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Title:

Zebra Mussels in the Neosho River Basin: Ecology and Economics

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The zebra mussel (*Dreissena polymorpha)* is an invasive freshwater mollusk introduced to North America in 1987. Since that time, its range has rapidly spread south and west across the United States, and its current contiguous range extends to Kansas. Kansas waterways are, therefore, on the forefront of this expansion, and a better understanding of the effects of this invasive species in Kansas waters will aid in the preparation for zebra mussel range expansion. With a goal of gaining a better understanding of the ongoing issues of this invasion into a newly-infested river basin, my research addressed two topics: 1. ecology of zebra mussel dispersal in the Neosho River Basin; and 2. economic implications of this infestation. The ecological aspect of my research consisted of monthly sampling of larval and adult zebra mussel populations from March to November 2011 at sites in the Upper Neosho River Basin in Kansas, as well as examining zebra mussels' utilization of various materials (PVC, concrete, steel, galvanized steel, pressure-treated wood, aluminum, and unionid shell) and effectiveness of the Intersleek® 970 Fluoropolymer foul release coating system. Zebra mussels showed differential colonization of reservoir reaches, with the greatest densities found closest to the reservoir dam. Following discharge from these reservoirs, zebra mussel numbers declined drastically. In downstream rivers, zebra mussel population spikes occurred in waters impounded by lowhead dams. Lastly, zebra mussels differentially colonized various materials, and the foul release coating system reduced their ability to colonize substrates. Assessment of the economic impacts of zebra mussels was conducted via a mailer survey sent to water rights holders in the Neosho and Walnut river basins. I estimate that the annual cost of zebra mussels in 2011 was $374,206 in the Neosho and $11,600 in the smaller Walnut.

Keywords: Zebra Mussel, *Dreissena polymorpha*, Aquatic Nuisance Species, Aquatic Invasive Species, Mollusk, Colonization, Substrate, Foul Release Coating, Management, Biofouling, Infestation, Dam, Lowhead Dam, Reservoir, River, River Basin, Cost, Economic, Mailer Survey, Water Rights, Neosho, Walnut, Kansas

Zebra Mussels in the Neosho River Basin: Ecology and Economics

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PREFACE

My thesis consists of four chapters, each of which is formatted for submission to a specific peer-reviewed journal: Chapter 1, Lowhead Dams Facilitate Downstream March of Zebra Mussels, is formatted for The Canadian Journal of Fisheries and Aquatic Sciences; Chapter 2, Distribution and Density of Zebra Mussels in Four Kansas Reservoirs, is formatted for The Southwestern Naturalist; Chapter 3, Zebra Mussel Colonization of Construction Materials, and Effectiveness of a Flouropolymer Foul Release Coating, is formatted for Transactions of the Kansas Academy of Science; and Chapter 4, Economic Impact of Zebra Mussels in the Neosho and Walnut River Basins, Kansas, is formatted for Transactions of the Kansas Academy of Science.

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Chapter 1

Lowhead Dams Facilitate Downstream March of Zebra Mussels

Abstract: In rivers of the upper Neosho basin, Kansas, USA, lowhead dams are facilitating the downstream dispersal of zebra mussels *(Dreissena polymorpha)*. I quantified densities of planktonic and settled zebra mussels in this recently-invaded river-reservoir system to examine potential effects of lowhead dams on dispersal dynamics of this invasive species. Although populations declined with distance from reservoir sources, densities repeatedly increased at sites inundated by lowhead dams compared to free-flowing areas, resulting in colonization along nearly 200 river-km. The pattern of zebra mussel dispersal in these rivers is best described by the downstream-march model, facilitated by lowhead dams acting as stepping stones. In rivers with lowhead dams, control of zebra mussel metapopulations may not be accomplished solely by limiting source-sink dynamics from upstream infested lakes.

Introduction

The zebra mussel *(Dreissena polymorpha)* is known to disperse from infested lakes and reservoirs into downstream rivers (Horvath et al. 1996). Mackie (1995) proposed that rivers that are slow enough, such as those impounded by reservoirs, could support self-sustaining populations of zebra mussels. Lowhead dams also alter the flow regime of rivers, creating a slowed and more lentic environment (Horvath et al. 1996, Tiemann et al. 2004), which could enable zebra mussels to more easily establish in rivers. However, no published studies have directly examined the role lowhead dams could play in the dispersal dynamics of zebra mussels within a river system. I tested for possible effects of lowhead dams on zebra mussel dispersal along the length of the recently-invaded upper Neosho River basin, Kansas, USA.

The study of zebra mussel dispersal dynamics has historically concentrated on lakes, reservoirs, and large river systems of Europe and the Great Lakes region of North America (Kern et al. 1994, Horvath et al. 1996, Stoeckel et al. 1997); few published studies have addressed this dispersal in North American Midwestern river-reservoir systems, which currently constitute the leading edge of westward expansion of this aquatic invasive species (Mackie 1995, U.S. Geological Survey 2012). Because adults are typically sedentary after settlement, natural dispersal of zebra mussels is largely dependent on the production of larvae (veligers) that are dispersed by currents and that can remain planktonic for up to 4 weeks (Stanczykowska 1977, Sprung 1989). Typically, due to rapid downstream transport in rivers, instream populations of zebra mussels rely on upstream sources of veligers in lakes and reservoirs rather than establishing self-sustaining populations (Mackie 1995, Horvath et al. 1996, Stoeckel et al. 1997).

However, Schneider et al. (1998), Havel et al. (2005), and Johnson et al. (2008) concluded that impoundments could aid dispersal of invasive species, including zebra mussels. The dispersal of zebra mussels from lakes and reservoirs into rivers has been described by three models: the large-river model, which predicts dispersal from reservoirs into rivers >30 m wide but rarely into smaller streams (Strayer 1991); the source-sink model, which predicts dispersal only a short distance downstream, limited by physical trauma to veligers, mortality while transitioning from a planktonic to a benthic lifestyle, and a decline in food sources (Horvath et al. 1996); and the downstream-march model, which predicts dispersal ad infinitum due to instream production of veligers from sequential downstream sources (Horvath et al. 1996).

The upper Neosho River basin in east-central Kansas, USA, includes the Neosho River and its main tributary the Cottonwood (Fig. 1). Marion Reservoir, in the headwaters of the Cottonwood River, has been infested with zebra mussels since 2008, and Council Grove City Lake, in the headwaters of the Neosho River, has been infested since 2010 (Kansas Department of Wildlife, Parks and Tourism 2012). The Cottonwood and Neosho rivers are similar in size, with mean widths <30 m, until their confluence, after which the Neosho has a mean width >30 m (U.S. Geological Survey 2013a). Both rivers are impounded by numerous lowhead dams throughout their length (Tiemann et al. 2004). Given the flow-altering effects of such dams on river systems, I assessed veliger and settled zebra mussel densities at and around four lowhead dams in the upper Neosho basin to test for possible effects of these dams on downstream dispersal of zebra mussels.

Materials and methods

To evaluate the potential role of lowhead dams in dispersal dynamics of zebra mussels, I quantified larval and settled (visible mussels attached to a substrate) zebra mussel densities at 13 sites in the upper Neosho River basin, Kansas (Fig. 1; Table 1). Sample locations included two reservoir outlet sites (MR Outlet and CG Outlet) which were the initial input for zebra mussels into the river systems, four lowhead dam sites (Cedar Point Dam, Cottonwood Falls Dam, Soden's Grove Dam, and Emporia Dam) hypothesized to be accumulating dispersing zebra mussels or harboring reproducing populations, seven control, free-flowing river sites (Cottonwood R. 1–4, Neosho R. 1–2), and the Neosho River downstream from its confluence with the Cottonwood.

Lowhead dam sites were located in the inundated area immediately upstream from each dam. To serve as controls for analysis of potential effects of these dams on zebra mussel abundance, two free-flowing river sites were sampled near each impoundment: one upstream and one downstream, both out of the direct influence of the dam. Free-flowing river sites located between two lowhead dams were used both as a downstream site for the dam immediately upstream and an upstream site for the dam downstream. Reservoir outlet sites were located within the outlet channel of Marion Reservoir and Council Grove Reservoir (Table 1; Fig. 1).

Sampling began once water temperature had reached 10º C (March 24, 2011), the minimum at which zebra mussel reproduction occurs (Stanczykowska 1977), and ended when temperature returned to below 10º C (November 22, 2011). Water temperature was monitored continuously via U.S. Geological Survey water-monitoring station 07182280 (Cottonwood River) and 07182390 (Neosho River), both at Neosho Rapids, Kansas.

Discharge was monitored continuously via USGS water-monitoring station 07179795 (Cottonwood River) and 07179500 (Neosho River) downstream from Marion Reservoir and Council Grove Reservoir, respectively. All sampling was conducted during daylight hours on the 24th of each month ± 5 days, and order of sites sampled each month was haphazard.

Veliger Sampling

To assess veliger densities, I collected plankton samples monthly at all 13 sites via a Wildco® (Yulee, Florida) Wisconsin sampler plankton net with 63-µm mesh and a 127-mm mouth. A General Oceanics, Inc. (Miami, Florida) 2030R mechanical flow meter was affixed into the net mouth to record length of each tow. Three samples were collected from the shoreline at each site each month, using approximately 6-m oblique tows that began at the substrate and ended at the water's surface (Marsden 1992). Each sample was preserved in 70% isopropyl alcohol and transported to the lab for examination. Utilizing a Zeiss cross-polarized light microscope (Oberkochen, Germany), veligers in each sample were identified with guides from Nichols and Black (1994), Johnson (1995), and the U.S. Army Corps of Engineers Environmental Laboratory (2012) and then quantified. Density (concentration) was calculated as the number of veligers per liter (π net mouth radius^2 x length of tow). Mean density of the three tows was calculated for each site each month.

Settled Adult and Juvenile Sampling

I sampled settled juveniles and adults via visual inspection, consisting of examining available substrate at accessible depths (to approximately 2.5 m) for 30 min. at each site each month. All zebra mussels encountered during this search were collected and preserved in 70% isopropyl alcohol and transported to the lab where they were counted.

At each site, I noted the type and size of substrate to which zebra mussels were attached, including concrete dam structure, raw steel, woody debris, and native unionid mussels. Substrate size was classified via a modified Wentworth scale: boulder >256 mm; cobble 64–256 mm; pebble 16–63; gravel 1–15 mm; sand 0.06–1 mm; and silt <0.059 mm (Cummings 1962).

Statistical Analysis

Statistical analyses were conducted using the Statistical Analysis System, version 18.2 (SAS Institute Inc., Cary, North Carolina), and results were considered significant at $\alpha \leq 0.10$ (Dayton 1998). Data were assessed for normality and homogeneity of variance with SAS Graphical Plotting and Univariate procedures, and all data were judged to be normal and homogeneous. I tested variation in larval and settled zebra mussel densities between lowhead dam (treatment) and free-flowing river (control) sites, as well as between outlet sites and initial downstream river sites, with repeated measures analysis of variance (ANOVAR). Dispersal patterns of zebra mussels were examined by graphical analysis and linear regression.

Results

Veligers and settled individuals were detected in all reservoirs and in the rivers connecting them, demonstrating that zebra mussels have dispersed downstream from Marion Reservoir and Council Grove City Lake into the Cottonwood River, Council Grove Reservoir, the Neosho River, and John Redmond Reservoir. Marion Reservoir and Council Grove City Lake appear to be the upstream source populations of zebra mussels for the Cottonwood and Neosho rivers, respectively (Smith and Edds 2012). Veligers and adults were collected up to 189 river-km downstream from the nearest reservoir source (Table 1).

Mean zebra mussel veliger densities were significantly greater at the four lowhead dam sites than at the seven control, free-flowing river sites (ANOVAR $F_{1,7} = 5.71$; $P = 0.05$) Mean veliger densities at dam sites ranged from 0.14/L (SE = 0.07) at Emporia Dam to 0.71/L (SE = 0.24) at Cedar Point Dam, compared to densities at free-flowing sites ranging from 0.03/L (SE = 0.01) at Cottonwood R. 3 and Cottonwood R. 4 to 0.20/L (SE = 0.09) at Cottonwood R. 1 and Cottonwood R. 2 (Table 2).

Although settled individuals showed the same general pattern as veligers, with elevated numbers at lowhead dams (Fig. 2), this pattern was not statistically significant (ANOVAR $F_{1,7} = 0.33$, $P = 0.58$). Mean number of settled individuals at dam sites ranged from 0.0/30-min. search (SE = 0.0) at the Emporia Dam to 10.70/30-min. search (SE = 6.08) at Cedar Point Dam compared to densities at free-flowing river sites from 0.0/30-min. search (SE = 0.0) at five sites to 8.40/30-min. search (SE = 8.14) at Cottonwood R. 1 (Table 2).

Graphical analysis (Fig. 3) illustrates that both veligers and settled zebra mussels exhibited generally higher numbers at each lowhead dam site than at the free-flowing river site immediately upstream, followed by a drop at the next downstream free-flowing river site. Mean veliger densities decreased linearly with distance from source reservoirs (t = 3.36, df = 1, P = 0.09, R^2 = 0.22), from 1.45/L (SE = 0.42) at MR Outlet to 0.03/L (SE = 0.01) at Cottonwood R. 4. Mean number of settled individuals, although showing the same general pattern of decrease downstream, did not demonstrate a significantly linear decline (t = 1.58, df = 1, P = 0.27, R^2 = 0.10). Mean numbers of settled individuals declined from 308.9/30-min. search (SE = 84.50) at MR Outlet to 0.0/30-min. search (SE = 0.0) at seven sites downstream. When analyzed separately, the earlier- and more heavily-infested Cottonwood River (sites MR Outlet – Cottonwood R. 4) showed a stronger linear pattern, both for veligers (t = 4.12, df = 1, P = 0.02, R^2 = 0.54) and settled individuals (t = 2.17, df = 1, P = 0.11, R^2 = 0.32), than the Neosho upstream from the confluence of these two rivers (sites CG Outlet – Neosho R. 2) (veligers t = -1.84, df = 1, P = 0.21, R^2 = 0.44; settled individuals t = -1.03, df = 1, P = 0.38, R^2 = 0.01).

There was no significant difference in zebra mussel densities between Marion Reservoir and Council Grove Reservoir outlet sites and the first sites downstream in the Cottonwood and Neosho rivers, for either veligers ($\bar{x}$ = 0.76/L, SE = 0.30 vs. $\bar{x}$ = 0.19/L, SE = 0.07) (ANOVAR $F_{1,1}$ = 1.61, P = 0.43; Fig. 4) or settled individuals ($\bar{x}$ = 86.22/30-min search, SE = 85.67 vs. $\bar{x}$ = 4.67/30-min. search, SE = 3.30 ($F_{1,1}$ = 1.01, P = 0.50; Fig. 4), indicating that transitioning from outlet channel habitat to free-flowing riverine did not have an effect on zebra mussel population size.

Settled zebra mussels were found in greatest numbers attached to large, stable substrate. Of all settled zebra mussels collected, 97% were attached to substrate >64 mm (58% boulder, 39% cobble). The remaining 3% were found on pebble, gravel, sand, silt, raw steel, concrete, woody debris, and native unionid.

Discharge in the Neosho River at the outlet of Council Grove Reservoir peaked in April and October at 170 m^3/sec and 220 m^3/sec, respectively (U.S. Geological Survey 2013b) (Fig. 5). Veliger densities at sites in the Neosho River (Council Grove Outlet – Neosho R. 2) exhibited peak densities in June and September (Fig. 5). Water temperatures at these sites surpassed 10º C in March, peaking in July at 30º C (Fig. 5). Cottonwood River discharge at the outlet of Marion Reservoir peaked in April at 127 m^3/sec and steadily declined throughout the year (U.S. Geological Survey 2013c) (Fig. 6). Veliger densities at sites in the Cottonwood River (Marion Reservoir Outlet – Cottonwood R. 2) peaked in June, July, and September (Fig. 6). Water temperature in the Cottonwood River surpassed 10º C in March and peaked in July at 32º C (Fig. 6).

