Risk Analyses for Establishment of Dreissenid Mussels at Selected Stations in the Watersheds of the San Jacinto and Lower Trinity Rivers

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Table of Contents

List of Figures

List of Tables

Executive Summary

AECOM requested a review of water quality data developed by Espey Consultants (EC), Inc. (2011) for the City of Houston and Coastal Water Authority relative to the potential for dreissenid mussels (i.e. zebra mussel, *Dreissena polymorpha*, and quagga mussel, *Dreissena rostriformis bugensis*) to establish sustainably reproducing populations in portions of the drainage basins of the San Jacinto and lower Trinity Rivers and Lake Houston. They also requested an analysis of the potential impact for dreissenid mussels to be introduced to isolated watersheds by interbasin water transfers, particularly to Lake Houston by water transfer from the Trinity River. Relevant data on surface water temperature regime, pH, calcium concentration, and oxygen concentration were reviewed to develop risk assessments for dreissenid mussel establishment at 11 sampling stations within these watersheds and for potential hydrological transport of mussel planktonic larvae (i.e., veligers) between them, especially between the Trinity River and Lake Houston via a proposed water diversion if Lake Livingston became infested with zebra mussels.

Analysis of water quality data indicated that nine stations (see Figure 1) had either moderate (Stations: EC_CWALynch, EC_CWAMid, EC_CWATRPS, and EC_LuceBayou) or high probabilities (Stations: EC_WestFork, EC_NEWPP, EC_Lake Houston_B1, EC_Lake Houston_B2 and SWQM_10896) for supporting sustainably reproducing zebra mussel populations. Only stations EC_Trincaper on the Trinity River and EC_WestFork on the West Fork of the San Jacinto River appeared to have a low probability for establishment of zebra mussel populations based primarily on mid-summer water temperatures exceeding the mussels' incipient upper thermal limit of 32°C (See Figure 1). In contrast, none of the 11 stations on the San Jacinto River or lower Trinity River drainages appeared capable of supporting sustainably reproducing quagga mussel populations because their mid-summer water temperatures exceeded this species' incipient upper thermal limit of 28°C. Thus, while the examined waterbodies, rivers and canals appeared to be resistant to quagga mussel invasion, most of them with the possible exception of the East Fork/Caney Creek arms of the San Jacinto River Drainage appeared capable of supporting zebra mussel populations.

If zebra mussels become established in Lake Livingston, mussel larvae carried downstream in the lower Trinity River could be transported to Lake Houston via the proposed Luce Bayou Interbasin Transfer Project (LBITP) from the Trinity River to Lake Houston. In contrast, if Lake Houston became infested with zebra mussels, diversion of water to the lower Trinity River is likely to result only in populations of low density as larvae would be carried downstream into Trinity Bay. While mid-summer surface water temperatures at the EC_LuceBayou intake may be too high to support a zebra mussel population, mussel spawning and presence of settlement competent mussel larvae would occur at cooler temperatures (12-24°C) allowing larval transport through a water diversion system to Lake Houston. Lake Houston has surface water temperature, pH, calcium concentration and dissolved oxygen regimes which make it likely to support a sustainably reproducing zebra mussel population. Similarly, establishment of a zebra mussel population in Lake Conroe on the West Fork of the San Jacinto River could also lead to downstream transport of mussel larvae into Lake Houston. Larval transport from the Trinity River through the Coastal Water Authority (CWA) Canal could cause zebra mussel infestation of Lynchburg Reservoir which, based on EC_CWALynch water quality data, appears to have a moderate probability of supporting a sustainably reproducing mussel population.

Because of the potential vulnerability of much of the San Jacinto and lower Trinity River watersheds to zebra mussel infestation and the potential for zebra mussels to be transferred from mussel-infested portions of Lake Texoma to nearby waterbodies on the upper reaches of the Trinity River watershed, it may be important to initiate periodic mussel monitoring at the 11 examined stations and at other relevant sites including Lakes Conroe and Livingston. Monitoring should include examination of plankton net tow samples[1] for the presence of zebra mussel larvae and deployment of mussel settlement monitors during the spring and fall when water temperatures (18-24°C) are most suitable for zebra mussel reproduction and settlement. In addition, hard surfaces at selected sites could be periodically examined by divers for the presence of adult mussels.

[1] Net tow sampling is a process whereby plankton is collected with a net made of fine mesh. The net is lowered into the water to a specified depth and then retrieved vertically or towed behind the vessel for a period of time and depth thus sampling a specific oblique depth of the water column. (NOAA, 2012)

1.0 Introduction

This report was prepared in response to a request from AECOM to review the potential for dreissenid mussels (i.e. zebra mussel, *Dreissena polymorpha*, and quagga mussel, *Dreissena rostriformis bugensis*) to establish sustainably reproducing populations in portions of the drainage basins of the San Jacinto and lower Trinity Rivers and Lake Houston. AECOM provided water quality data on these watersheds developed by Espey, Inc. (2011) for the City of Houston and Coastal Water Authority. Data on surface water temperature regime, pH, calcium concentration, and oxygen concentration were reviewed for 11 stations within the watersheds of the San Jacinto and lower Trinity Rivers (locations of the 11 stations can be seen on Figure 1) from which risk probabilities were determined for either zebra or quagga mussels developing sustainably reproducing populations. These four water quality parameters were chosen for development of risk assessment for mussel population development because they are generally considered to most determine environmental suitability for both species (Claudi and Mackie 1994; McMahon 1996). Also examined was the potential for hydrological transport of planktonic mussel larvae (i.e., veliger larvae) between the watersheds of the San Jacinto and lower Trinity Rivers and Lake Houston via water diversions.

