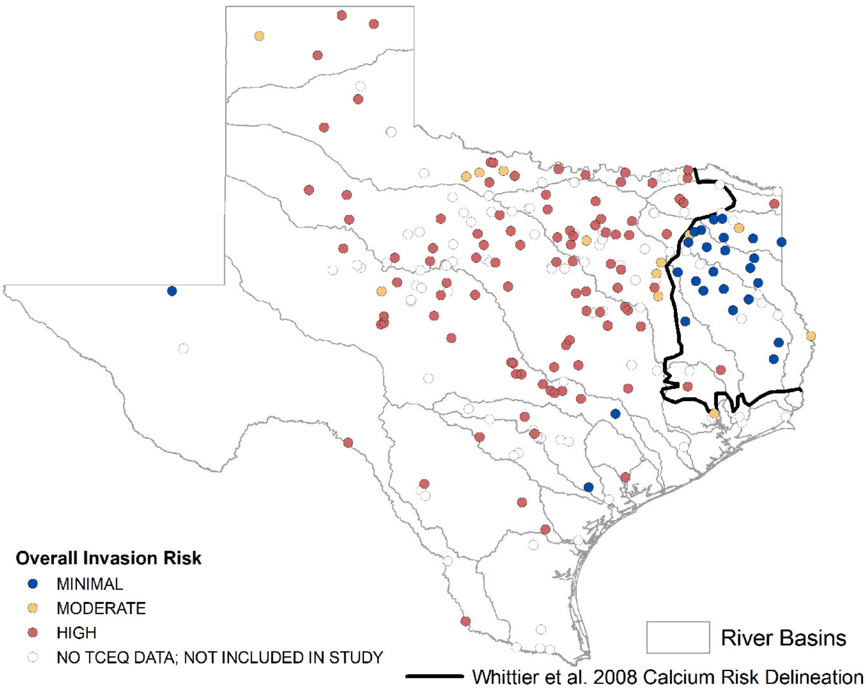

Figure 5. Overall zebra mussel establishment risk categorization of 133 Texas water bodies based on calcium, pH, salinity, and temperature. Major water bodies not included in this study due to lack of TCEQ water quality data are shown for context of the study extent. The Whittier et. al. low calcium/low risk zone delineation is shown to demonstrate level of agreement with that study, which is relatively high with some noteworthy exceptions. The Cypress, Sabine, and Neches River basins referenced in the text are the three East Texas basins with predominantly minimal risk water body categorizations.

population development, development, neither veligers nor settled zebra mussels have been detected in any monitored moderate or minimal risk water bodies or reported in such water bodies (i.e., by partners or the public). Results of assessment validation are shown in supplementary material Table S1.

Discussion

Out of a total of 236 public water bodies with motorized boating access identified in Texas, this study was able to successfully conduct a water body-specific establishment risk assessment for 133 of them (56%). Most of the water bodies evaluated (70.7%) were found to be high risk for zebra mussel establishment. This notably includes all but two water bodies in the Texas Panhandle (i.e., northwest) and South Texas, areas identified by climate-based models as low risk for zebra mussel establishment (Drake and Bossenbroek 2004; Barnes and Patiño 2020). The results of this study showed calcium to be the most significant limiting factor for zebra mussel establishment in Texas. Results of calcium analysis corresponded well with the previous findings of Whittier et al. 2008 of low risk of establishment in East Texas. However, this more detailed analysis found nuances within the low-risk zone identified by that study, with calcium being a limiting factor primarily in the Cypress, Neches, and Sabine river basins, some water bodies being moderate rather than low risk, and some water bodies within this zone having adequate calcium and overall high risk of successful establishment.

With the exception of Rita Blanca Lake in the Texas Panhandle (moderately high pH) and Purtis Creek State Park Lake (moderately low pH), pH was only a limiting factor for water bodies located within the very low-risk calcium zone identified by Whittier et al. (2008). This suggests potential influence on water body pH of low buffering activity of calcium carbonate and calcium phosphates. While pH alone was the determining factor for low to moderate risk for zebra mussel establishment for seven water bodies within this zone lacking calcium data and further supported such determinations for water bodies with calcium data, pH was likely related to calcium concentrations and these results support the importance of calcium as the key limiting factor for zebra mussel establishment. However, if pH levels are more variable in an area targeted for assessment, inclusion of pH in assessment would be recommended.

Salinity was not a significant limiting factor for zebra mussel establishment in Texas, with only four water bodies with known saline inputs experiencing salinities that resulted in low to moderate risk categorization. Saline water intrusion (i.e., brine leakage from geological formations) into the Pecos River upstream of Red Bluff Reservoir increases salinity to consistently high levels (Miyamoto et al. 2007), and this was the only water body designated as low risk due to salinity. Lakes Kemp, Diversion, and Wichita were determined to be moderate risk for establishment based on recurring periods of several consecutive years with salinity levels not conducive to, or only moderately conducive to, establishment. For lakes Kemp and Diversion, US Army Corps of Engineers Tulsa District chloride control studies have found three naturally occurring salt emission areas in the watershed above Lake Kemp – which is upstream of Diversion Lake (Wurbs 2011). Lake Wichita periodically receives water via a canal from Diversion Lake when water levels become low (Robert Mauk, TPWD, *pers. comm.*) and, consequently, experiences periodic high salinity levels. This suggests that inclusion of salinity in risk assessment has only minimal benefits if water bodies with brine inputs are known, but could be of benefit when such information is not readily available.