Discussion

Riverine areas impounded by lowhead dams exhibited elevated densities of veliger and settled zebra mussels compared to upstream and downstream free-flowing waters, with distinct population spikes noted at each of four dams. This observation is consistent with Mackie's (1995) prediction that if river flow is slowed enough, such as effected by a lowhead dam, veligers can settle and attach, and populations can become self-sustaining. Mackie (1995) maintained that without mainstream reservoirs, zebra mussels would not be the nuisance they are in North American rivers today. The lowhead dams I studied also impounded the mainstream, although on a smaller scale than reservoirs, and their slower waters supported zebra mussel populations that subsidized populations downstream. Thus, I expect that rivers with lowhead dams are more susceptible to zebra mussel dispersal, colonization, and thus the ecological and economic problems that come with their spread.

Mackie (1995) also predicted that the availability of concrete dam structure would promote attachment of individuals and subsequent development of zebra mussel populations. Although the availability of large substrate was extremely important for zebra mussels in the rivers I studied, with 97% of settled individuals being collected from cobble and boulders, I found only 0.02% of the total number of settled individuals in these rivers attached to the concrete dams. Instead, the lowhead dam effect seems to have been mainly a function of the more lake-like environment (e.g. deeper, slower water) behind the dams, which resulted in a buildup of veligers and facilitated settling and instream recruitment.

Lowhead dams have documented effects on the physical habitat of the Neosho River, including deeper, slower water with more cobble and boulder in the inundated area upstream from dams (Tiemann et al. 2004). Those dams negatively affect macroinvertebrate evenness (Tiemann et al. 2004) and % EPT (a biological indicator water quality metric derived as a proportion of collected macroinvertebrates in the orders Ephemeroptera, Plecoptera, and Trichoptera) (Tiemann et al. 2005). Lowhead dams in the Neosho also influence spatial patterns of Neosho River fish assemblages (Gillette et al. 2005) and negatively impact the federally-listed Neosho Madtom (Ictaluridae: *Noturus placidus*) (Tiemann et al. 2004). Dean et al. (2002) demonstrated consequences of

Neosho River lowhead dams on unionid (Unionoida) mussel species richness and evenness. My results illustrating the facilitation of zebra mussel dispersal by lowhead dams in the Neosho basin provide yet another example of the faunal change brought about by these relatively small, instream dams. Synergisms of dams, zebra mussels, and impaired water quality can have far-reaching effects on river systems (Watters and Myers Flaute 2010).

Of the three hypothesized dispersal models (large-river, source-sink, and downstream-march), the best fit for the Neosho River basin is the downstream-march. The large-river model clearly does not apply, given the presence of larval and settled zebra mussels in both the Neosho and Cottonwood rivers upstream from their confluence in waters < 30m wide. The source-sink model predicts that zebra mussels will disperse only short distances downstream, with upstream source populations providing the only input of individuals, and no instream recruitment (Horvath et al. 1996). However, zebra mussels in the Neosho River basin dispersed great distances downstream (nearly 200 river-km) from sources in the infested reservoirs and, given the population spikes at lowhead dams, it appears that local reproduction exceeded mortality. These dams acted as stepping stones that provided habitat suitable for instream recruitment, facilitating sequential colonization of and unrestricted spread into downstream reaches, i.e., the downstream march. Further evidence for applicability of the downstream-march model is the short time (3 years) over which colonization occurred throughout this river system, a result not typically seen in rivers (Horvath et al. 1996). It will be important to continue monitoring zebra mussel dispersal and colonization patterns in the upper Neosho River basin to assess future extent of the invasion and gauge the continued suitability of the downstream-march model for this system.

Horvath et al. (1996) concluded that the best model to describe zebra mussel dispersal in a system of lakes connected by streams in the St. Joseph River basin in Indiana-Michigan, USA, was the source-sink model, wherein mussels did not establish self-sustaining populations and dispersed only short distances (10–12 km) downstream. Even though zebra mussels had been present in that system for at least 3–5 years, adults were found in “appreciable densities” only within 1 km of their source population, declining in density from > $1000/m^2$ to about $10/m^2$, and decreasing exponentially until only isolated mussels were found downstream.

In the upper Neosho River basin, regression analysis showed a linear decline in veliger densities downstream from source reservoirs, a result more consistent with predictions of the downstream-march than the source-sink model of dispersal, in which numbers may decline exponentially (Horvath et al. 1996). The relatively small number of settled zebra mussels downstream, as well as at lowhead dams, could have been due to the short time of infestation in this basin (3 years for the Cottonwood River and 1 year for the Neosho River upstream from their confluence), a hypothesis consistent with the observed more extensive colonization of the Cottonwood River than the Neosho River.

The headwater reservoirs of the upper Neosho River basin (Marion Reservoir and Council Grove City Lake) are providing the initial source of potential colonizers for downstream riverine environments, similar to patterns observed in many river systems (e.g., Bobeldyk et al. 2005). However, in the Neosho basin, as zebra mussels disperse downstream they receive supplemental boosts in numbers in the waters impounded by lowhead dams. Although I have no direct evidence for instream recruitment, the zebra mussels I collected at lowhead dams were of mature size (Delmott 2013). The alternative hypothesis, that veligers are simply accumulating behind the dams, is inconsistent with Tiemann et al.'s (2004) conclusion that water chemistry, turbidity, particulate organic carbon, and chlorophyll *a* were not significantly influenced by lowhead dams in the Neosho River. This suggests that retention time is insufficient for substantial accumulation of plankton behind lowhead dams in this basin, and argues against the hypothesis of zebra mussel larval accumulation and in favor of the instream recruitment of veligers, consistent with predictions of the downstream-march model. Definitive evidence of instream production awaits reproductive studies.

In general, maximum veliger densities, even at the MR Outlet ($\bar{x}$ = 1.45/L, maximum = 2.76/L), were less than those in other rivers. Stoeckel et al. (1997) recorded veliger densities from 0–160/L in seasonal samples at multiple sites in the Illinois River, Illinois, and Kern et al. (1994) noted veliger densities from 0–315/L in the Rhine River, Germany. Keppner et al. (1997) documented veliger densities of 24–53/L in the Niagara River, New York, 0.1–9.7/L in the Ohio River, Kentucky, and 0.05–177/L in the Mississippi River from Iowa to Louisiana, whereas Stoeckel et al. (2004) collected 0.2–340 veligers/L in the upper Mississippi River.

It is likely that the relatively low veliger densities in the upper Neosho River basin, Kansas, were due, at least in part, to a difference in infestation time and size of the source reservoirs and their zebra mussel populations. At sites in the lower reaches of Marion and Council Grove reservoirs, the primary sources for veligers discharged into the Cottonwood and Neosho rivers, respectively, mean monthly veliger densities from

March–November 2011 were 3.95/L (SE = 1.56) in Marion and 0.87/L (SE = 0.30) in Council Grove (Smith and Edds 2012). The earliest detection of zebra mussels in the Neosho River basin occurred 3 years prior to my study. Lake Michigan, the primary source for upper Illinois River zebra mussels studied by Stoeckel et al. (1997), had been infested for 7 years. The Rhine River studied by Kern et al. (1994) had likely been infested for more than 150 years. With time to develop an extensive infestation, zebra mussel densities in the Neosho basin could increase and become more similar to those found in other river systems. However, given the many differences in hydrological variables among systems and the relatively small size of Kansas' contributing source reservoirs (from Council Grove City Lake's 1.75-km^2 to John Redmond Reservoir's 38-km^2), zebra mussel densities in the Neosho basin may never reach those of larger systems.

In addition to the effects of lowhead dams, zebra mussel dispersal in the upper Neosho basin is likely influenced by the rate of discharge from source reservoirs and local water temperatures. Despite relatively high discharge in the Cottonwood River in the spring, 2011 was a drought year in the basin (U.S. Geological Survey 2012), and low discharge may have limited zebra mussel dispersal in these rivers. Veliger abundance was more congruent with temperature than with discharge (Figs. 5–6).

The most suitable model for zebra mussel dispersal in the upper Neosho River basin, Kansas, is the downstream-march model facilitated by lowhead dams acting as stepping stones. Schneider et al. (1998), Havel et al. (2005), and Johnson et al. (2008) showed that artificial impoundments (i.e., dams and reservoirs) act as stepping stones for the proliferation of zebra mussels throughout a river basin. In the upper Neosho River basin, lowhead dams function as stepping stones between reservoirs. Zebra mussel population densities were not significantly different between source reservoir outlets and the first free-flowing river sites downstream, indicating that Neosho basin riverine habitat is suitable for this nuisance species (Whittier 2008). Densities of zebra mussel veligers in these rivers declined linearly with distance from source reservoirs but experienced boosts at each successive lowhead dam. Although densities of settled individuals at lowhead dams were not significantly greater than at free-flowing river sites, likely due to relatively low population densities in source reservoirs plus the short time since colonization of these rivers, graphical analysis showed clear spikes in their numbers at dams. These lowhead dams facilitate the downstream march of zebra mussels in this river system by providing favorable habitat for colonization and instream recruitment, resulting in a riverine metapopulation not solely dependent upon sources of veligers from upstream reservoirs. Thus, in the Neosho basin, and in other situations like it, management and control of zebra mussels in rivers cannot be accomplished solely by limiting source-sink dynamics from upstream lakes or reservoirs.

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Table 1. Distribution of 13 sample sites among three site types for zebra mussel study in the upper Neosho River basin, Kansas, USA, March–November 2011, with names of impoundments on each river, and river-kilometers from source population; see Fig. 1 for orientation of sites. MR = Marion Reservoir, CP = Cedar Point, CF = Cottonwood Falls, SG = Soden's Grove, CG = Council Grove Reservoir.

River	Impoundment	Site Type	Site Name	River-km
Cottonwood	Marion Reservoir	–	–	–
		Outlet	MR Outlet	2.8
		Control	Cottonwood R. 1	24.2
			Cottonwood R. 2	92.2
			Cottonwood R. 3	140.5
			Cottonwood R. 4	199.0
		Dam	CP Dam	50.1
			CF Dam	118.2
			SG Dam	189.5
Neosho	Council Grove City Lake	–	–	
	Council Grove Reservoir	–	–	
		Outlet	CG Outlet	0.9
		Control	Neosho R. 1	42.0
			Neosho R. 2	98.8

	Dam	Emporia Dam	77.8
		Below Confluence	111.9
John Redmond Reservoir	–	–	

Table 2. Zebra mussel mean (SE) number of veligers/L and settled individuals/30-min search at upstream control (free-flowing), dam, and downstream control (free-flowing) sites near four lowhead dams in the upper Neosho River basin, Kansas, March–November 2011.

Dam	Life Stage	Upstream Control	Dam	Downstream Control
Cedar Point Dam				
	Veligers	0.20 (0.09)	0.71 (0.24)	0.21 (0.10)
	Settled	8.40 (8.14)	10.70 (6.08)	0.70 (0.52)
Cottonwood Falls Dam				
	Veligers	0.21 (0.10)	0.45 (0.20)	0.03 (0.01)
	Settled	0.70 (0.52)	2.30 (2.01)	0.00 (0.00)
Soden’s Grove Dam				
	Veligers	0.03 (0.01)	0.21 (0.08)	0.03 (0.01)
	Settled	0.00 (0.00)	0.10 (0.11)	0.00 (0.00)
Emporia Dam				
	Veligers	0.08 (0.05)	0.14 (0.07)	0.04 (0.02)
	Settled	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

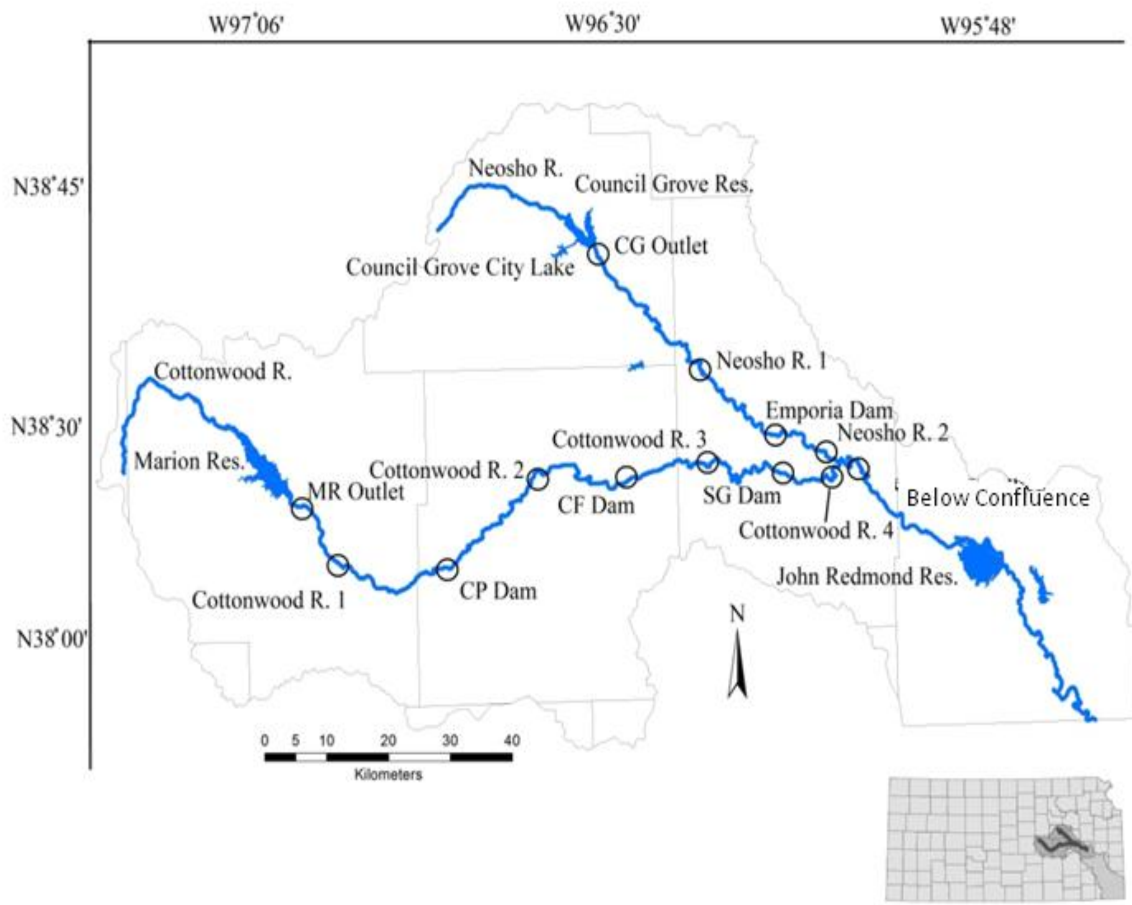


Figure 1. Sample sites for zebra mussel study in the upper Neosho River basin, Kansas, USA (inset), March–November 2011. Site types are summarized in Table 1.