2.0 Habitat Requirements

Freshwater mussels in Texas occur in still waters or those of moderate flows, including rivers and streams, lakes, reservoirs, ponds, and canals. They lives within a variety of substrate types, but most frequently firm mud, stable sand, and gravel, including combinations of these types, and in relatively shallow water to depths of many meters. Within such habitat conditions, the most limiting factor for fresh mussels is the lack of dissolved oxygen. Many mussels tolerate wide ranges in water temperatures as long as extremely hot or cold extremes are avoided and annual fluctuations support normal breeding activity. Freshwater mussels usually require environments that are very stable over long periods of time, with changes to their environments, including modifications to terrestrial ecosystems, resulting in an intolerant environment for the mussels. (Howells, 2009)

Habits in which freshwater mussels do not thrive include deep shifting sand (slow moving mussles cannot maintain positions in rapidly positions in rapidly moving substrates), deep soft silt (they may sink and smoother), scoured cobble and bedrock (where they cannot dig or may be easily swept away), server long-term dewatering due to drought or drawdown (that exposes mussels to temperature extremes desiccation, precludes feeding, etc), dramatically fluctuating water levels (mussels move slowly and cannot respond quickly), dense beds of aquatic macrophytes (that confound digging into the substrate, reduce phytoplankton food sources, and may be oxygen deprived at times), substrates covered with algal layers or sticks and leaves (confound movement, may block feeding and breathing), low-quality polluted waters (many are very intolerant of pollution), saline waters (only two species tolerate even minimal levels of salinity), lack of host fishes (that are necessary for reproduction), and for some species impounded waters (many species require flowing waters and cannot survive in reservoir conditions). (Howells, 2009).

It is important to minimize impacts to freshwater mussel habitat where possible to allow for mussels to thrive and reproduce. As well as the habitats described above, silt-laden turbid waters, (that can clog gills or preclude host fishes seeing female lures or conglutinates contacting glochidia), and unstable banks (which can fall and cover mussels resulting in an unsuitable mussel habitat) can also result in adverse impacts for mussels. (Howells, 2009)

3.0 Bases for Risk Assessment of Probabilities for Establishment of Sustainably Reproducing Dreissenid Mussel Populations

The adaptations of *D. polymorpha* (zebra mussel) and *Dreissena rostriformis bugensis* (quagga mussel) to abiotic environmental factors are relatively similar. This is not unexpected as the two species are closely related congeners (Stepien et al 2002; Orlova et a. 2005; Albrecht et al 2007) estimated to have diverged 221,000 ±78,000 years ago (Stepien et al 2002). Thus, there has been relatively little time for the evolution of distinctly different physiological adaptations between them. However, where good comparative data exists, they have revealed subtle differences in these species' adaptations to physical factors that could impact their ability to develop sustainably reproducing populations in the examined stations on the watersheds of the San Jacinto and lower Trinity Rivers and in Lake Houston. The most important physical factors for sustaining reproducing populations of zebra and quagga mussels are generally agreed to be summer surface water temperatures, calcium concentration, pH, and dissolved oxygen concentration (Claudi and Mackie 1994; McMahon 1996). It was these four factors that were extracted from physical surface water data provided by AECOM to assess the probability for dreissenid mussel population establishment at the selected stations. Inspection of Table 1 indicates that there are far more data available on the physiological adaptations to these four abiotic factors for zebra mussels relative to quagga mussels. But where comparative data exists, conclusions were drawn regarding the potential risk of each species to establish sustainably reproducing populations in the 11 sites for which AECOM provided water quality data.

3.1. *Temperature Tolerance*

Studies indicate that zebra mussels appear to have a somewhat higher incipient (i.e., long-term) upper thermal limit (29-32°C) than quagga mussels (28°C) (Table 1). Their greater thermal tolerance may allow them to be more successful in the warm shallow water habitats characteristic of the lower Trinity River and Lake Houston where surface water temperature at depths of <1.5 m reach or exceed 30°C during summer months. A lower incipient upper thermal limit may be the main factor that has prevented quagga mussel colonization of the lower Mississippi River where zebra mussels have become well established (United States Geological Survey 2011a, 2011b). The temperature limits for zebra mussel larval development to a settled juvenile stage are 12-24°C but the same data are unknown for quagga mussels Table 1).

The upper temperature limit for spawning by both species is 24°C, but quagga mussels may initiate spawning at a lower temperature of 9°C while zebra mussels initiate spawning at >12°C (Table 1). Peak spawning in both species occurs between 18-24°C. The temperature range for larval development is 12-24°C in zebra mussels, and is unknown but likely similar in quagga mussels (Table 1). For this reason, zebra mussel spawning/settlement seasons in Lake Texoma, Texas, are limited to spring and fall periods separated by summer cessation of spawning and settlement when water temperatures exceed 24°C (McMahon, unpublished data). This is also likely to be the case if zebra mussel populations become established in the watersheds of the San Jacinto and lower Trinity Rivers.

3.2. *Calcium Requirements*

Published studies indicate that zebra mussels require calcium concentrations that are ≥8-12 mg Ca/L (Hincks and Mackie 1997; Mellina and Rasmussen 1994) and for quagga mussels, ≥12 mg Ca/L (Jones and Ricciardi 2005) (Table 1). However, 12 mg Ca/L is the generally accepted lower limit for both species (Whittier et al, 2008) and was, thus, used as the lower limit for developing colonization risk assessments for both species in the watersheds of the San Jacinto and lower Trinity Rivers.

3.3 *pH Requirements*

Studies indicate that the tolerated incipient pH range for zebra mussels is 6.0 to 8.5-9.6 (Bowman and Bailey 1998; Hincks and Mackie 1997). However, zebra mussel pH tolerance can vary between habitats because it is impacted by the presence of critical ions such as Ca^{2+} and Mg^{2+} (Table 1). The pH range for successful larval development to a settled juvenile in zebra mussels is estimated to be 7.4-9.4 (Sprung 1987). It is unknown but likely similar in quagga mussels. For this reason, a pH of ≥7.4 was considered the lower limit for both species in development of colonization risk assessments for the watersheds of the San Jacinto and lower Trinity Rivers.