Despite Texas being at the southernmost extent of the North American range of zebra mussels and temperature affecting population dynamics (Schwalb et al. 2023), temperature was not a significant limiting factor for establishment, with only five water bodies determined to be minimal risk and two moderate risk. All of the minimal to moderate risk water bodies are power plant cooling reservoirs, which experience higher temperatures due to heated power plant effluent. Notably, there are a few additional power plant reservoirs in Texas for which data were not available that may also have reduced risk of establishment. However, based on temperature data from multiple stations within each water body across ten years, the effects of temperature even in these water bodies would likely be localized or intermittent. Therefore, zebra mussels could potentially become established during cooler years or in cooler areas of power plant reservoirs, although establishment of a thriving population is unlikely and populations established during cooler years may not persist. This suggests that temperature may not be a factor throughout most of the introduced North American range of this species, except that temperature should be evaluated for power plant cooling reservoirs to assess risk level as temperature regimes within these water bodies can vary spatially as well as temporally.

Assessment validation based on known occurrences of zebra mussels in Texas and early detection monitoring supported the results of this study. All water bodies in this study where zebra mussels are currently or previously (i.e., one eradication site) present were determined by this study to be high risk for establishment. Although a single adult was detected in high-risk Lake Ray Hubbard in 2011 and a population never developed, it is likely that an insufficient number of individuals was introduced to successfully become established. Zebra mussels have not been detected in any of the four moderate and seven minimal risk water bodies that are being monitored due primarily to infrastructure concerns causing water body controlling authorities to expend resources to monitor despite risk level. Furthermore, following the detection of a single veliger in moderate-risk Lake Fork in 2015, no population has developed.

This study represents one of the few efforts to conduct a water body-specific zebra mussel establishment risk assessment based on water body physicochemical characteristics and is the first such assessment for Texas. Additionally, previous studies using water body-specific physicochemical data have used more complex modeling or interpolation approaches (Wells et al. 2010; Sepulveda et al. 2023). This study presents Texas as a case study of simplistic methods not requiring modeling that can easily be employed elsewhere and comparisons with previous predictions and known zebra mussel invasions suggest assessment using these methods can improve on some previous risk assessments. The results of this study identify additional areas of risk not predicted by climate-based models (Drake and Bossenbroek 2004; Barnes and Patiño 2020) and further refine results of interpolated assessment based on calcium alone (Whittier et al. 2008). Although data were unavailable for 103 of the major water bodies in Texas, this study provides valuable insights that can be used to predict risk level for those water bodies. With the exception of water bodies in East Texas in the Cypress, Sabine, and Neches river basins, power plant lakes, and lakes with known significant saline inputs, we recommend that all lakes not included in this study be considered high risk for zebra mussel establishment. Assessments and prediction potential provided by this study can provide invaluable insights for determining need for mitigation planning to control mussel fouling of water infrastructure and for guiding early detection monitoring and prevention efforts. Our methods and recommendations for utilizing these case study results also provide a simplistic model that can be employed elsewhere by natural resource managers provided water quality data are available or can be obtained. Although calcium and pH were found to be the most significant limiting factors in Texas, it is recommended that all parameters in this study be included in assessments in other geographic areas, particularly if other limiting parameters are known to be variable, power plant reservoirs are present, and brine inputs are not well known.

There are several key limitations to this study and the approach it represents. Most importantly, if water quality data are not available, time required to collect such data could be substantial. However, the National Water Quality Portal data utilized by Sepulveda et al. (2023) may facilitate use of these methods in the U.S. when other data are lacking. Calcium data, in particular, were found to often be lacking in both this study and Sepulveda et al. (2023), yet are critical for risk assessment. While we made use of the interpolated data of Whittier et al. (2008) for sites lacking data, we recommend only doing so for lakes considered by that study to be high risk as was done in this study, as we found nuances in calcium concentrations exceeding predictions within the low-risk zone identified in that study based on calcium, and Sepulveda et al. (2023) found that interpolation led to low predictive accuracy. Field collection of calcium data, when lacking, would lead to higher predictive accuracy. Furthermore, the relationship between calcium and zebra mussel survival and establishment may not be straightforward (Misamore 2022), particularly if pH is conducive to establishment (Ramcharan et al. 1992) or if magnesium levels are sufficient (Dietz et al. 1994). This study also did not assess risk of establishment of zebra mussels' congener, the quagga mussel (*Dreissena bugensis*), which has also become invasive and warrants consideration. However, the use of zebra mussels represents a more conservative approach, and if assessment for quagga mussels is desired, the methods of this study could be followed with one key physical risk factor difference of a high temperature threshold of 30 °C (Kappel et al. 2015). Finally, the use of this simplistic approach comes with tradeoffs as compared to other more complex (e.g., gravity) modeling approaches that consider not only establishment risk but also introduction risk. This approach offers the benefit of simplicity but should be considered a tool in adaptive management to be combined with information on proximity of invaded water bodies and water body attractiveness to boaters or boater movement data to seek to target early detection monitoring most effectively.

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Authors' contribution

Both authors contributed to study conceptualization, design and methodology, and manuscript preparation. Data analysis was conducted by McGarrity.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Results of zebra mussel establishment risk analysis and validation for 133 Texas water bodies. Data include physicochemical data used in assessment and zebra mussel invasion status, by water body.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2024/Supplements/MBI_2024_McGarrity_McMahon_SupplementaryMaterial.xlsx