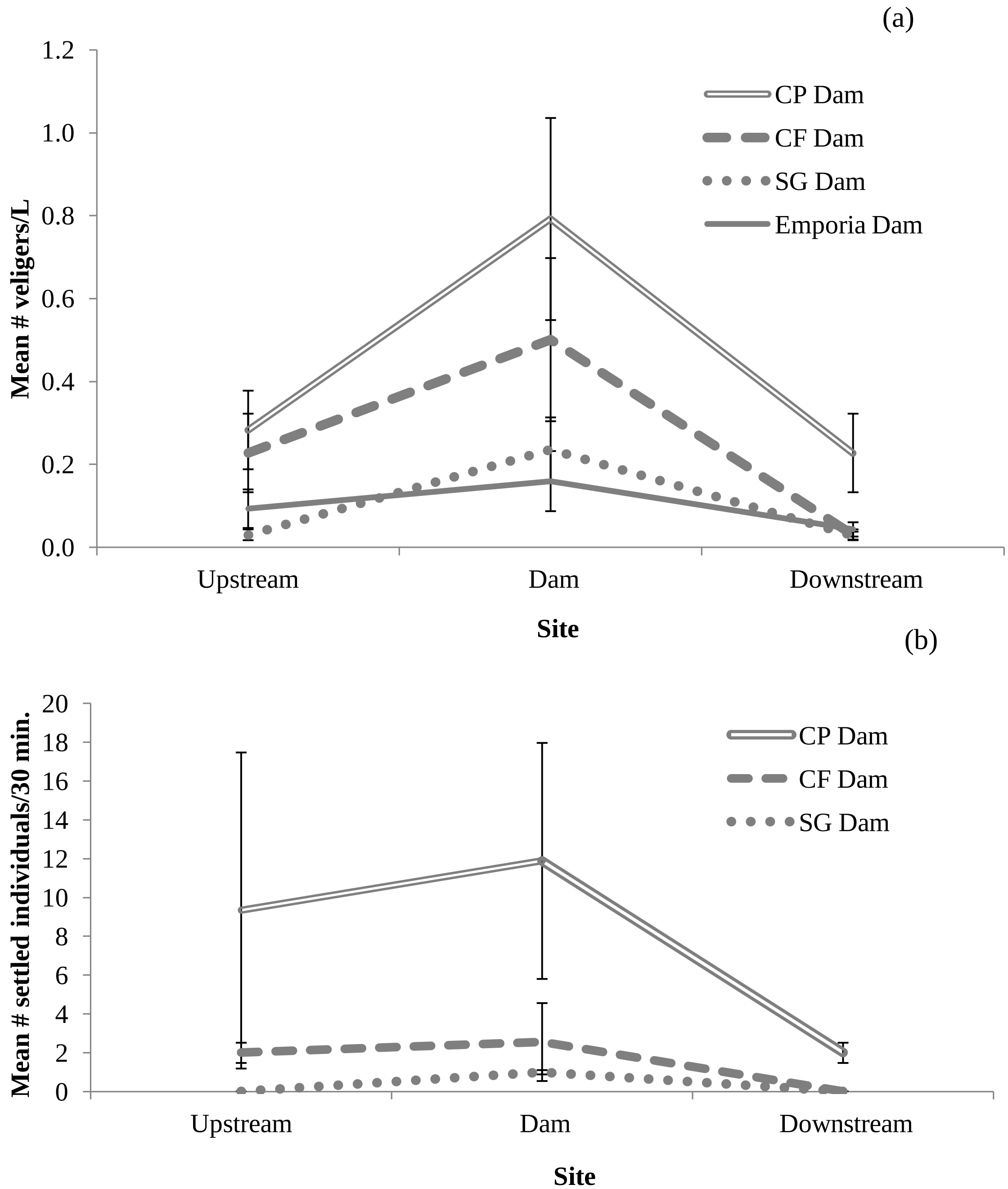


Figure 2. (a) Mean (± SE) number of zebra mussel veligers/L and (b) mean (± SE) number of settled individuals/30-min search at upstream control (free-flowing), dam, and downstream control sites near four lowhead dams in the upper Neosho River basin, Kansas, March–November 2011. See Table 1 for key to site names. No settled individuals were found at the Emporia Dam site.

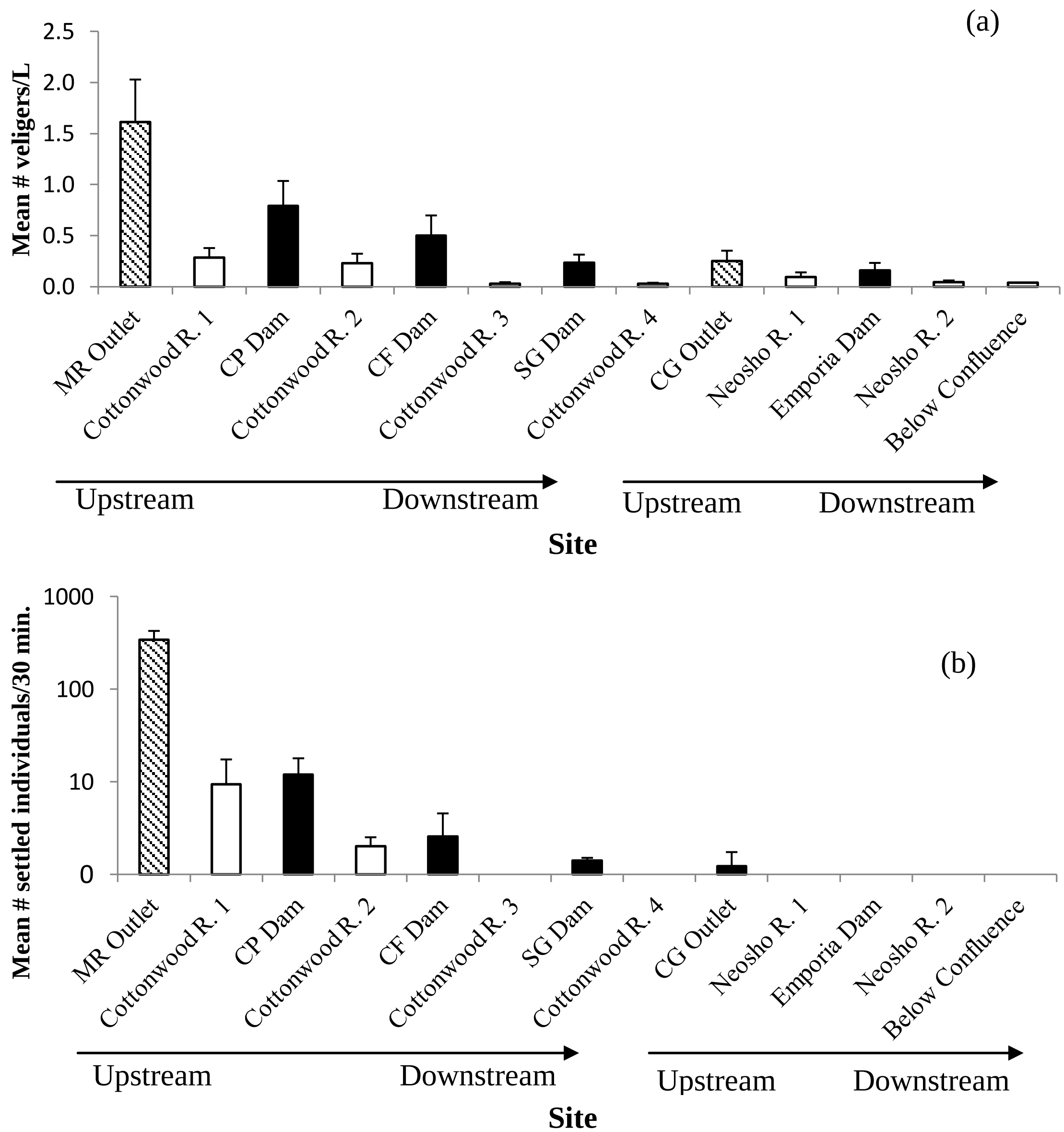


Figure 3. (a) Mean zebra mussel veliger densities and (b) mean number of settled zebra mussels/30-min search (log scale) in the Cottonwood River downstream from Marion Reservoir (sites MR Outlet–Cottonwood R. 4), Neosho River downstream from Council Grove Reservoir (sites CG Outlet–Neosho R. 2), and Neosho River downstream from the confluence of the Cottonwood and Neosho rivers, Kansas, March–November 2011; diagonal bars = outlet sites, open bars = free-flowing river sites, filled bars = lowhead dam sites. Error bars = 1 SE.

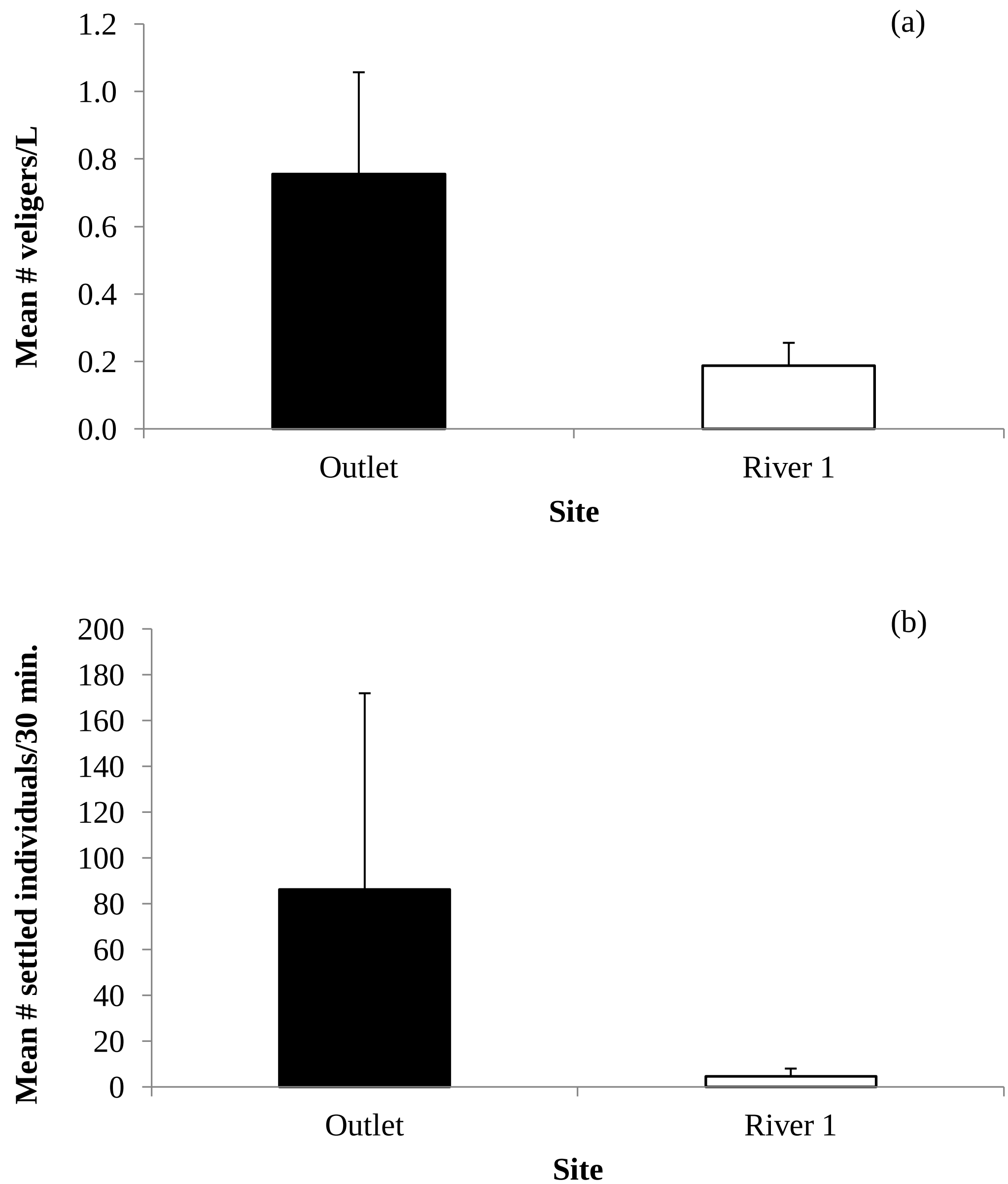


Figure 4. (a) Mean density of zebra mussel veligers and (b) mean number of settled zebra mussels/30-min. search, March–November 2011, at outlets of Marion and Council Grove reservoirs, Kansas, vs. first river site downstream from each in the Cottonwood and Neosho rivers, respectively. Error bars = 1 SE.

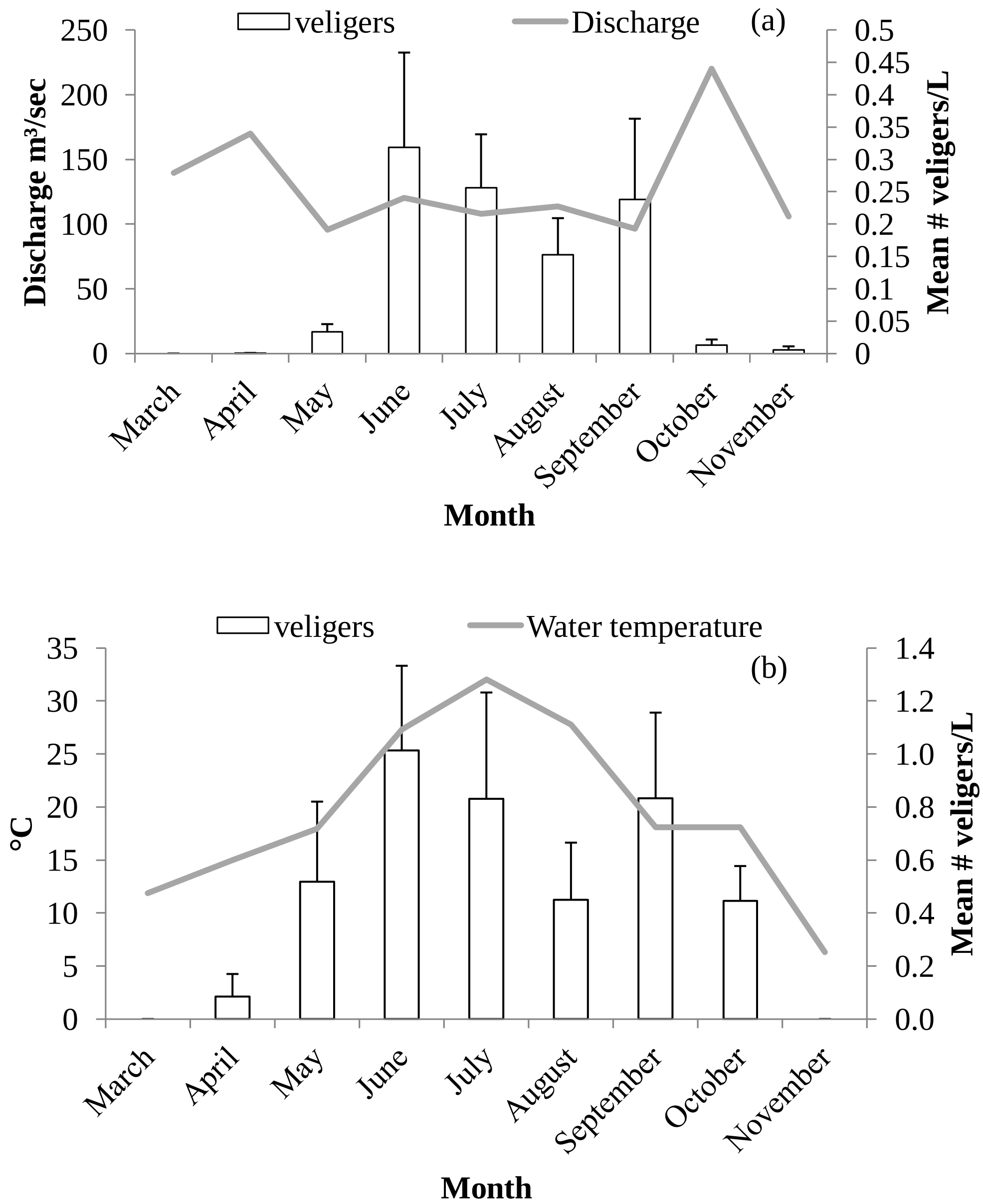
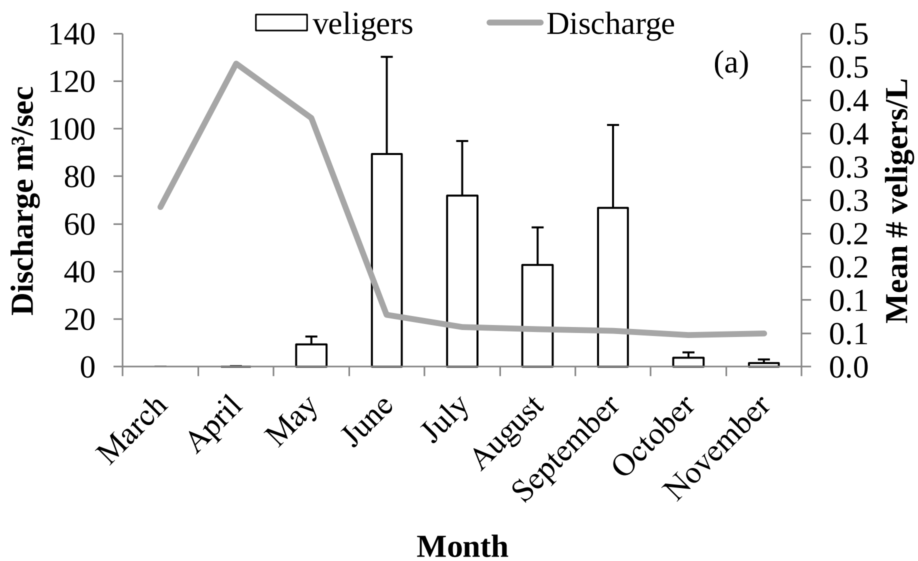


Figure 5. (a) Mean monthly discharge from Council Grove Reservoir and mean zebra mussel veliger density for all months and sites CG Outlet – Neosho R. 2 and (b) mean monthly water temperature and mean veliger density for the Neosho River, Kansas, March–November 2011. Temperature data from U.S. Geological Survey (2013a), and discharge data from U.S. Geological Survey (2013b). Error bars = 1 SE.