3.4 Oxygen Requirements

Zebra and quagga have generally similar tolerances of hypoxic conditions with incipient tolerated levels for adults considered to be >10% of full air oxygen saturation (i.e., partial pressure O_2 = 2.13 kPa) (Johnson and McMahon 1998, unpublished data). While unknown in quagga mussels, the lower oxygen concentration limit for development in zebra mussels to a settled juvenile is considered to be 32 percent of full air oxygen saturation (i.e., partial pressure O_2 = 4.3 kPa) (Sprung 1987) (Table 1). Based on roughly equivalent lower O_2 concentration limits for both species, an oxygen concentration of ≥32 percent full air oxygen saturation (i.e., partial pressure O_2 = 4.3 kPa) was considered the requirement for larval development to a settled juvenile in both species for the purpose of this risk assessment. Because both species have a relatively low tolerance of hypoxia, they would be unlikely to penetrate hypoxic hypolimnetic waters below depths of 5-6 m in Lake Houston (Table 2).

4.0 Risk Assessment Methodology

Water quality data was provided by AECOM for 11 stations located on the watersheds of the San Jacinto and lower Trinity Rivers and Lake Houston. Three stations were located on the San Jacinto River watershed above Lake Houston, five stations on the lower Trinity River watershed, and three stations were in Lake Houston. Station site identifications and locations are displayed on Figure 1 and are:

1. EC_NEWPP, City of Houston's (COH) Intake for Northeast Water Purification Plant (NEWPP) near Lake Houston, San Jacinto River
2. EC_CWALynch, Coastal Water Authority (CWA) Canal before Lynchburg Reservoir, San Jacinto River
3. EC_WestFork, West Fork, San Jacinto River near Humble, TX (at US 59)
4. SWQM_10896, Trinity River 125 m upstream of FM 787, near Romayor, Liberty Co., TX

5. EC_CWATRPS, CWA Canal at Trinity River near Dayton, TX
6. EC_CWAMid , CWA Canal at diversion to Cedar Point Lat. System, transferring water from the Trinity River to Lynchburg Reservoir
7. EC_TrinCaper, Trinity River at Hwy 105 (5 miles upstream of Capers Ridge diversion point)
8. EC_LuceBayou, Luce Bayou above Lake Houston near Huffman, TX
9. EC_EastFork, Lake Houston west of Magnolia Point, East Fork San Jacinto River/Caney Creek Arm in Lake Houston
10. EC_Lake Houston_B1, Lake Houston near U.S. Geological Survey (USGS) 295554095093401 (Site B, inside solar bees)
11. EC_Lake Houston_B2, Lake Houston near USGS 295826095082200 (Site A, outside solar bees)

The main data set consisted of water quality data for all sample sites except Surface Water Quality Monitoring (SWQM) taken on 8/24, 9/9-14, 9/28, and 10/13 during 2010 (Table 2).

Additional data included continuously monitored water quality for the following:

- EC_NEWPP from mid-2008 through mid-2010
- EC_LuceBayou from 1990 through 1999, and 2000
- SWQM_10896 from 1990 through 1999
- Lake Houston from 1990 through 2010.

Water quality data sets for all sampling stations were examined for the four factors most likely to impact successful establishment of zebra or quagga mussels including summer surface water temperatures, calcium concentration, surface water pH, and surface water dissolved oxygen concentration (Table 1).

Based on best available peer reviewed data on zebra and quagga mussel tolerance limits for these physical parameters (see section 2.0 above and Table 1), specific levels of each parameter were selected that represented the probability of a waterbody to host a sustainably reproducing mussel population. Three probability categories for establishment of sustainably reproducing zebra or quagga mussel populations were developed for each physical parameter. These were:

1. Low Probability: mussels are unlikely to establish a sustainably reproducing population
2. Moderate Probability: mussels may establish a population but stress resulting from a physical parameter(s) approaching tolerated limits may prevent massive colony development
3. High Probability: All examined physical water parameters fall with the limits for establishment of a thriving, sustainably reproducing mussel population capable of attaining high density.

The ranges of the four water quality parameters examined corresponding to these three risk probability levels are set out in Table 3.

5.0 Quagga Mussel Risk Assessment

The maximum incipient upper thermal limit of quagga mussels from the warm surface waters of Lake Mead (NV and AZ) has been estimated to be 28°C (Morse, 2009) which is similar to other estimates for this species (Spidle et al 1995) (Table 1). Quagga mussels appear to be able to survive and develop dense populations in the shallow surface waters of Lake Mead because ambient water temperatures rarely exceed their incipient upper thermal limit of 28°C, and if they do, only for very short durations rarely exceeding 30°C (Morse, 2009). Thus, quagga mussels in Lake Mead do not appear to be exposed to lethal temperatures for long enough to induce extensive mortality. In contrast, at all 11 sites examined in San Jacinto and lower Trinity Rivers and in Lake Houston, summer surface water temperatures appeared to exceed the 28°C incipient upper thermal limit of quagga mussels by ≥2°C (see station surface water temperatures for 8/24 and 9/14/2010 in Table 2). The lowest recorded surface water temperature among the examined stations was 30.1°C at EC_NEWPP on 9/14/2010 (Table 2). Thus, long-term exposure to surface water temperatures greater than the 28°C incipient upper limit of quagga mussels would be highly likely to inhibit establishment of this species anywhere in the watersheds of the San Jacinto and lower Trinity Rivers. Therefore, an overall risk assessment of low probability for establishment of a sustainably reproducing population of quagga mussels was assigned to all 11 examined stations (Table 4). Continuous data sets for EC_NEWPP, EC_LuceBayou, SWQM_10896, and Lake Houston also indicated that surface water temperatures remained above the 28°C incipient upper thermal limit of quagga mussels for extended periods during summer months. At stations EC_Lake Houston_B1 and EC_Lake Houston_B2 surface water temperatures on 8/24 and 9/14/2011 exceeded 29°C to depths of 4-5 m where waters became too hypoxic to support quagga mussels (Tables 1 and 2) suggesting that cooler hypolimnetic waters would be too hypoxic during summer months to provide guagga mussels a refuge from lethal summer epilimnetic water temperatures. In addition, at the EC_LuceBayou and EC_EastFork stations, mean calcium concentrations of 12.92 and 11.56 mg Ca/L (Table 4), were at levels low enough that moderate or low risks of quagga mussel establishment could be assigned, respectively. In contrast, all 11 stations had mean surface water O_2 concentrations and pH levels that exceeded those required for high probability of establishment of a quagga mussel population.

6.0 Zebra Mussel Risk Assessment

Unlike quagga mussels, the relatively higher incipient upper thermal limit of zebra mussels, particularly in warm southwestern waterbodies, of 32°C (Morse, 2009) prevented assignment of a low probability of establishment for the 11 examined stations based on water temperature regime alone (Table 4). Thus, the probability for establishment of a sustainably reproducing zebra mussel population is individually discussed for each station below.

6.1 EC_NEWPP, COH Intake for NEWPP

The EC_NEWPP station had an O_2 concentration range (34.7-75.5% of full air O_2 saturation), mean pH (8.0), mean calcium concentration (15.77 mg Ca/L), and summer surface water temperatures (31.1-31.4°C) (Table 2) that all fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. This assessment was supported by data recorded from mid-2008 to mid-2010 at the station which indicated that surface water temperature, pH and calcium concentration all generally remained within limits to support assignment of a high probability for zebra mussel establishment.

6.2 *EC_CWALynch, CWA Canal before Lynchburg Reservoir*

The EC_CWALynch station had an O_2 concentration range (76.2-96.5% of full air O_2 saturation), mean pH (7.5), and mean calcium concentration (15.77 mg Ca/L) (Table 2) that fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, its relatively elevated surface water temperatures of 31.6-32.5°C fell within a range for moderate risk of zebra mussel population establishment (Table 2). Thus, this station was assigned a moderate risk for zebra mussel population establishment at low density levels in spite of having O_2 concentration, pH and calcium concentration regimes capable of supporting a sustainably reproducing population (Table 4). On the assumption that water enters the CWA canal from the Trinity River through an intake structure near the EC_CWATRPS station, it is possible that if Lake Livingston became infested with zebra mussels that the mussel's planktonic larvae could be carried downstream in the Trinity River to be entrained in water transferred from EC_CWATRPS intake through the CWA Canal to be released into the Lynchburg Reservoir at the EC_CWALynch station. For that reason water quality parameters in Lake Lynchburg proper should be examined to estimate the likelihood that it could support a sustainably reproducing zebra mussel population.

6.3 *EC_WestFork, West Fork San Jacinto River near Humble, TX (at US 59)*

The EC-WestFork station had an O_2 concentration range (64-6-117.0% of full air O_2 saturation), mean pH (8.1), mean calcium concentration (23.7 mg Ca/L) and summer surface water temperatures (31.0-32.0°C) (Table 2) that all fell within the limits to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, as this station appears to be located on the West Fork of the San Jacinto River and does not appear to have an impounded waterbody upstream of its location, it may not be suitable for development of a zebra mussel population as water flow would transport the mussel's planktonic mussel downstream before they could reach the settlement stage (i.e., 2-3 weeks).

6.4 *SWQM_10896, Trinity River 125 m upstream of FM 787, near Romayor, Liberty Co., TX*

Based on data collected at the SWQM_10896 station from 1990-1999, surface water O_2 concentration was generally >50%, pH ranged from 6.3 – 8.85, but was generally >7.0, calcium concentration ranged from 24-45 mg Ca/L, and summer surface water temperatures generally did not exceed 32°C. Thus, the range for all four parameters fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population.

6.5 *EC_CWATRPS, CWA Canal near Dayton, TX*

The EC_CWATRPS station had an O_2 concentration range (80.3-107.6% of full air O_2 saturation), mean pH (7.8), and mean calcium concentration (38.8 mg Ca/L) (Table 2) that fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, its relatively elevated surface water temperatures of 31.7-32.7°C (Table 2) fell within the range for moderate risk of zebra mussel population establishment (Table 4). Thus, this station was assigned a moderate risk for zebra mussel population establishment at low density levels in spite of having O_2 concentration, pH and calcium concentration regimes capable of supporting a sustainably reproducing mussel population (Table 4). Lake Livingston lies upstream of station EC_CWATRPS, if Lake Livingston became infested with a viable zebra mussel population, larvae could be hydrologically transported downstream from that site to settle in vicinity of the EC_CWATRPS Station and/or be entrained at the station's intake to be transported through the CWA Canal to Lynchburg Reservoir.

6.6 *EC_CWAMid, CWA Canal at diversion to Cedar Point Lat. System*

The EC_CWAMid station had an O_2 concentration range (65.6-76.4% of full air O_2 saturation), mean pH (7.5), and mean calcium concentration (38.7 mg Ca/L) (Table 2) that fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, its elevated surface water temperatures of 32.4-33.3°C (Table 2) fell outside the upper 32°C incipient upper thermal limit of zebra mussels allowing this site to be assigned a low risk probability for mussel population establishment (Table 4) in spite of having O_2 concentration, pH and calcium concentration regimes capable of supporting a sustainably reproducing population (Table 4). However, if Lake Livingston became infested with zebra mussels, planktonic mussel larvae transported down the Trinity River during cooler reproductive periods (12-24°C) could be carried through the CWA Canal, on which EC-CWAMid is situated, to infest Lynchburg Reservoir if the reservoir proves capable of sustaining a reproducing population.