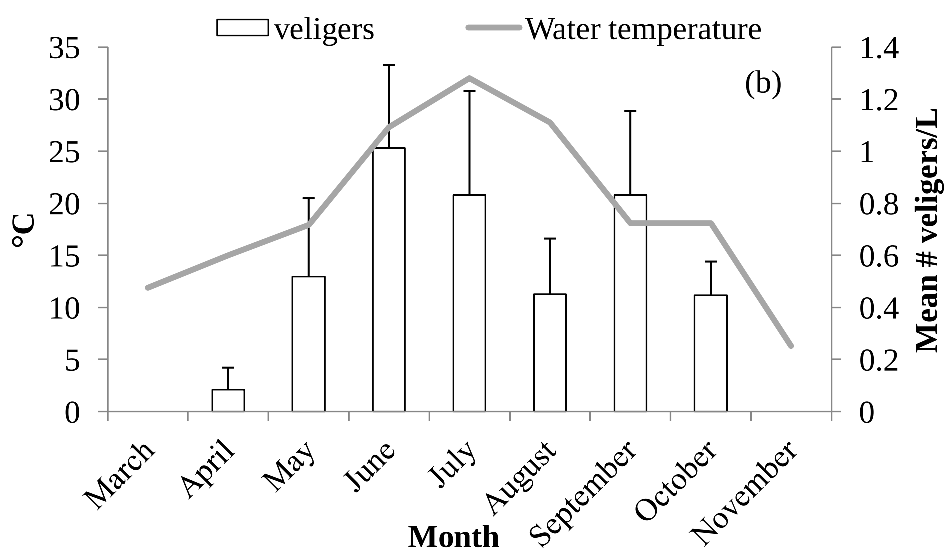


Figure 6. (a) Mean monthly discharge from Marion Reservoir and mean zebra mussel veliger density for all months and sites MR Outlet – Cottonwood R. 4 and (b) mean monthly water temperature and mean veliger density for the Neosho River, Kansas, March–November 2011. Temperature data from U.S. Geological Survey (2013a), and discharge data from U.S. Geological Survey (2013c). Error bars = 1 SE.

Chapter 2

Distribution and Density of Zebra Mussels in Four Kansas Reservoirs

ABSTRACT─I assessed zebra mussel *(Dreissena polymorpha)* distribution and density in four newly-infested manmade reservoirs in the upper Neosho River basin, Kansas, from March-November 2011. Density was estimated via monthly plankton samples to monitor veligers, visual searches to detect settled zebra mussels, and colonization substrates to monitor settling zebra mussels. Upstream infested impoundments were the source of zebra mussels dispersing into downstream impoundments in the basin. Marion Reservoir had greater veliger densities downlake than in its upper region, while veliger densities in the other three reservoirs were not significantly different among lake regions. Pooled data from the four reservoirs showed a pattern of more veligers and adults downlake. Veliger and adult densities were less in the outlet downstream from Marion Reservoir than in the downlake portion of the lake; pooled data from all four reservoirs showed a similar pattern. Greater veliger abundance in the lower region of reservoirs could be due to downlake accumulation resulting from water currents and flow. Increased veliger abundance downlake could lead to greater adult abundance, as could the greater availability of suitable substrate near the dam. Differences among reservoirs could reflect differences in time since infestation, as well as variability in temperature and local physicochemical factors.

The highly invasive zebra mussel *(Dreissena polymorpha)* was introduced to North America in 1987 in Lake St. Clair, in the Great Lakes system (Mackie et al., 1989), and has spread quickly, primarily moved overland by recreational boat traffic that carries adults and microscopic veligers (Padilla et al., 1996; Bossenbroek et al., 2007; Strayer, 2009). The current contiguous range of zebra mussels encompasses a large portion of the eastern and central United States. They have spread from their initial point of introduction in the Great Lakes as far south as Louisiana and reach the most westward point of their contiguous range in Kansas (United States Geological Survey, http://nas.er.usgs.gov/). Zebra mussels were first documented in Kansas in 2003, and have since been detected in many reservoirs and rivers in the state, including in the Neosho basin (Kansas Department of Wildlife, Parks and Tourism, http://www.kdwpt. state.ks.us.

Planktonic veligers, which are moved by currents and wave action, are the natural means of dispersal for zebra mussels (Stoeckel et al., 1997; Fahnenstiel et al., 1999; Rehmann et al., 2003). Veligers remain suspended in the water column until they mature (8-35 days), after which they settle-out and attach to a suitably stable substrate (Horvath et al., 1996; Horvath and Lamberti, 1999*a*; Horvath et al., 1999). As the range of zebra mussels has spread, their biological and economic burden has increased, and will continue to do so as they are introduced farther into western North America (Pimentel et al., 2005). Zebra mussels decrease phytoplankton populations, and thus actively compete with native mussels and game fishes (MacIssac, 1996; Schloesser et al., 1996). They also commonly occlude intake pipes of water treatment and electrical generation facilities, thereby increasing expenses (Pimentel et al., 2005). These effects are estimated to cost more than $100 million annually in North America (Strayer, 2009).

As zebra mussels expand their range, studying their distribution and density within and comparing among reservoirs, as well as in rivers upstream and downstream, will increase our understanding of their ecology, and aid our ability to manage them in previously uninfested waters. Reservoirs can act as stepping-stones that facilitate the spread of zebra mussels across the landscape (Schneider et al., 1998; MacIsaac et al., 2004; Havel et al., 2005). A systematic comparison of longitudinal reaches in the newly-invaded, calcium-rich manmade reservoirs of the Midwest has yet to be conducted, even though reservoirs are quite susceptible to invasive species (Havel et al., 2005). I studied density and distribution of adult and juvenile zebra mussels in four reservoirs in the upper Neosho basin in eastern Kansas. Given the potential for accumulation of larval zebra mussels behind the dam due to downlake flow and wind-generated currents (George and Edwards, 1976), I predicted that the greatest density of veligers would be found in the downlake portion of these reservoirs. With downlake accumulation of larvae and the abundance of large, stable substrate conducive to zebra mussel colonization and growth (Marsden and Lansky, 2000), I predicted that settled individuals would also be more abundant in this region. I also predicted that no zebra mussels would be found upstream from headwater reservoirs in the basin, and that densities of both life stages would decrease in the outlet channel downstream from the dam.

Study area —The upper Neosho River basin includes four reservoirs infested with zebra mussels (Marion Reservoir, Council Grove City Lake, Council Grove Reservoir, and John Redmond Reservoir) and two infested rivers (the Cottonwood and Neosho) (Kansas Department of Wildlife, Parks and Tourism, http://kdwpt.state.ks.us/) (Fig. 1). The initial introduction of zebra mussels in the Neosho basin occurred in Marion Reservoir and was confirmed in 2008 (Kansas Department of Wildlife Parks and Tourism, http://kdwpt.state.ks.us/). Marion Reservoir is a 25-km^2 impoundment constructed on the headwaters of the Cottonwood River in 1968 (United States Army Corps of Engineers, http://corpslakes.usace.army.mil/visitors/states.cfm?state=KS). Zebra mussels were detected in Council Grove City Lake in 2010 (Kansas Department of Wildlife, Parks and Tourism, http://kdwpt.state.ks.us/). This lake is a 1.75-km^2 water source for the city of Council Grove constructed on a tributary (Canning Creek) of the Neosho River in 1942. Council Grove Reservoir is a 13.4-km^2 impoundment of the Neosho River constructed in 1964. It was declared infested with zebra mussels in 2011 (Kansas Department of Wildlife, Parks and Tourism, http://kdwpt.state.ks.us/). The Neosho River continues downstream, is joined by the Cottonwood, and is impounded in John Redmond Reservoir, a 38-km^2 flood control lake constructed in 1964. The presence of zebra mussels was confirmed in John Redmond Reservoir in 2010 (Kansas Department of Wildlife, Parks and Tourism, http://kdwpt.state.ks.us/).

MATERIALS AND METHODS—I sampled each of these reservoirs monthly during the typical zebra mussel reproductive season (March-November) in 2011. Each reservoir was sampled in three sections: upper, middle, and lower; the upper section was located closest to the inlet and the lower section was located closest to the outlet. Upper sites were typically shallow (less than 2 m deep), and generally lacked substrate larger than silt or sand. Middle sites were generally slightly deeper than upper sites, with a substrate ranging from sand to cobble. Lower sites were typically deepest (2+ m), with cobble and boulder commonly available. Additionally, for each reservoir, a site in the river upstream (inlet) and a site in the outlet channel were sampled to search for zebra mussels, giving a total of 20 sites examined monthly.

I sampled zebra mussel veligers (in all stages of development) plus juveniles and adults (in all stages of development, collectively termed “settled individuals” given that I did not determine their sexual maturity). Sampling began when water temperatures reached 10ºC, the approximate water temperature believed to trigger zebra mussel reproduction (Stanczykowska, 1977; Fong et al., 1995). Water temperatures were monitored via United States Geological Survey (USGS) water monitoring station 07182280 on the Neosho River at Neosho Rapids, Kansas, and USGS station 07182390 on the Cottonwood River at Neosho Rapids, Kansas; they both reached 10ºC on March 24. Sampling concluded when water temperatures returned to less than 10ºC; this occurred on November 22. All sampling was conducted on the 24th of each month ± 5 days, and the order of sites sampled each month was haphazard. Local surface water temperature was measured with an alcohol thermometer at the time of sampling. Reservoir discharge and elevation were obtained from the USGS (2013) National Water Information System, http://www.usgs.gov/water/.

Veliger sampling ─I used a student plankton net with 63-µm mesh and a 127-mm mouth (Wildco®, Yulee, Florida) to sample veligers. Shoreline oblique tows (Marsden, 1992) were pulled to collect samples; tows began at the substrate and ended at the water’s surface. Post-hoc analysis showed no difference between densities calculated from shoreline oblique tows and vertical tows taken by Kansas Department of Wildlife, Parks and Tourism personnel from a boat in the offshore pelagic zone (N. S. Holoubek, Emporia State University, pers. comm.). A mechanical flow meter (model 2030R, General Oceanics, Inc., Miami, Florida) was affixed into the mouth of the net to calculate the volume of water sampled. Each tow was approximately 6 m long, but actual distance was measured by the flow meter.

I collected three samples monthly at each site. Following each tow, I washed the inside of the net with veliger-free tap water and preserved the entire sample in 70% isopropyl alcohol. After all three veliger samples had been collected at a site, I washed the inside of the net with tap water and preserved that in a sample jar to allow assessment of whether or not the washing process had removed all veligers. If large numbers of veligers had been found in this rinse sample (i.e., greater than 10% of the mean number of veligers found in the three samples), then calculated veliger densities could have been adjusted to account for veligers not completely removed in the washing process; however, this was not necessary because subsequent examination of these samples detected only a small number of veligers (maximum of 7% of the mean).

After sampling each site, I soaked the net in 99% isopropyl alcohol for at least 10 minutes to prevent contamination among sites. Samples were transported to the laboratory for examination under a Zeiss cross-polarized light microscope at 25, 100, and 400X. I identified veligers with guides from Nichols and Black (1994), Johnson (1995), and the United States Army Corps of Engineers Environmental Laboratory (http://el.erdc.usace.army.mil/zebra/zmis/zmishelp/veliger_analysis_ techniques.htm) and then quantified all samples without subsampling. I calculated density (concentration) as the number of veligers per liter of water sampled.

Juvenile and adult sampling ─I sampled juveniles and adults via visual inspection at each site and with colonization units. Visual inspection consisted of 30 min of examining available substrate in accessible depths (< approximately 2.5 m). All zebra mussels encountered during the timed search were collected, preserved in 70% isopropyl alcohol, and transported to the lab, where they were counted.

Colonization units consisted of a two-holed concrete block, 40 x 20 x 20 cm, with 0.5 cm holes drilled through its wall to attach a 10 x 10 x 0.16 cm, grey PVC plate secured by white plastic zip ties to the inside. Two colonization units were placed at each site in April, submerged to approximately 1 m depth, and tethered with a galvanized steel cable to a point onshore. To evaluate colonization, I examined one unit at each site in July and the other in November by removing the PVC plate and counting visible zebra mussels attached to the exposed face.

Statistical analysis ─I conducted statistical analyses with the *Statistical Analysis System*, version 18.2 (SAS Institute Inc., Cary, North Carolina), and considered results significant at $\alpha \leq 0.10$ (Dayton, 1998). I assessed normality and homogeneity of variance with SAS' Graphical Plotting and Univariate procedures, and judged all data to be normal and homogeneous. I tested hypotheses regarding variation in zebra mussel densities among site types (upper, middle, and lower) with repeated measures analysis of variance

(ANOVAR), followed by Tukey's multiple comparisons test where appropriate, both for veligers and settled individuals.

RESULTS─No veligers, settled individuals, or artificial substrate colonizers were found upstream from Marion Reservoir (Cottonwood River). Veligers were detected at the inlet site of Council Grove City Lake (Neosho River), approximately 500 m upstream from the lake, in July (mean = 0.47 veligers L^{-1}, *SE* = 0.06) and August (mean = 0.25 veligers L^{-1}, *SE* = 0.10). Zebra mussels were not detected at any other time with any other method.

Among all sites and reservoirs, zebra mussel veliger densities increased throughout the reproductive season (Figs. 2-6). Mean veliger densities in reservoirs ranged from 0.17 L^{-1} (*SE* = 0.11) in the upper section of Council Grove Reservoir to 3.95 L^{-1} (*SE* = 1.56) in the lower section of Marion Reservoir (Table 1). Mean number of settled individuals per 30-min search ranged from 0.10 (*SE* = 0.11) in the upper section of Council Grove Reservoir and John Redmond Reservoir to 652.70 (*SE* = 113.25) in the lower section of Marion Reservoir (Table 1). Mean density of settled individuals on colonization units ranged from 0.0 m^{-2} (SE=0.0) at all sites in John Redmond Reservoir, Council Grove Reservoir, and the upper sites at Marion Reservoir and Council Grove City Lake to 37,500 m^{-2} (*SE* = 16,201.9) in the lower section of Council Grove City Lake (Table 1).

Only Marion Reservoir exhibited statistically different veliger densities among upper, middle, and lower sections (ANOVAR $F_{2,6} = 6.01$, $P = 0.07$; Fig. 2). Council Grove City Lake (ANOVAR $F_{2,6} = 6.89$, $P = 0.14$; Fig. 3), Council Grove Reservoir

(ANOVAR $F_{2,6}$ = 6.24, P = 0.11; Fig. 4), and John Redmond Reservoir (ANOVAR $F_{2,6}$ = 6.35, P = 0.22; Fig. 5) did not. Tukey's test differentiated Marion Reservoir upper vs. lower sections, but grouped the middle section with the other two. Pooled data for all four reservoirs showed statistically different veliger densities among upper, middle, and lower sections (ANOVAR $F_{2,6}$ = 6.27, P = 0.03; Fig. 6). Tukey's test differentiated upper vs. lower sections, but grouped middle with the other two sections.

None of the reservoirs showed statistically different numbers of settled individuals found during the 30-min search among upper, middle, and lower sections (Marion Reservoir ANOVAR $F_{2,6}$ = 3.66, P = 0.13, Fig. 2; Council Grove City Lake ANOVAR $F_{2,6}$ = 3.42, P = 0.33, Fig. 3; Council Grove Reservoir ANOVAR $F_{2,6}$ = 4.02, P = 0.12, Fig. 4; John Redmond Reservoir ANOVAR $F_{2,6}$ = 4.53, P = 0.16, Fig. 5). However, pooled data from all four reservoirs did suggest a significant difference ($F_{2,6}$ = 3.54, P= 0.097; Fig. 6). Tukey's test differentiated upper vs. lower sections, but grouped the middle section with the other two.

No reservoirs exhibited statistically different densities of zebra mussels settled on artificial substrates among upper, middle, and lower sections (Marion Reservoir ANOVAR $F_{2,6}$ = 1.24, P = 0.11, Fig. 2; Council Grove City Lake ANOVAR $F_{2,6}$ = 0.94, P = 0.43, Fig. 3; while Council Grove Reservoir and John Redmond Reservoir exhibited no colonization at all. Figs. 4 and 5). Pooled data also indicated no difference ($F_{2,6}$ = 1.03, P = 0.44; Fig. 6).