6.7 *EC_TrinCaper, Trinity River at Hwy 105 (5 miles upstream of Capers Ridge diversion point)*

The EC_TrinCaper station had an O_2 concentration range (84.3-108.5% of full air O_2 saturation), mean pH (8.2) and mean calcium concentration (35.68) (Table 2) that fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, its elevated summer surface water temperatures of 32.2-32.6°C (Table 2) fell outside the incipient upper thermal limit of zebra mussels at 32°C (Table 3). Thus, this station was assigned a low risk for zebra mussel population establishment in spite of having O_2 concentration, pH and calcium concentration regimes capable of supporting a sustainably reproducing mussel infestation (Table 4).

6.8 *EC_LuceBayou, Luce Bayou above Lake Houston near Huffman, TX*

The EC_LuceBayou station had an O_2 concentration range (45.3-108.4% of full air O_2 saturation) and mean pH (7.9) (Table 2) that fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, its mean calcium concentration of 12.92 mg Ca/L and relatively elevated summer surface water temperatures of 31.4-32.6°C (Table 2) both fell within the range for moderate risk of zebra mussel population establishment (Table 4). Thus, the EC_LuceBayou station was assigned a moderate risk for zebra mussel population establishment in spite of having O_2 concentration and pH regimes capable of supporting a sustainably reproducing population (Table 4).

6.9 *EC_EastFork, Lake Houston west of Magnolia Point, East Fork San Jacinto River/Caney Creek Arm in Houston, Texas*

The EC_EastFork station had an O_2 concentration range (117.0-137.9% of full air O_2 saturation) and mean pH (8.8) (Table 2) that fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. However, its mean calcium concentration of 11.6 mg Ca/L and elevated summer surface water temperatures of 34.5-34.9°C (Table 2) both fell well outside the tolerated limits of zebra mussels at >12 mg Ca/L and <32°C (Table 3). Thus, this station was assigned a low risk for zebra mussel population establishment in spite of having O_2 concentration and pH regimes capable of supporting a sustainably reproducing population (Table 4).

6.10 *EC_Lake Houston_B1, Lake Houston near USGS 295554095093401 (Site B, inside solar bees)*

Physical surface water data collection was limited to 8/24 and 9/14/2011 at the EC_Lake Houston_B1 station. Based on this relatively limited data set, surface water (depth 0.5 m) at the *EC_Lake Houston_B1* station had an O_2 concentration range (120.3-153.6% of full air O_2 saturation), mean pH (8.8), mean calcium concentration (14.0 mg Ca/L) and summer surface water temperatures (30.9-32.0°C) (Table 2) that all fell within the limits required to assign a high risk for establishment of a reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. While this risk assessment was based on only two sampling periods, a longer-term data set on surface water temperature, O_2 concentration and pH (1990-2010) provided by AECOM supported the high probability assessment.

6.11 *EC_Lake Houston_B2, Lake Houston near USGS 295826095082200 (Site A, outside solar bees)*

Physical surface water data collection was limited to 8/24 and 9/14/2011 at the EC_Lake Houston_B2 station. Based on this relatively limited data set, the EC_Lake Houston_B2 station (depth = 0.5 m) had an O_2 concentration range (117.9-153.2% of full air O_2 saturation), mean pH (8.9), and summer surface water temperatures (30.9-32.1°C) (Table 2) that all fell within the limits required to assign a high risk for establishment of a sustainably reproducing zebra mussel population (Table 4) if a large enough introduction of individuals occurred to initiate a population. Calcium concentration data was not available for the EC_Lake Houston_B2 station so it was assumed to be similar to that for the EC_Lake Houston_B1 station at 14.0 mg Ca/L. While this risk assessment was based on only two sampling periods, a longer-term data set on surface water temperature, O_2 concentration and pH (1990-2010) provided by AECOM supported the high probability assessment.

7.0 Discussion, Conclusions and Recommendations

Based on an analysis of water quality data provided by AECOM, nine of the eleven stations of interest appeared to have either a moderate (i.e., EC_CWALynch, EC_CWAMid, EC_CWATRPS, and EC_LuceBayou) or high probabilities (i.e., EC_WestFork, EC_NEWPP, EC_Lake Houston_B1, EC_Lake Houston_B2 and SWQM_10896) to support a sustainably reproducing zebra mussel population. Only the EC_Trincaper and EC_WestFork Stations appeared to have a low probability of supporting a sustainably reproducing zebra mussel population based primarily on mid-summer water temperatures exceeding the zebra mussel's incipient upper thermal limit of 32°C (Table 4). In contrast, none of the stations appeared to be able to support sustainably reproducing populations of quagga mussels primarily because their mid-summer water temperatures exceeded this species' incipient upper thermal limit of 28°C (Table 4). Thus, while the examined waterbodies, rivers and canals appear to be resistant to quagga mussel invasion, most of them with the possible exception of the East Fork/Caney Creek arms of the San Jacinto River Drainage (Figure 1, Table 4), appear capable of supporting zebra mussels.