Significantly fewer veligers were detected in the Marion Reservoir outlet channel than in its lower region (ANOVAR $F_{1,3}$ = 16.05, P = 0.098; Fig. 2), but this was not the case at Council Grove City Lake (ANOVAR $F_{1,3}$ = 11.47, P = 0.12; Fig. 3), Council

Grove Reservoir (ANOVAR $F_{1,3}$ = 14.02, P = 0.34; Fig. 4), or John Redmond Reservoir (ANOVAR $F_{1,3}$ = 12.43, P = 0.18; Fig. 5). Pooled data for all four reservoirs showed significantly fewer veligers at the outlet sites (mean = 0.76 L^{-1}, SE = 0.30) than in the lower section of these reservoirs (mean = 2.52 L^{-1}, SE = 0.72) (ANOVAR $F_{1,3}$ = 16.56, P = 0.03; Fig. 6).

The number of settled individuals per 30-min search was less in the outlet channel than in the lower section of Marion Reservoir (ANOVAR $F_{1,3}$ = 7.01, P = 0.09; Fig. 2), but not in the other three reservoirs (Council Grove City Lake ANOVAR $F_{1,3}$ = 6.66, P = 0.14, Fig. 3; Council Grove Reservoir ANOVAR $F_{1,3}$ = 4.89, P = 0.12, Fig. 4; John Redmond Reservoir ANOVAR $F_{1,3}$ = 5.43, P = 0.19, Fig. 5). Pooled data showed significantly fewer individuals at outlet sites (mean = 86.2, SE = 85.67) than in lower sections of the reservoirs (mean = 296.8, SE = 157.71) (ANOVAR $F_{1,3}$ = 5.72, P = 0.097; Fig. 6). Colonization of PVC substrates at reservoir outlet sites was not significantly different from that in the lower section of any reservoir (Marion Reservoir ANOVAR $F_{2,6}$ = 2.01, P = 0.11, Fig. 2; Council Grove City Lake ANOVAR $F_{2,6}$ = 1.20, P = 0.22, Fig. 3; While Council Grove Reservoir, Fig. 4; and John Redmond Reservoir , Fig. 5 exibited no colonization at either site, nor was pooled data from all four reservoirs (ANOVAR $F_{1,3}$ = 1.27, P = 0.34) (Fig. 6).

DISCUSSION—It is important to note that this study was conducted during a single, particularly hot and dry year when reservoir inflow, elevation, and discharge were low (Fig. 7). Low reservoir elevation could have decreased zebra mussel densities due to adult mortalities, and low discharge could have limited the number of zebra mussels dispersing from these reservoirs. Nonetheless, veliger densities appeared to be more congruent with temperature than with discharge or elevation (Figs. 2-5; 7).

Although a small number of veligers were detected in Council Grove City Lake's inlet creek, those were likely spread the short distance upstream from the infested lake by wind and waves that are known to transport plankton (George and Edwards, 1976; Verhagen, 1994; Rehman et al., 2003). No other zebra mussels were detected upstream from Council Grove City Lake or Marion Reservoir; thus, I conclude that those lakes hold the upstream source populations for the Neosho basin.

Within each reservoir, zebra mussel veligers showed pulses in density: Marion in May, July, and September; Council Grove City Lake in June, July, and September; Council Grove Reservoir in May, June, July, and September; and John Redmond Reservoir in April, May, and June. These pulses could be the result of site-specific variation in temperature or other local physicochemical properties of the water, which are known to affect the zebra mussel reproductive cycle and vary widely among populations (Nichols, 1996).

Differences among reservoirs could be due to difference in time since infestation. Pooled data from the four reservoirs, as well as the overall patterns displayed in Table 1, suggest that zebra mussel veliger densities and the number of settled individuals were greatest in the lower section and least in the upper section. Individually, however, only Marion Reservoir exhibited this pattern, and only for veligers. Marion had been infested longer than the other reservoirs (3 years), so perhaps this pattern is most fully expressed in older, more established populations. It is also possible that the relatively short time available for colonization explains the lack of statistical significance in settled individuals and colonizers.

In addition to the potential for accumulation of zebra mussel veligers as a result of downlake flow of water, the apparent greater densities in lower reservoir reaches could be because zebra mussel introductions likely often occur near boat ramps and marinas (Padilla et al., 1996), which were more abundant in the lower section of the reservoirs in this study. If these areas were indeed the point of introduction, they would have had the longest time for population growth. Greater zebra mussel abundance in the downlake portion of reservoirs could also be due to the abundance of suitable substrate near the dam. Substrate in upstream portions of these reservoirs is composed mainly of silt and clay, which suffocates settling larvae (Hunter and Bailey, 1992), whereas lower portions have larger substrate, including cobble and boulder, plus riprap on the dam, which provides excellent habitat for settling zebra mussels (Hunter and Bailey, 1992).

Fewer zebra mussels of both life stages were detected in the outlet channel than in the lower reach of Marion Reservoir; this was also true for the pooled data, but not for the other three reservoirs. It is likely that zebra mussel populations have yet to fully establish in the lower reaches of these other lakes to an extent sufficient to demonstrate a statistical difference between these two site types (Table 1). This decrease in the outlet channels is likely due to the trauma experienced while passing through the outlet, which can damage veligers (Horvath and Lamberti, 1999*a*). Additionally, the dramatically more lotic environment may sweep dispersing veligers downstream before they have a chance to settle on the ample structure of riprap and concrete at the outlet sites; velocities greater than 1 m sec^{-1} limit zebra mussel settlement (Orlova, 2010).

Maximum veliger densities in these four reservoirs were less than those found in other studies (Horvath and Lamberti 1999*b*, Severson 2007). Precision of my monthly veliger density estimates is demonstrated by concurrence with samples taken in Marion Reservoir by Kansas Department of Wildlife, Parks and Tourism personnel (N. S. Holoubek, Emporia State University, pers. comm.). Horvath and Lamberti (1999*b*) found zebra mussel veliger densities in Christiana Lake, Michigan (ca. 50 km from Lake Michigan), 110 L^{-1}, with means ranging from 26.9 (SE = 12.4) to 59.4 (SE = 28.6). Severson (2007) examined veliger densities in El Dorado Reservoir, a shallow manmade reservoir in south-central Kansas where, in July 2006, veliger densities peaked at 118 veligers L^{-1}. This could indicate that the four reservoirs I studied have not reached peak veliger densities.

Knowledge of areas of lesser or greater densities is important to informing monitoring efforts directed at detecting new infestations of zebra mussels. Chances of detecting zebra mussels at initial low densities would be increased if samples were taken in areas of likely introduction and, thus, greater density, such as near marinas and boat ramps, and in the lower portion of reservoirs. For this overall pattern of longitudinal variation to be exhibited, it may be that zebra mussel populations must be fully established, which can take several years following infestation. Zebra mussel populations will also decrease after transitioning from the lentic lower reaches of the reservoir to the lotic outlet channels. Additionally, populations are likely to vary throughout the year, largely dependent upon the local water temperature, which is known to trigger reproductive processes (Fong et al., 1995); however, this variation should occur within the framework of longitudinal increase, with the highest densities found in the lower reaches of reservoirs.

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Table 1─Zebra mussel mean (*SE*) number of veligers L^{-1}, number of settled individuals 30-min $search^{-1}$, and number of colonizers m^{-2} on PVC substrate in inlet, upper, middle, lower, and outlet sections of four reservoirs in the upper Neosho River basin, Kansas, March-November 2011.

Reservoir	Zebra Mussel	Inlet	Upper	Middle	Lower	Outlet
Marion Reservoir						
	Veligers	0 (0.0)	1.03 (0.73)	2.24 (0.84)	3.95 (1.56)	1.45 (0.42)
	30-minute search	0 (0.0)	8.89 (5.52)	130.60 (34.55)	652.70 (113.25)	308.90 (84.50)
	Colonization units	0 (0.0)	0 (0.0)	1600 (711.8)	3700 (1613.0)	0.50 (0.50)
Council Grove City Lake						
	Veligers	0.07 (0.06)	1.33 (0.68)	1.29 (0.54)	1.76 (1.00)	0.39 (0.20)
	30-minute search	0 (0.0)	0.40 (0.34)	77.70 (27.30)	301.40 (84.92)	0 (0.0)
	Colonization units	0 (0.0)	0 (0.0)	6150 (3091.1)	37500 (16201.9)	0 (0.0)
Council Grove Reservoir						
	Veligers	0 (0.0)	0.17 (0.11)	0.46 (0.15)	0.87 (0.30)	0.23 (0.10)
	30-minute search	0 (0.0)	0.10 (0.11)	16.10 (17.27)	86.20 (36.16)	1.10 (0.52)

	Colonization units	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
John Redmond Reservoir						
	Veligers	0 (0.0)	0.86 (0.58)	1.10 (0.57)	2.48 (0.93)	0.44 (0.13)
	30-minute search	0 (0.0)	0.10 (0.11)	5.40 (2.01)	20.00 (4.93)	0.40 (0.24)
	Colonization units	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)

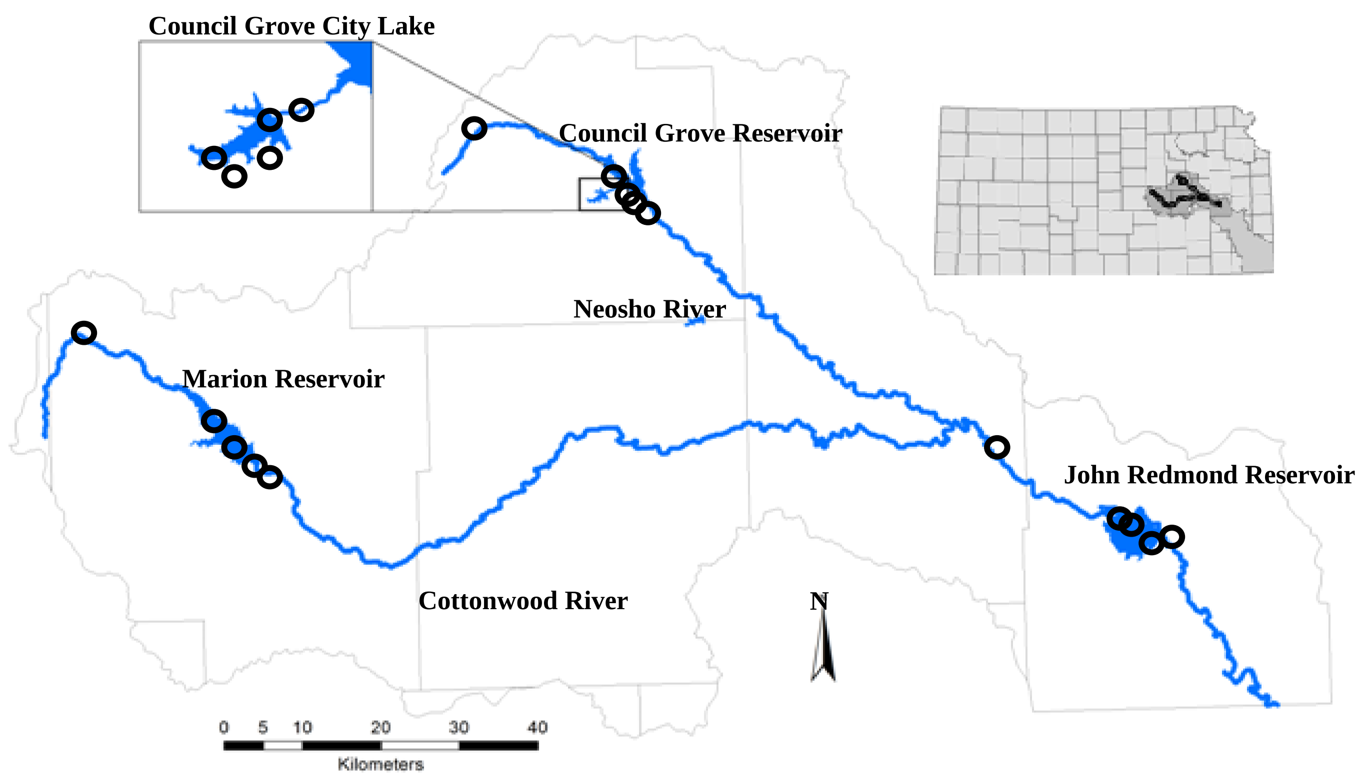
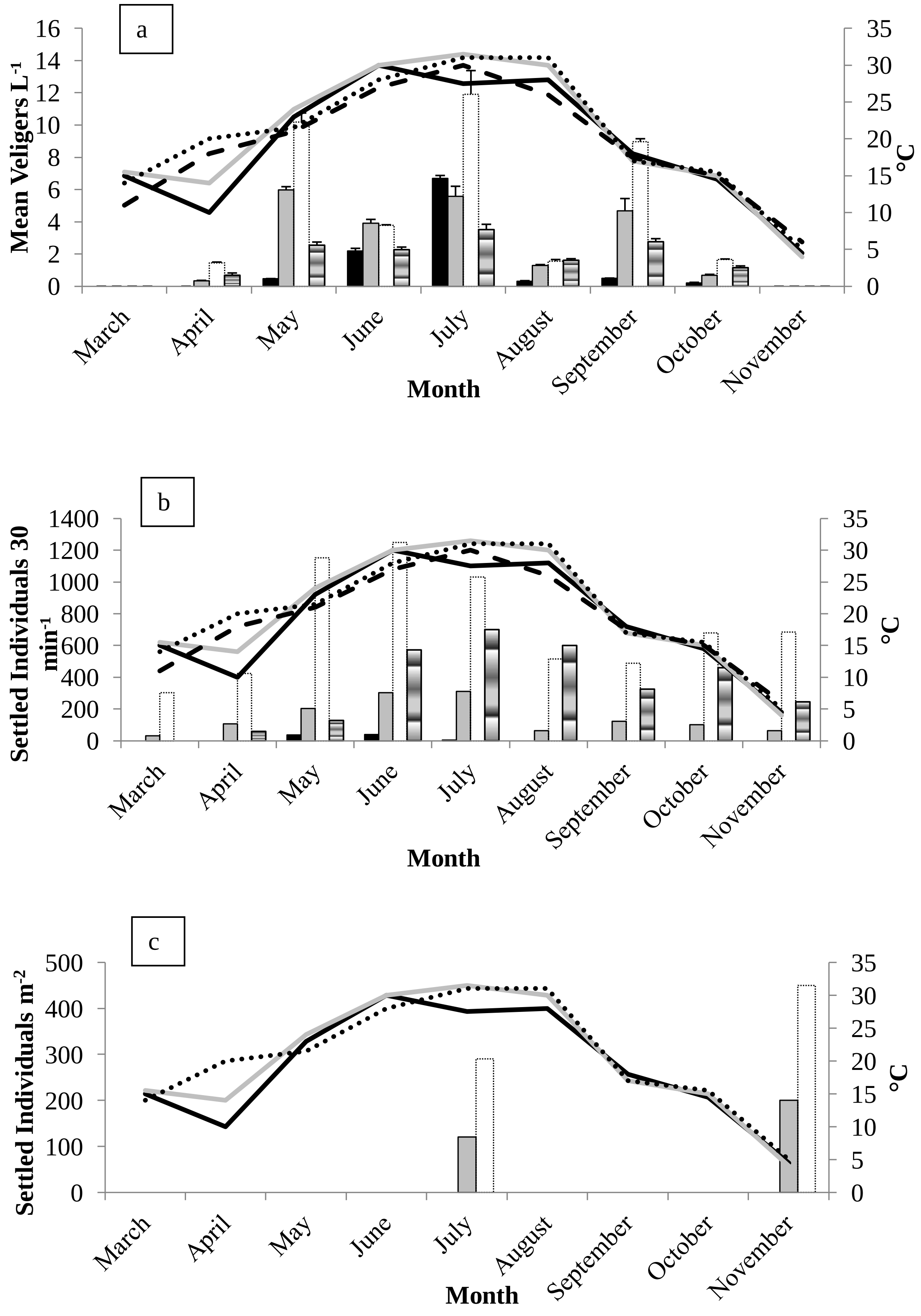


Fig. 1—Twenty sample sites for zebra mussel survey in the upper Neosho River basin, Kansas, March-November 2011. Location of the basin in Kansas is shown in inset.