Zebra mussels were first discovered in Texas on the south shore of the lower end of Lake Texoma on April 3, 2009 (Texas Parks and Wildlife Department, 2009). By the fall of 2011, a dense population of zebra mussels, often in excess of 50,000 individuals, had developed on hard surfaces on the north and south shores of the lower half of the lake (McMahon, personal observations). Soon after zebra mussels were discovered in Lake Texoma, the North Texas Municipal Water District (NTMWD) voluntarily shut down a pipeline that transferred water from Lake Texoma on the Red River Drainage to Lake Lavon on the East Fork of the Trinity River where its main water treatment facility was located (U.S. Army Corps of Engineers, Fort Worth District, 2011). The pipeline presently remains shutdown in order to prevent infestation of Lake Lavon with zebra mussels as a result of settlement of larvae entrained on water transfers from Lake Texoma. Since 25 percent of NTMWD water supplies come from Lake Texoma, the continued shutdown of the Texoma conduit has caused severe water shortages in the municipalities that it serves and an unprecedented drawdown of Lake Lavon during the summer of 2011(North Texas Municipal Water District 2011a, 2011b). Zebra mussel infestation has also been associated with a massive cyanobacteria bloom in Lake Texoma during the summer of 2011 (U.S. Army Corps of Engineers, Tulsa District 2011). Adult zebra mussels can also be transferred between isolated waterbodies attached to the hulls of boats and on previously submerged material and equipment (Claudi and Mackie 1994). During 2011, boats previously moored in Lake Texoma with adult zebra mussels attached to their hulls were transferred to and found moored at marinas on Lake Lavon and Lake Ray Hubbard, which is also on the East Fork of the Trinity River, suggesting that movement of recreational boats from Lake Texoma could eventually lead to the establishment of zebra mussels in reservoirs on the upper Trinity River Basin.

Quagga mussels were first observed in the Boulder Basin of Lake Mead (Nevada /Arizona) in 2007. Their larvae were rapidly transported downstream to infest Lakes Mohave and Havasu (McMahon, 2011). Similarly, establishment of zebra mussels in waterbodies on the upper Trinity River watershed could rapidly lead to mussel infestation of downstream waterbodies, such as Lake Livingston. Soon after the initial establishment of quagga mussels in the lower Colorado River, movement of larvae via interbasin water transfers from Lakes Mead and Mohave led to the establishment of sustainable infestations in a number of reservoirs in southern California and central Arizona (U.S. Geological Survey 2011).

Similarly, if a zebra mussel population became established in Lake Livingston due to downstream hydrological transport of planktonic larvae from an infested reservoir(s) on the upper Trinity River watershed or by overland transport on recreational boats or other material or equipment previously moored or submerged in a mussel-infested waterbody such as Lake Texoma, larvae being carried downstream in the lower Trinity River could be transported to Lake Houston via the proposed water diversion system from the lower Trinity River to EC_Luce Bayou for release into Lake Houston (Figure 1). While waters at EC_LuceBayou were considered too warm during mid-summer to support a zebra mussel population (Table 4), mussel spawning leading to the presence of larvae in the water column would occur at cooler temperatures (12-24°C, Table 1) allowing their transport through a water diversion system to Luce Bayou into Lake Houston whose surface water temperature, pH, calcium concentration and oxygen concentration regimes indicate a high probability for supporting a sustainably reproducing mussel population (Table 4). Similarly, establishment of a zebra mussel population in Lake Conroe upstream of Lake Houston on the West fork of the San Jacinto River could also lead to infestation of Lake Houston (Figure 1). Larval transport from the Trinity River through the CWA Canal could also lead to zebra mussel infestation of Lynchburg Reservoir which was assessed to have a moderate probability of supporting a sustainably reproducing mussel population at the EC_CWALynch outfall. Indeed, transport of larvae on water transfers from zebra mussel infested waterbodies could potentially lead to establishment of new populations in isolated, previously uninfested waterbodies capable of supporting mussel populations. For these reasons, the water quality of Lakes Livingston, and Conroe and Lynchburg Reservoir should also be assessed for their capacity to support sustainably reproducing zebra mussel populations.

Overall this risk assessment suggests that the waterways and reservoirs on the watersheds of the San Jacinto and lower Trinity Rivers encompassed by the examined stations would be highly resistant to quagga mussel invasion due to their summer surface water temperatures being elevated above its incipient upper thermal limit of 28°C (Figure 1, Table 4). In contrast, zebra mussels with a higher incipient thermal limit of 32°C could become established in many of the waterways and waterbodies encompassed by the examined stations (Figure 1, Table 4). For this reason it may be important to initiate a monitoring system at these and other relevant stations, including Lakes Conroe, Livingston, and Houston, for the presence of zebra mussel larvae via examination of plankton net samples taken during peak spawning periods when surface water temperatures are 18-24°C. Samples can be examined for the presence of mussel veliger larvae with cross-polarized light microscopy (Johnson, 1995), flow-cell cytometry and/or PCR (Polymerase Chain Reaction) molecular analysis (Hosler, 2011). If detected, transfers of water containing mussel larvae can be halted in order to avoid mussel introduction to uninfested receiving waterbodies. Presence of a reproducing mussel population can also be detected by deployment and periodic examination of juvenile settlement monitors during the spring and fall when water temperatures are most suitable for reproduction and settlement at 18-24°C (McMahon 1996). In addition, hard surfaces can be periodically examined by Scuba divers for the presence of adult mussels (Claudi and Mackie 1994).

8.0 References

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Figure 1. Map of sampling stations (highlighted in pink) for which water quality data was examined for the potential for zebra or quagga mussels to develop sustainably reproducing populations (from Espey Consultants, Inc. 2011).

Table 1. Comparison of resistance adaptations to physical factors of zebra (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*).