Marion Reservoir

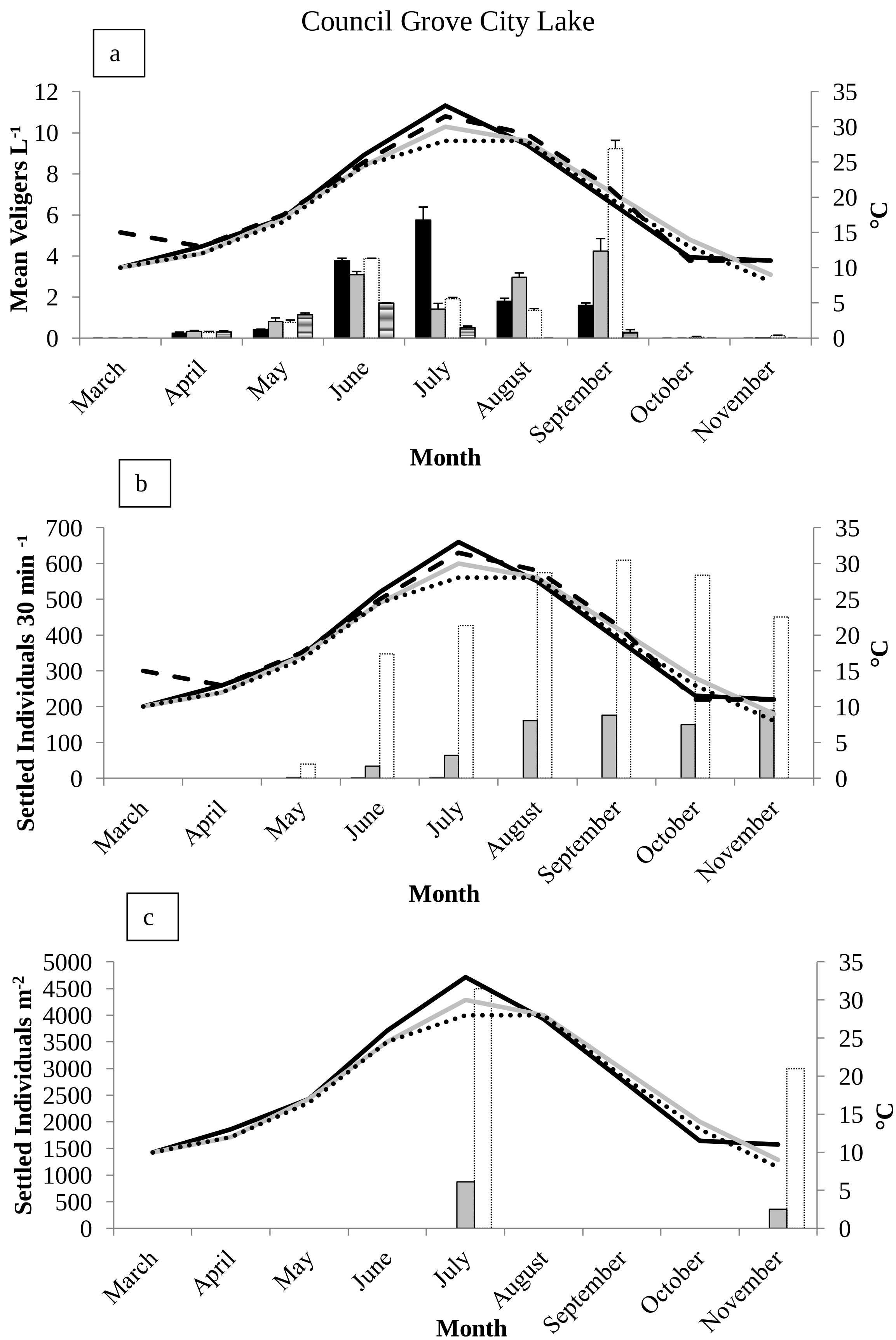


= Upper, = Middle, = Lower, = Outlet

= Upper Water Temp., = Middle Water Temp., = Lower Water Temp.,

----- = Outlet Water Temp.

Fig. 2—(a) Mean density of zebra mussel veligers (number L^{-1}), (b) number of settled zebra mussels 30-min $search^{-1}$, and (c) number of settled individuals m^{-2} on PVC substrate, with local water temperature, March-November 2011, in upper, middle, lower, and outlet sections of Marion Reservoir, Kansas. Error bars = 1 SE.



Council Grove City Lake
a
Mean Veligers L-1
°C
March
April
May
June
July
August
September
October
November
Month
b
Settled Individuals 30 min -1
°C
Month
c
Settled Individuals m-2
°C
Month

= Upper, = Middle, = Lower, = Outlet

= Upper Water Temp., = Middle Water Temp., = Lower Water Temp.,

----- = Outlet Water Temp.

Fig. 3—(a) Mean density of zebra mussel veligers (number L^{-1}), (b) number of settled zebra mussels 30-min $search^{-1}$, and (c) number of settled individuals m^{-2} on PVC substrate, with local water temperature, March-November 2011, in upper, middle, lower, and outlet sections of Council Grove City Lake, Kansas. Error bars = 1 *SE*.

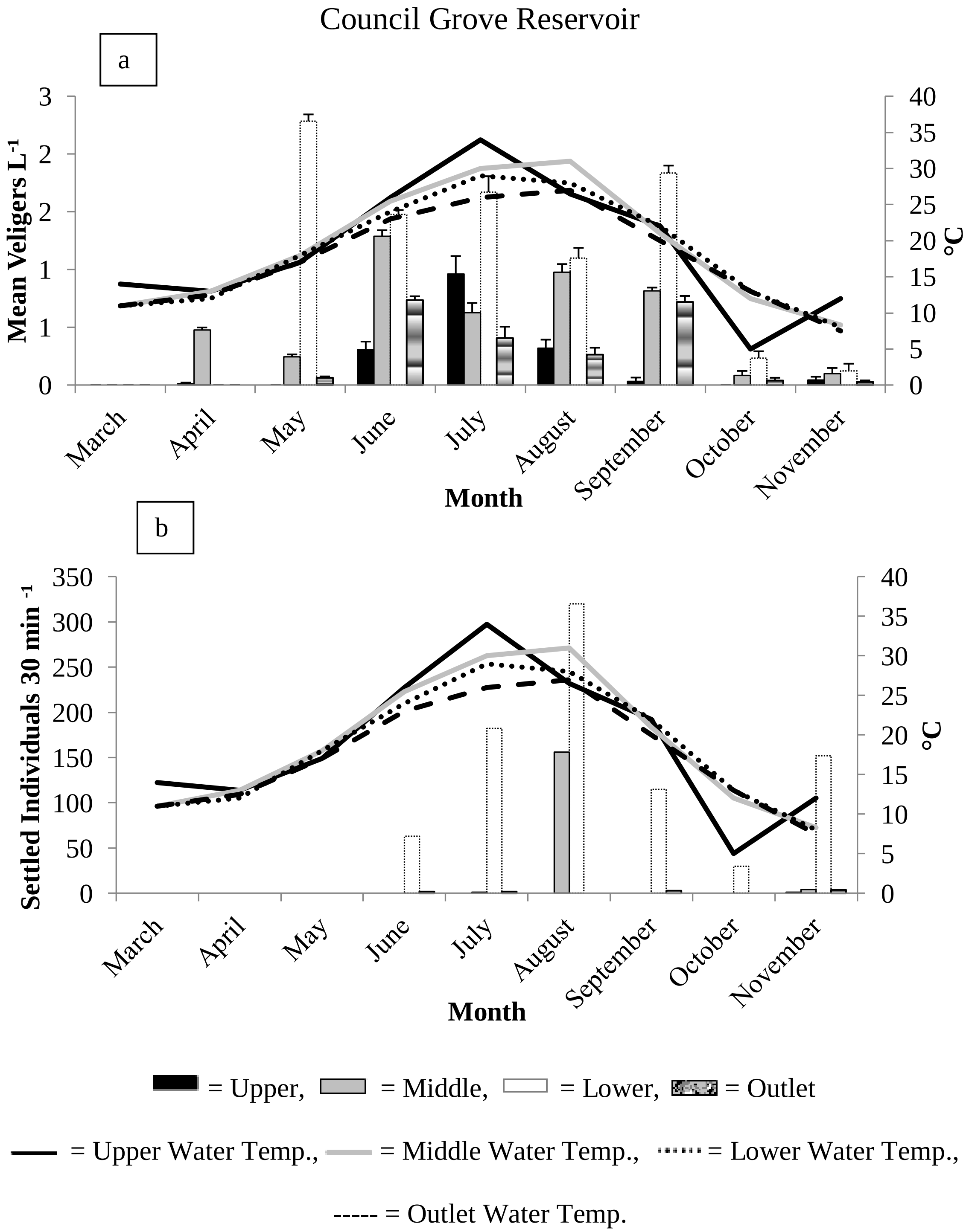


Fig. 4—(a) Mean density of zebra mussel veligers (number L^{-1}) and (b) number of settled zebra mussels 30-min $search^{-1}$, with local water temperature, March-November 2011, in

upper, middle, lower, and outlet sections of Council Grove Reservoir, Kansas. Error bars = 1 *SE*. No settled individuals were found on PVC substrate PVC substrate in Council Grove Reservoir.

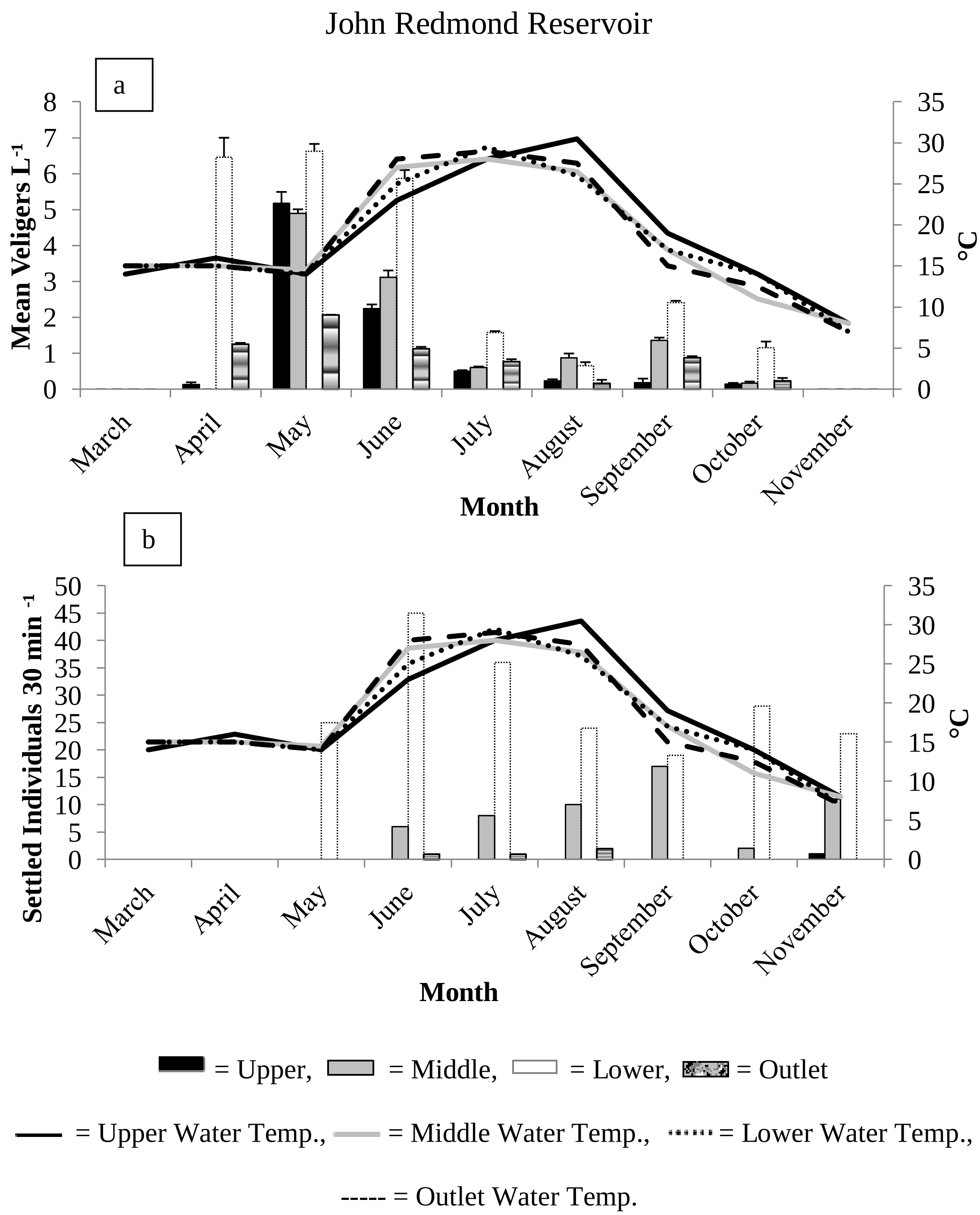


Fig. 5—(a) Mean density of zebra mussel veligers (number L^{-1}) and (b) number of settled zebra mussels 30-min search^{-1}, with local water temperature, March-November 2011, in

upper, middle, lower, and outlet sections of John Redmond Reservoir, Kansas. Error bars = 1 *SE*. No settled individuals were found on PVC substrate in John Redmond Reservoir.

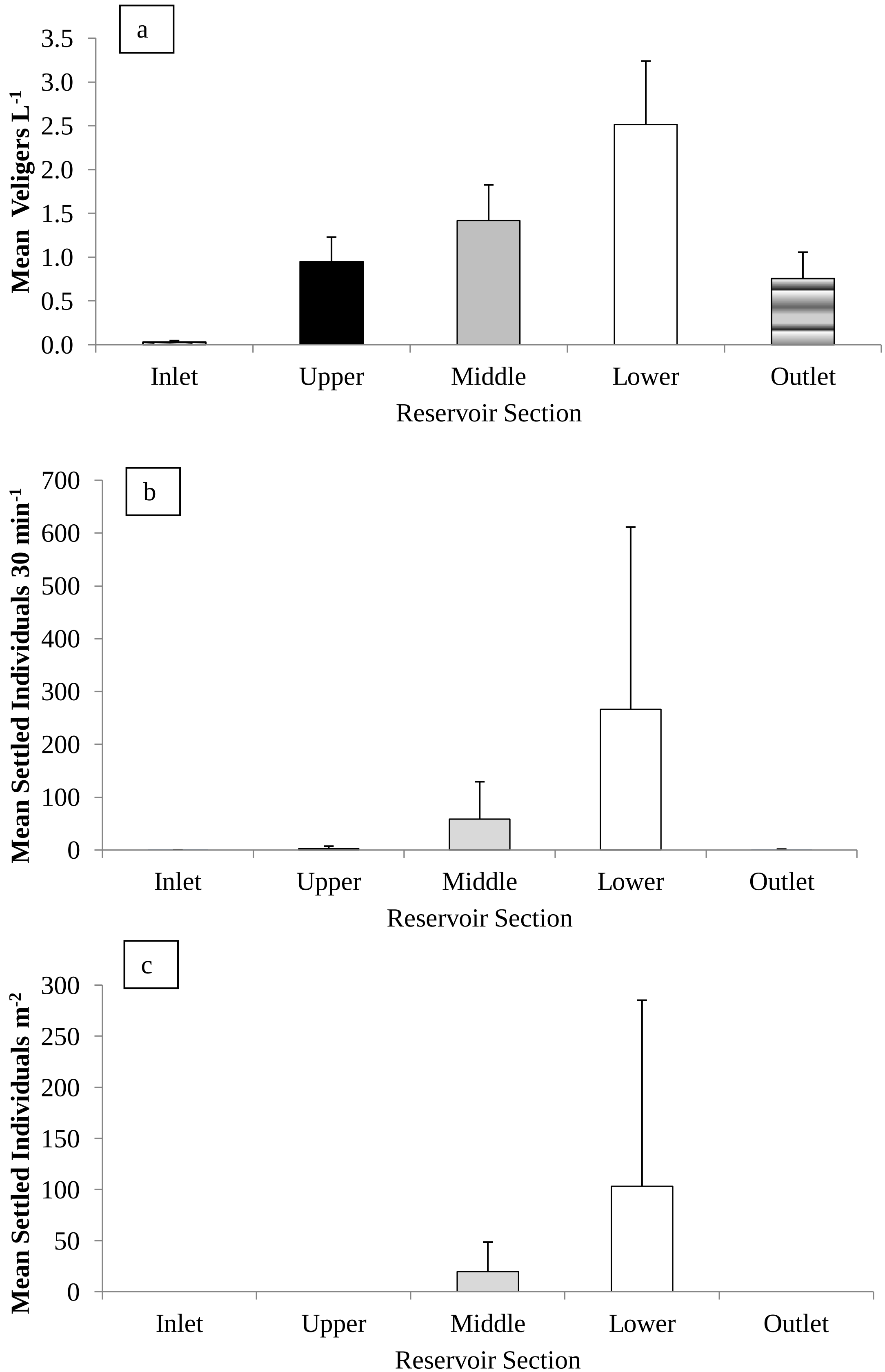

a
Mean Veligers L-1
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Inlet
Upper
Middle
Lower
Outlet
Reservoir Section
b
Mean Settled Individuals 30 min-1
700
600
500
400
300
200
100
0
Inlet
Upper
Middle
Lower
Outlet
Reservoir Section
c
Mean Settled Individuals m-2
300
250
200
150
100
50
0
Inlet
Upper
Middle
Lower
Outlet
Reservoir Section

Fig. 6—Pooled data for (a) mean density of zebra mussel veligers, (b) mean number of settled zebra mussels 30-min search^{-1}, and (c) mean number of settled individuals m^{-2} on PVC substrate, March-November 2011, in inlet, upper, middle, lower, and outlet sections of four reservoirs (Marion Reservoir, Council Grove City Lake, Council Grove Reservoir, and John Redmond Reservoir) in the upper Neosho River basin, Kansas. Error bars = 1 *SE*.