Physical Factor	Zebra Mussels	Quagga Mussels	Comment	References
Incipient Upper Thermal Limit	29-32°C in N. America	28°C in N. America	Can vary based on individual size and nutritional condition, prior temperature experience and season of the year. Thermal tolerance appears subject to selection by elevated temperatures. Likely to be greater for populations at lower latitudes and in waterbodies receiving thermal effluents.	Elderkin and Klerks 2005 Hernadez 1995 Iwanyzki and McCauley 1993 Karateyev et al 1998 Morse 2009 Spidle et al. 1995
Incipient Lower Thermal Limit	0°C	0°C	Temperate species which survive over winter in iced over waterbodies in the northern portions of their range.	Karateyev et al 1998 McMahon 1996 McMahon et al 1995
Spawning Temperature	12°-24°C	9°-24°C	Spawning is maximized in *D. polymorpha* ≥18°-20°C which is also likely to be the case in *D. r. bugensis*	Claxton and Mackie 1998 Karateyev et al 1998
Temperature for Larval Development	12-24°C	unknown	The lower limit may be reduced for *D. r. bugensis* but requires experimental confirmation.	Claxton and Mackie 1998 Sprung 1987
Calcium	<8-12 mg Ca^{2+}/L	<12 mg Ca^{2+}/L	Based primarily on presence absence data in the St. Lawrence River	Hincks and Mackie 1997 Mellina and Rasmussen 1994 Jones and Ricciardi 2005
pH	Range = 6.0 to 8.5-9.6 pH 7.4-9.4 for larval development	Unknown	Ca^{2+} and other ion concentrations may impact the tolerated pH range.	Bowman and Bailey 1998 Hincks and Mackie 1997 Sprung 1987
Low Oxygen Tolerance as % of full air O_2 Saturation	Po_2 >10.0% Po_2 > 32.3% for larval development Byssogenesis inhibited at ≤10%	Po_2 >10%	Appears to be temperature dependent – tolerance increases at lower temperatures. Likely to be greater in *D. polymorpha.*	Johnson and McMahon 1998 Matthews and McMahon 1999 McMahon and Johnson unpublished

Table 2. Summary of sampling data for water temperature (°C), calcium concentration (mg Ca/L) , pH, and oxygen concentration (mg O_2/L) at selected sites from the watersheds of the San Jacinto and lower Trinity Rivers and Lake Houston.

Site Code and Location	Date of Sample	Depth (m)	Temperature °C	mg Ca/L	pH	mg O_2/L
EC_WestFork	8/24/2010	0.30	31.0	24.99	7.50	4.80
West Fork San Jacinto River near Humble, TX (at US 59)	9/14-15/2010	0.10	32.0	15.90	8.20	8.40
	9/20/2010	0.10	27.5	23.30	8.20	8.60
	10/13/2020	0.10	24.8	30.45	8.50	9.70
Mean Values		**0.15**	**28.8**	**23.66**	**8.10**	**7.88**
EC_NEWPP	8/24/2010	4.88	31.4	16.20	7.80	2.56
COH Intake for NEWPP	9/14/2010	4.88	30.1	14.49	7.60	5.70
	9/28/2010	4.88	27.4	15.80	8.00	5.50
	10/4/2010	4.88	25.5	16.59	8.60	4.90
Mean Values		**4.88**	**28.6**	**15.77**	**8.00**	**4.67**
EC_CWALynch	8/24/2010	0.25	32.5	40.43	7.20	6.70
CWA Canal before Lynchburg Reservoir	9/14/2010	0.10	31.6	33.61	7.70	5.60
	9/28/2010	0.10	27.2	34.90	7.70	7.20
	10/13/2010	0.10	24.9	42.40	7.50	6.70
Mean Values		**0.14**	**29.1**	**37.84**	**7.53**	**6.55**
EC_CWAMid	8/24/2010	0.10	33.3	41.14	7.30	4.90
CWA Canal at diversion to Cedar Point Lat. System	9/14/2010	0.10	32.4	33.99	7.60	5.10
	9/28/2010	0.10	27.8	34.90	7.70	6.00
	10/13/2010	0.10	25.2	44.72	7.50	5.40
Mean Values		**0.10**	**29.7**	**38.69**	**7.53**	**5.35**
EC_CWATRPS	8/24/2010	0.30	32.7	41.01	7.30	5.80
CWA Canal near Dayton, TX	9/14/2010	0.10	31.7	34.19	7.80	5.60
	9/28/2010	0.10	26.2	36.60	8.50	8.70
	10/13/2010	0.10	25.3	43.71	7.70	6.80
Mean Values		**0.15**	**29.0**	**38.88**	**7.83**	**6.73**
EC_TrinCaper	8/24/2010	0.35	32.6	37.68	8.10	6.10
Trinity River at Hwy 105 (5 miles upstream of Caper's Ridge diversion point)	9/14/2010	0.10	32.2	32.76	8.50	7.90
	9/28/2011	0.10	29.3	36.60	8.60	8.20
	10/13/2010	0.10	27.2	43.31	7.70	7.60
Mean Values		**0.16**	**30.3**	**35.68**	**8.23**	**7.45**
EC_LuceBayou	8/24/2010	0.10	32.6	13.07	8.20	8.10
Luce Bayou above Lake Houston near Huffman,TX	9/14/2010	0.10	31.4	11.74	8.90	8.00
	9/28/2010	0.10	27.2	13.20	6.80	3.60
	10/13/2010	0.10	24.9	13.66	7.80	8.20

Table 2. Continued

Site Code and Location	Date of Sample	Depth (m)	Temperature °C	mg Ca/L	pH	mg O_2/L
EC_EastFork	8/24/2010	0.30	34.5	12.76	8.30	8.20
Lake Houston west of	9/14/2010	0.30	34.9	9.25	8.60	9.60
Magnolia Point, East Fork San Jacinto River/ Caney	9/28/2010	0.10	29.8	11.80	8.50	9.30
Creek Arm in Houston	10/13/2011	0.10	26.6	12.43	8.50	9.60
Mean Values		**0.20**	**31.5**	**11.56**	**8.48**	**9.18**
EC_Lake Houston_B1	8/24/2010	0.00	32.1		7.90	9.30
Lake Houston near		0.50	32.0		8.00	9.16
USGS_295554095093401 (Site B, inside solar bees)		1.00	31.9		8.14	8.80
		2.00	31.8		8.14	8.40
		3.00	31.8		8.12	8.60
		4.00	31.3		8.00	6.10
		5.00	31.0		7.70	4.30
		6.00	30.6		7.60	1.50
		7.00	30.2		7.20	1.60
	9/14/2010	0.00	30.9	13.98	9.50	11.40
		0.50	30.9		9.50	11.40
		1.00	30.7		9.40	10.70
		2.00	30.5		9.30	9.70
		3.00	30.5		9.30	9.20
		4.00	29.7		8.20	3.90
		5.00	28.9		7.70	0.20
		6.00	28.6		7.00	0.00
Mean Values (Depth 0.5)		**0.50**	**31.5**	**13.98**	**8.75**	**10.28**
EC_Lake Houston_B2	8/24/210	0.00	32.3		8.10	9.10
Lake Houston near		0.50	32.1		8.20	8.60
USGS_295826095082200 (Site A, outside solar bees)		1.00	31.8		8.20	8.30
		2.00	31.2		7.80	4.00
		3.00	31.1		7.70	3.30
		4.50	31.0		7.50	2.00
	9/14/2020	0.00	31.3		9.50	11.80
		0.50	30.9		9.50	11.40
		1.00	30.7		9.40	10.80
		2.00	30.4		9.40	10.30
		3.00	30.3		9.30	9.20
		4.00	29.4		8.30	4.00
		4.30	29.1		7.70	1.50
Mean Values (Depth 0.5)			**31.5**	**---**	**8.85**	**10.00**

Table 3. Comparison of the probability for successful invasion of waterbodies based on key physical parameters and resistance adaptations to physical factors for zebra (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*) (See Table 1 for toleration of key physical parameters in dreissenid mussels).

		Probability of Successful Colonization		
Physical Factor	**Species**	**Low Probability**	**Moderate Probability**	**High Probability**
Maximum 30-day average summer surface water temperature	Zebra Mussel	>32°C	30-32°C	<30°C
	Quagga Mussel	>28°C	27-28°C	<27°C
Average surface water calcium concentration	Zebra Mussel	<12 mg/L	12-14 mg/L	>14 mg/L
	Quagga Mussel	Calcium Concentration Limits Unknown		
Average surface water pH	Zebra Mussel	<7.0	7.0-7.4	>7.4
	Quagga Mussel	pH Limits Unknown		
Average low oxygen concentration (% of full air O2 Saturation)	Zebra Mussel	<10%	10-25%	>25%
	Quagga Mussel	<10%	10-30%	>30%

Table 4. Risk probabilities for dreissenid mussels to invade and develop sustainably reproducing populations at selected sites in the watersheds of the San Jacinto and Lower Trinity Rivers and Lake Houston. Key: + = high probability, 0 = moderate probability, - = low probability. Assessments not in parentheses are for zebra mussels while those within parenthesis are for quagga mussels.

Site and Location	O_2 Concentration % Air saturation	pH Mean	Ca Mean mg/L	Temperature Summer Surface Water 8/24 and 9/14/2011	Risk Level
EC_NEWPP, COH Intake for NEWPP	34.7-75.5% **+ (+)**	8.0 **+ (+)**	15.77 **+ (+)**	30.1-31.4°C **+ (-)**	**+ (-)**
EC_CWALynch, CWA Canal before Lynchburg Reservoir	76.2-92.5% **+ (+)**	7.5 **+ (+)**	37.8 **+ (+)**	31.6-32.5°C **0 (-)**	**0 (-)**
EC_WestFork, West Fork San Jacinto River near Humble, TX (at US 59)	64.6-117.0% **+ (+)**	8.1 **+ (+)**	23.7 **+ (+)**	31-32°C **+ (-)**	**+ (-)**
SWQM_10896, Trinity River 125 meters upstream of FM 787, near Romayor, Liberty Co., TX	≥50% **+ (+)**	7.6-8.1 **+ (+)**	28-45 **+ (+)**	≤32°C during summer **+ (-)**	**+ (-)**
EC_CWATRPS, CWA Canal near Dayton, TX	80.3-107.6% **+ (+)**	7.8 **+ (+)**	38.8 **+ (+)**	31.7-32.7 **0 (-)**	**0 (-)**
EC_CWAMid , CWA Canal at diversion to Cedar Point Lat. System	65.6-76.4% **+ (+)**	7.5 **+ (+)**	38.7 **+ (+)**	32.4-33.3°C **- (-)**	**- (-)**
EC_TrinCaper, Trinity River at Hwy 105 (5 miles upstream of Capers Ridge diversion point)	84.3-108.5% **+ (+)**	8.2 **+ (+)**	35.68 **+ (+)**	32.2-32.6 **- (-)**	**- (-)**
EC_LuceBayou, Luce Bayou above Lake Houston near Huffman,TX	45.3-108.4% **+ (+)**	7.9 **+ (+)**	12.92 **0 (0)**	31.4-32.6°C **0 (-)**	**0 (-)**
EC_EastFork, Lake Houston west of Magnolia Point, East Fork San Jacinto River/Caney Creek Arm in Houston	117.0-137.9% **+ (+)**	8.8 **+ (+)**	11.56 **- (-)**	34.5-34.9°C **- (-)**	**- (-)**
EC_Lake Houston_B1, Lake Houston near USGS 295554095093401 (Site B, inside solar bees) depth = 0.5 m	120.3-153.6% **+ (+)**	8.8 **+ (+)**	14.0 **+ (+)**	30.9-32.0°C **+ (-)**	**+ (-)**
EC_Lake Houston_B2, Lake Houston near USGS 295826095082200 (Site A, outside solar bees) depth=0.5 m	117.9-153.2% **+ (+)**	8.9 **+ (+)**	Not Available	30.9-32.1°C **+ (-)**	**+ (-)**