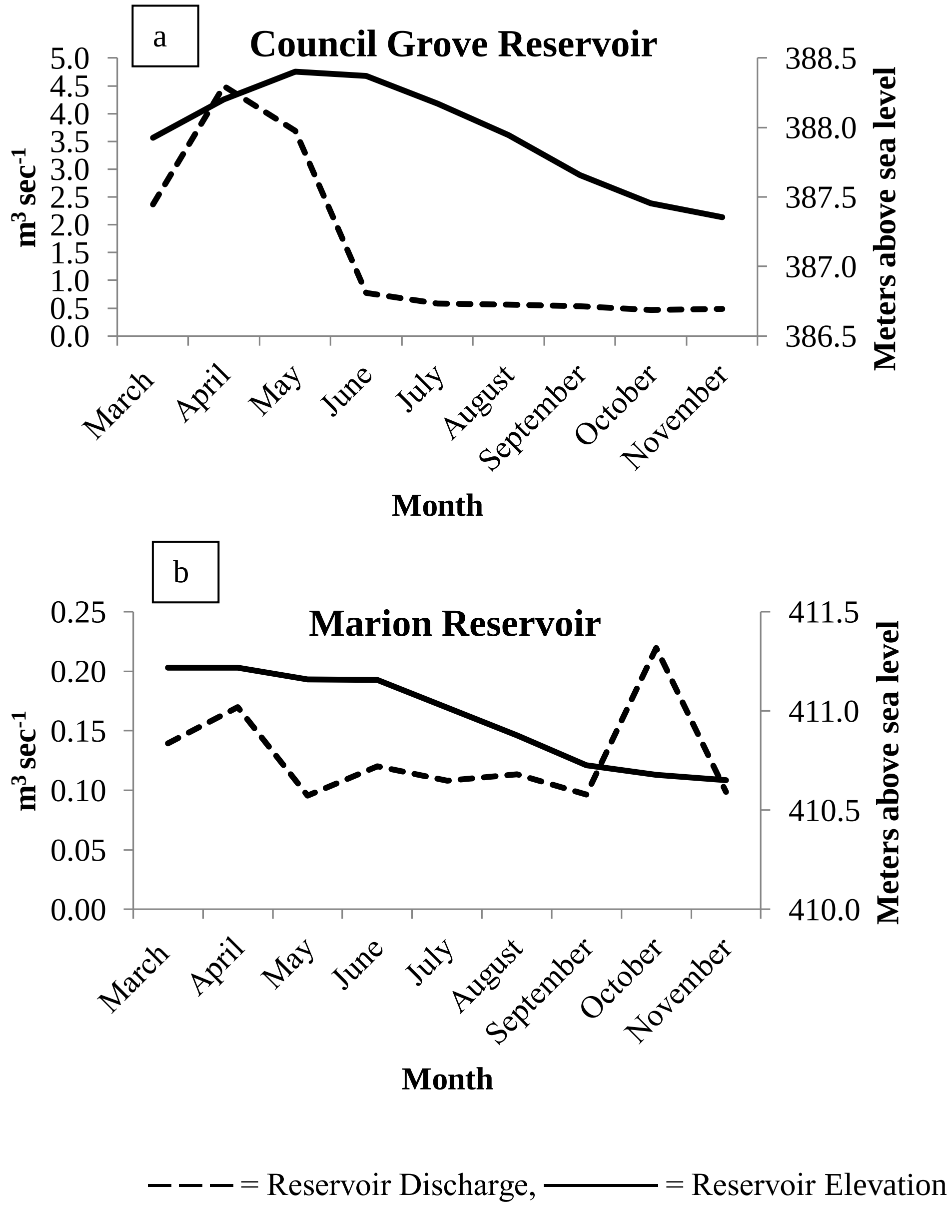


Fig. 7─Discharge (m^3 sec^{-1}) and lake elevation (meters above mean sea level) for (a) Council Grove Reservoir, (b) Marion Reservoir, and (c) John Redmond Reservoir, Kansas, March-November 2011. Data from U.S. Geological Survey (2013). Data for Council Grove City Lake unavailable.

Chapter 3

Zebra Mussel Colonization of Construction Materials, and Effectiveness of a Flouropolymer Foul Release Coating

I compared zebra mussel *(Dreissena polymorpha)* colonization of six commonly used construction materials (PVC, concrete, steel, galvanized steel, pressure-treated wood, aluminum) plus a native unionid mussel shell, and examined effectiveness of the Intersleek® 970 Fluoropolymer foul release coating system applied to the six materials in limiting colonization by this aquatic nuisance species. Coated and uncoated substrates were deployed in Marion Reservoir, Kansas, from April 2011 to August 2012. Density of colonizing zebra mussels was evaluated in July and November 2011, and durability of the substrates was monitored until August 2012. Coated materials showed signs of pitting but did not delaminate from the materials to which they were applied. Mussels differentially utilized materials, with 8 of the 13 substrates being colonized. PVC was colonized more heavily than galvanized steel plus all surfaces coated with foul release fluoropolymer, which were largely mussel-free. These results suggest that use of particular materials and coatings may aid management of some zebra mussel infestations.

Keywords: Zebra Mussel, *Dreissena polymorpha*, Colonization, Foul Release Coating, Management, Biofouling, Substrate, Fluoropolymer, Non-chemical Control.

Introduction

The invasive and biofouling zebra mussel (Bivalvia: Veneroida: Dreissenidae, *Dreissena polymorpha)* has rapidly spread in North America, and can be extremely detrimental to human aquatic infrastructure such as docks, dam gates, pipes or submersible pumps. Accumulation of zebra mussels can degrade integrity of these structures or constrict water flow to ineffectual levels, leading to more than $100 million in annual expenditures in North America (Strayer 2009). In addition to economic costs, zebra mussels commonly colonize unionid mussels (Bivalvia: Unionoida: Unionidae), constituting a direct threat to these native mollusks by restricting their movement and impairing their acquisition of food and oxygen (Schloesser, Nalepa and Mackie 1996; Ricciardi, Neves and Rasmussen 1998; Baker and Hornbach 2008).

Zebra mussels differentially colonize various construction materials in the Great Lakes (Kilgour and Mackie 1993; Marsden and Lansky 2000). Kilgour and Mackie (1993) found that materials containing copper, zinc, and aluminum were colonized to a lesser degree than black steel, stainless steel, and pressure-treated wood; additionally, surfaces with a low coefficient of friction, covered with Teflon™, showed reduced degrees of colonization. Marsden and Lansky (2000) demonstrated zebra mussel preference for PVC compared to Plexiglas and glass, and a strong avoidance of galvanized steel. Differential colonization of materials by zebra mussels has not yet been tested outside of the Great Lakes region or in rivers.

Newly developed fluoropolymer foul release coatings, designed to reduce the coefficient of friction of the surface to which they are applied to the point that zebra mussels cannot remain attached to the surface (International Marine 2011), have yet to be tested on zebra mussels. Skaja (2010) described several fluoropolymer-based foul release coating systems with chemical and physical properties that caused the zebra mussel congener, the invasive quagga mussel (*Dreissena rostriformis*), to release in flowing water, and Tordonato and Skaja (2012) showed that fluorinated, silicone-based foul release coating was largely effective at protecting aquatic infrastructure from the quagga mussel.

The recent introduction of zebra mussels into the Neosho River basin, Kansas, provided an opportunity for local investigation of colonization of construction materials, coating systems, and unionid mussels. I examined zebra mussel colonization on different substrates and coatings in Marion Reservoir and the Cottonwood River, Kansas. This 2509-hectare reservoir is located in the headwaters of the Cottonwood River in Marion County, and was constructed by the U.S. Army Corps of Engineers in 1968. Marion Reservoir has been infested with zebra mussels since at least 2008, and maintains a large and reproductively viable population (Kansas Department of Wildlife Parks and Tourism 2013); zebra mussel veligers and adults are now also in the Cottonwood River downstream (Smith and Edds 2012). I hypothesized that zebra mussels would differentially colonize materials, but that they would not colonize those treated with fluoropolymer foul release coating.

Materials and Methods

I compared zebra mussel colonization on six construction materials commonly used in the Neosho River basin (PVC, concrete, steel, galvanized steel, pressure-treated wood, and aluminum) and the same six materials treated with Intersleek® 970

Fluoropolymer foul release coating, produced by International® Marine Paints, Gateshead, U.K. The coating was applied under laboratory conditions to the specifications of International® Marine Paints (International Marine 2011) at the Bureau of Reclamation Materials Testing Laboratory, Denver, Colorado. A native freshwater mussel valve (Unionidae: *Tritogonia verrucosa*) was also included in the trials. Materials were attached by white plastic zip ties onto colonization units consisting of two, 2-holed concrete blocks, 40 x 20 x 20 cm, with 0.5 cm holes drilled through their walls to attach a 10 x 10 cm piece of each of the 13 treatments (Fig. 1). The unionid valve was irregular in shape, not 10 x 10 cm, but did have 100 cm^2 available for zebra mussel colonization.

In April 2011, I placed two sets of colonization units at 1-m depth and anchored them to the bank via cable in the lower reach of Marion Reservoir, within 1 km of the dam, over cobble and sand substrate. Two sets were also placed at 1-m depth in the Cottonwood River approximately 1.5 river-km downstream from the reservoir outlet, over cobble and mud substrate. One colonization unit at each site was evaluated in July 2011 and the other was evaluated in November 2011 by removing each plate and counting visible zebra mussels attached to the exposed face. Observation of sampling plates continued until August 2012 to monitor durability of the foul release coating system. At both sites, surface water temperatures were monitored monthly with a thermometer and through USGS gauging station #07182280 located at Neosho Rapids, KS, in the Cottonwood River. Discharge data for the river was collected from USGS gauging station #07179795 in the Cottonwood River, 200 m downstream from the Marion Reservoir outlet.

Statistical analyses to test for differential colonization were conducted with the *Statistical Analysis System,* version 18.2 (SAS Institute Inc., Cary, North Carolina), and results were considered statistically significant at $P \leq 0.10$ (Dayton 1998). Data were assessed for normality and homogeneity of variance with SAS' Graphical Plotting and Univariate procedures, and all data were judged to be normal and homogeneous. Differences in the number of zebra mussels colonizing materials were analyzed with repeated measures analysis of variance (ANOVAR), followed by Tukey's post-hoc multiple comparisons test.

Results

Reservoir discharge exhibited two peaks, in April at 6.00 cfs and in October at 7.75 cfs. Minimum discharge was recorded in May at 3.38 cfs. Water temperature at both sites surpassed 10º C by March, and returned to below 10º C in November. Water temperature at the Marion lower sampling site peaked in July and August at 31º C, whereas water temperatures at the Cottonwood River site peaked in July at 35º C. This shows that local water temperatures and discharge rates were within reasonable ranges for zebra mussel survival and settling (Stanczykowska 1977; Fong et al. 1995; Stoeckel et al. 1997).

Colonization units in the river gathered no zebra mussels on any substrate. Thus, subsequent results are based solely on samples from the reservoir. By July 2011, 7 of the 13 substrates had been colonized by zebra mussels (PVC, concrete, aluminum, steel, pressure-treated wood, native unionid valve, and fluoropolymer-coated galvanized steel). In November 2011, 7 of the 13 were colonized (PVC, concrete, aluminum, steel, pressure-treated wood, native unionid valve, and galvanized steel). All material plates that had been colonized by July, except fluoropolymer-coated galvanized steel, showed increases in the density of colonizing zebra mussels by November (Table 1).

Among the uncoated materials, PVC was most heavily colonized during both periods, with 2900 zebra mussels/m^2 in July and 4500/m^2 in November (Table 1). The least-colonized uncoated material was galvanized steel, with no attached zebra mussels in July and 300/m^2 in November (Table 1). Materials treated with foul release coating were nearly mussel-free (Table 1). Only one zebra mussel (=100/m^2) was found attached to any coated material, and it was loosely attached to algae on the coated galvanized steel in July. No other zebra mussels were found attached to any other coated material plate at any time (Table 1).

There was a significant difference in the mean number of zebra mussels colonizing different substrates (ANOVAR $F_{12,25}$=4.99, p=0.0036). Tukey’s test showed uncoated PVC to be more heavily colonized than a group comprised of galvanized steel plus all coated substrates (Fig. 2).

Discussion

Results of my study were consistent with those from the Great Lakes region, corroborating findings that material type can affect the degree of colonization by zebra mussels (Kilgour and Mackie 1993; Marsden and Lansky 2000). Although Marion Reservoir has different physiochemical properties and temperature regimes from the Great Lakes, colonization on different materials was similar. Kilgour and Mackie (1993) found copper, galvanized iron, and aluminum to be less susceptible to colonization by zebra mussels than stainless steel, asbestos, and polypropylene. Marsden and Lansky (2000) demonstrated greater zebra mussel affinity for PVC than Plexiglas, for those two materials over glass, and a strong avoidance for galvanized steel. Among untreated materials in my study, PVC was colonized most extensively and galvanized steel was colonized least.

Most likely, avoidance of galvanized steel was due to its coating with zinc, known to be toxic to mollusks (Havlik and Marking 1987). Walz (1975) and Kilgour and Mackie (1993) also showed that materials containing substances toxic to mollusks, including zinc, copper, and aluminum, reduced zebra mussel colonization. However, zebra mussels were not entirely absent from any of my uncoated samples, a result similar to findings of Kilgour and Mackie (1993) in which galvanized and aluminum plates were among the least colonized materials, but still exhibited some colonization.

Kilgour and Mackie (1993) found PVC less colonized than either pressure-treated wood or steel, however I found PVC the most heavily colonized. This result could be due to the grey color of the PVC used in my experiment; although not overtly stated what color was used, had Kilgour and Mackie (1993) used commonly available white PVC during their study, this would introduce a variable between the two studies. Material coloration can affect the degree of zebra mussel colonization, with darker colored materials exhibiting heavier colonization (Tordonato and Skaja 2012).

The native unionid valves in my experiment were also heavily colonized. During field work, I observed live unionids that had been colonized by zebra mussels,with the greatest numbers near the unionid’s incurrent siphon. This and other direct threats to native mussels (e.g., Schloesser, Nalepa and Mackie 1996; Ricciardi, Neves and

Rasmussen 1998; Baker and Hornbach 2008) suggest that unionids in Kansas, including several threatened and endangered species, could be negatively affected by zebra mussels. The possible colonization of native unionids by zebra mussels makes it important to conduct monitoring within this invasive species' expanding range (Mulhern, Obermeyer and Angelo 2002). Conservation and recovery plans developed to aid unionids may need modification to address this new threat.

It is important to remember that my study was limited to one year in one reservoir and river, and to a single replicate of colonization substrates in each habitat. I can make no conclusions for the lotic habitat, due to the lack of colonization in the river, which was likely due to a combination of factors, including the lower density of veligers in the river than in the reservoir (Smith and Edds 2012) and the shorter residence time for the few veligers in the flowing water. However, discharge and water temperature were within suitable ranges for settlement to occur.

The Intersleek® 970 Fluoropolymer foul release coating exhibited nearly mussel-free performance, regardless of the material to which it was applied, indicating that zebra mussels colonization on this coating sytem was inhibited in a manner similar to that for quagga mussels shown by Skaja (2010) and Tordonato and Skaja (2012). A single individual zebra mussel loosely attached to a developing layer of periphyton on one coated galvanized steel plate was the only attached zebra mussel found on a coated plate throughout the study. Accumulation of periphyton is a concern, however, because Kavouras and Maki (2003) showed that biofilms facilitate attachment of zebra mussels. Following evaluation of colonization of the coated materials, durability of the coating system was periodically monitored for visible degradation until August 2012. During this time, coated plates did begin to show some signs of wear and continued colonization by periphyton. Nearly all coated plates in colonization units in the Cottonwood River showed signs of pitting, although no treatments delaminated (peeled away from the coated material). Coated materials in Marion Reservoir also showed some signs of pitting, although to a lesser degree than samples in the Cottonwood River, and none of those samples delaminated from their coated material. Durability of these foul release coating systems remains an issue and it appears that durability likely varies among sites. Because these coating systems are quite costly to apply and maintain, continued investigation could reveal systems that are more efficient and cost effective than those currently available.

Replacement of easily colonized surfaces with more resistant surfaces and coatings could be used to help manage local zebra mussel populations in some instances. However, because these approaches are expensive and do not eliminate zebra mussels entirely, they should be used only as part of an overall zebra mussel control or mitigation plan, not a standalone blanket resolution to a zebra mussel infestation, and users of these systems should be cautioned accordingly. Coatings should be considered as temporary fixes to local zebra mussel problems rather than solutions to large-scale infestations.

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Table 1. Density of zebra mussels (#/m^2) attached to various materials in replicate colonization units placed in Marion Reservoir, Kansas, in April 2011. One unit was examined in July and the other in November 2011.

	Density (#/m^2)	
Material Type	July	November
PVC	2900	4500
Native unionid valve	1800	2700
Pressure-treated wood	600	2400
Concrete	500	2100
Aluminum	400	2100
Steel	500	1700
Galvanized steel	0	300
Coated galvanized steel	100	0
Coated PVC	0	0
Coated pressure-treated wood	0	0
Coated concrete	0	0
Coated aluminum	0	0
Coated steel	0	0

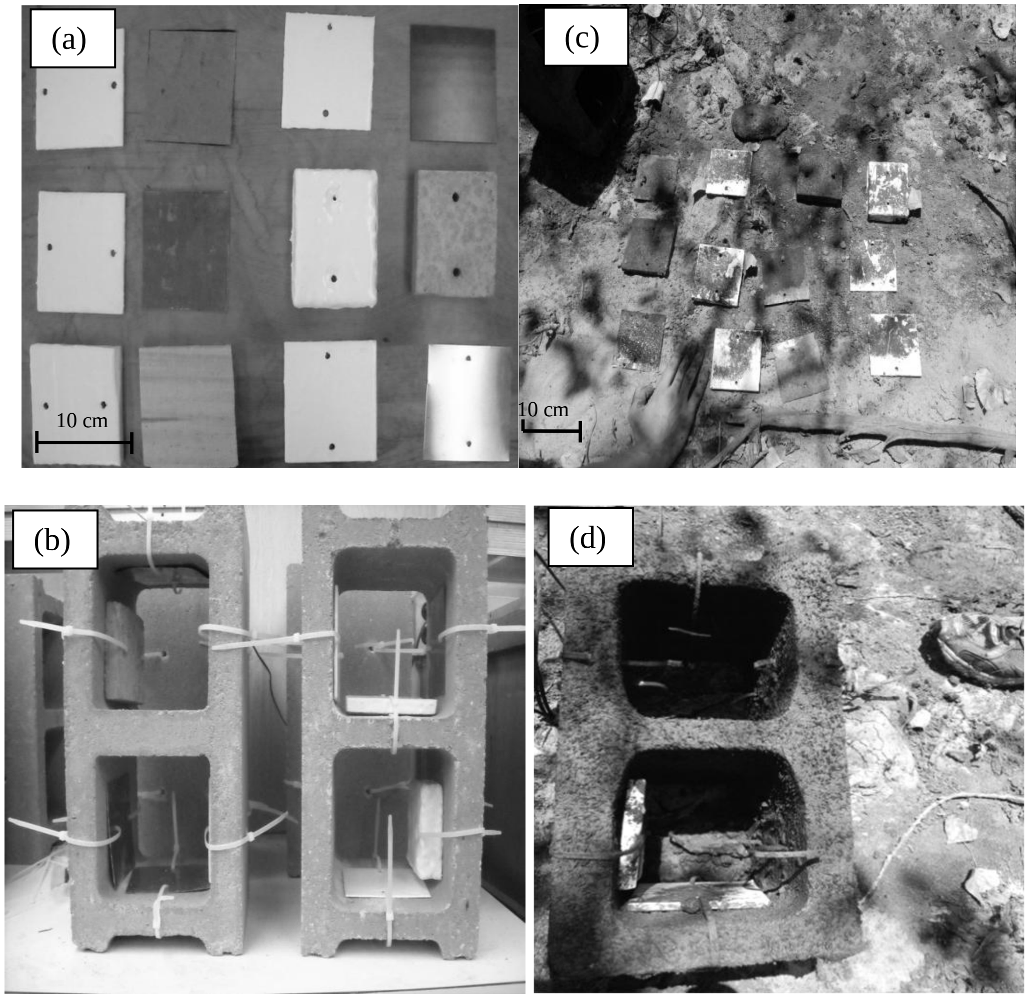

Figure 1. (a) 10 x 10 cm material plates before attachment onto colonization units; from left to right: top row -- coated galvanized steel, galvanized steel, coated PVC, PVC; middle row -- coated steel, steel, coated concrete, concrete; bottom row -- coated pressure-treated wood, pressure-treated wood, coated aluminum, aluminum; unionid not pictured; (b) complete colonization unit with material plates attached before sampling; (c) materials after 4 months in Marion Reservoir; from left to right: top row --unionid; second row -- steel, coated steel, concrete, coated concrete; third row -- pressure-treated wood, coated pressure-treated wood, PVC, coated PVC; fourth row -- aluminum, coated aluminum, galvanized steel, coated galvanized steel; and (d) half of one colonization unit with material plates attached after 4 months in Marion Reservoir.

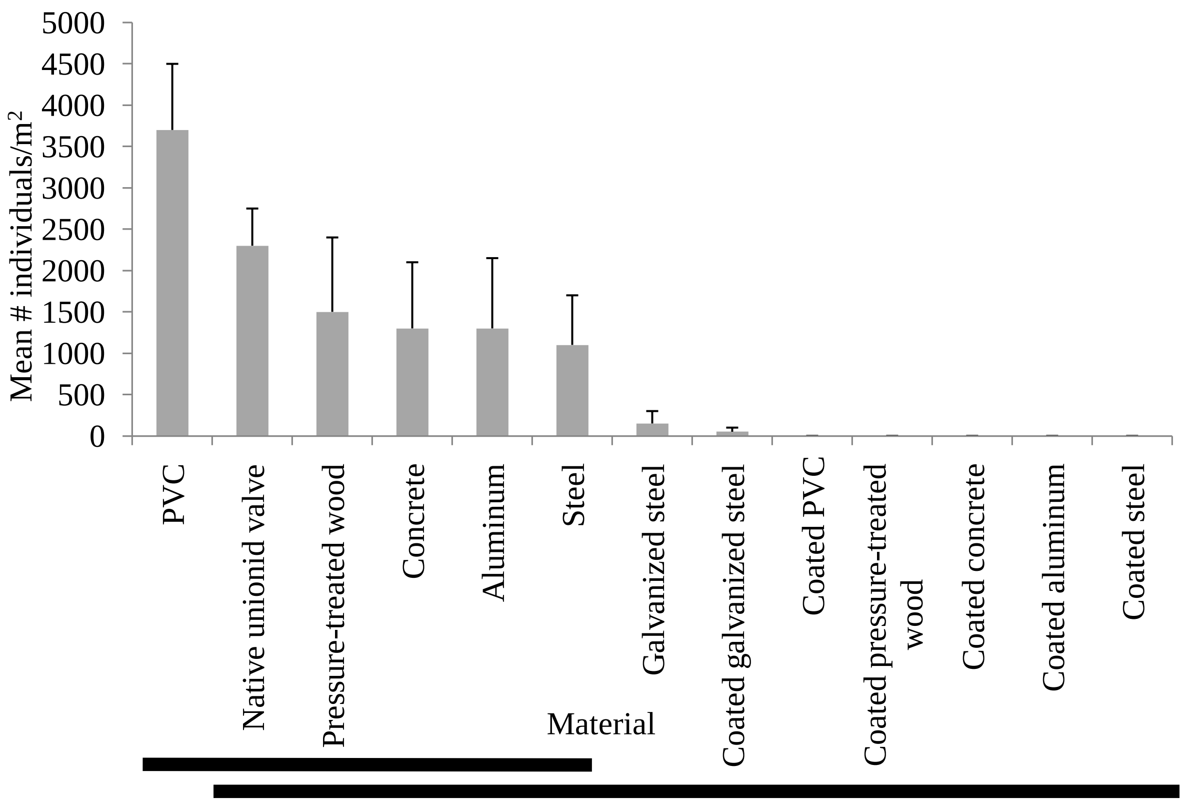

Figure 2. Mean number of zebra mussels/m² attached to various materials in Marion Reservoir, Kansas, July and November 2011 error bars = 1 SE. Materials not grouped with horizontal lines showed significantly different colonization (Tukey's test).

Chapter 4

Economic Impact of Zebra Mussels in the Neosho and Walnut River Basins, Kansas

I evaluated the financial costs to water rights holders associated with zebra mussels *(Dreissena polymorpha)* in two Kansas river basins via mailer surveys, and used that information to project potential spending after the Neosho Basin has been more fully invaded. In 2011, $385,806 was spent in the two basins to mitigate the effects of zebra mussels to raw water users, including $374,206 in the larger Neosho and $11,600 in the smaller Walnut. This is a substantial increase from previous estimates of zebra mussel related spending in Kansas and is an economic hardship for citizens of the basins. Costs will likely increase in coming years after a full infestation of zebra mussels has established in the Neosho Basin. Specifically, annual expenditures within the Neosho Basin are projected to range between $424,335 and $1,509,054.

Key words: Zebra mussel, Infestation, Cost, Economic, Water rights, ANS, AIS, *Dreissena polymorpha*, Survey

Introduction

Each year, the cost of managing, mitigating, or removing invasive species increases. The Nature Conservancy (2012) has estimated that $1.4 trillion dollars is spent yearly worldwide due to invasive species, with $138 billion being expended in the U.S. alone (TNC 2012). In the U.S., an estimated 50,000 non-native species have been introduced, either accidentally or intentionally (Pimentel, Zuniga and Morrison 2005). Most introductions of plants and vertebrates have been intentional, but most microbe and invertebrate introductions have been accidental (Pimentel, Zuniga and Morrison 2005). One of the most prominent of these unintended invaders is the zebra mussel *(Dreissena polymorpha)*.

The invasive zebra mussel negatively impacts native species by directly competing for basal planktonic food supplies (Baker and Levinton 2003), and it affects anthropogenic use of raw water such as treatment of municipal drinking water or the generation of electricity by clogging intake pipes and fouling critical infrastructure (O'Neill 1997). Given these impacts, several investigators have attempted to assess the economic costs incurred due to zebra mussels. Sun (1994) projected that nearly $5 billion would be spent to prevent, control, and mitigate zebra mussels in the Great Lakes region from 1990–2000. O'Neill (1997) assessed the overall direct economic impact to 35 states, including Kansas, and three Canadian provinces from zebra mussels to be $69 million in 1995. Cataldo (2001) estimated that, over the preceding 10 years, damages to primary infrastructure affected by zebra mussels (intake pipes, water filtration, equipment, power plants, etc.) totaled $3.1 billion in the Great Lakes region. Strayer (2009) calculated costs incurred due to zebra mussels in North America as exceeding $100 million annually. These evaluations vary widely over a variety of areas and time scales, and have used varying survey methods. Estimation of the economic impacts of zebra mussel infestations is in its infancy, and additional comparative assessments over newly invaded regions are vital to appropriately estimate the costs of zebra mussels (Lovell, Stone and Fernandez 2006). Few empirical studies exist, but the invasion of zebra mussels into the Neosho River Basin, Kansas, in 2008 provided an opportunity to assess costs during the initial invasion of a river basin.

Zebra mussels were introduced to Kansas in 2003 in El Dorado Reservoir in the Walnut River Basin and have quickly spread, currently infesting 10 of the 12 major Kansas river basins (KDWPT 2013) (Fig. 1). There has been little examination of the economic impact of zebra mussels in Kansas, potential or realized, although these impacts could be extensive, and no studies have addressed an entire basin within the state. O'Neill (1997) assessed economic costs associated with zebra mussels nationwide via mailer surveys and included four randomly-selected raw-water-dependent water treatment facilities in Kansas. He found that the cost to combat zebra mussels in Kansas during 1989-1995, inclusive, totaled approximately $6,300, or about $225 annually per facility.

Mann et al. (2010) used costs reported in the literature to estimate economic risks in the Columbia River Basin in the U.S. Northwest associated with the potential establishment of zebra mussels at new facilities. This type of assessment can be reliable when comparable representatives for each water user type can be found; however, given variability among types of water use and geographical areas, such estimates can be unreliable. I evaluated costs in a river basin currently undergoing a zebra mussel invasion (the Neosho), and developed projections of future economic impacts based on those costs and costs in an adjacent and more fully-invaded basin (the Walnut) (Fig. 1). Both basins were evaluated via mailer survey of water rights holders, i.e. individuals or corporations permitted to utilize raw water resources (KDA 2013). Although using mailer surveys to evaluate economic costs of zebra mussels is not a new concept, the idea of identifying specific water rights holders to survey is, allowing for a more empirical evaluation of the direct economic impact of zebra mussels than sending mailers to randomly selected water users or pooling data reported in literature. This allows for a more empirical based assessment of the economic cost of zebra mussels, a need identified by Lovell, Stone and Fernandez (2006).

Materials and Methods

To assess economic impacts of the zebra mussel invasion in the Neosho and Walnut basins, I conducted a mail survey of surface water rights holders identified via the Kansas Water Office (KWO) and Kansas Department of Agriculture (KDA). A total of 189 water rights holders in the Neosho Basin (16,317 km^2) and 14 in the smaller Walnut Basin (6,164 km^2) were identified (KWO 2013), and were grouped into six water use categories: irrigation, recreation, municipal, industrial, sediment storage, and stock water). These water use categories are defined by KWO and indicate how the raw water is to be used. Any water rights holders who held a single water right for multiple water use types was asked to define their specific water use type in the mailer survey. After combining responses for the Neosho and Walnut, I calculated mean expenditure for each water use category. The mailer sent to water rights holders consisted of a cover letter (Appendix A) that oriented readers to the goals of the survey, along with a questionnaire (Appendix B) designed to assess costs associated with managing zebra mussels at each recipient's facilities or operations during 2011, including costs of additional chemicals, manual cleaning of equipment, increases in employee wages or hours worked, retrofitting of equipment, reduced productivity, additional or replacement equipment, etc.

Neosho Basin water rights holders were sent mailers in October 2011. This was followed by a second mailer to all non-respondents in the Neosho Basin in November (Appendix C). According to the KDA, of the 189 Neosho Basin water rights holders, 22 held rights for multiple water use categories. All recipients were asked to identify their primary water use, and, for those with multiple water use purpose rights, their stated primary purpose was used for analysis. The 14 Walnut Basin water rights holders all held single-purpose water rights, and they were sent the same questionnaire and cover letter in November 2011 (Appendix D), with a follow-up to non-respondents in December (Appendix E). For all respondents from both basins, responses were kept confidential and no respondents were or will be identified by any descriptor other than their water use category.

Because the more recently invaded Neosho Basin lacked responses from infested facilities, these responses were pooled with those from the more fully infested Walnut Basin and were used to develop three projections of zebra mussel related costs to water rights holders in the Neosho Basin after a more complete infestation of facilities has occurred. The first projection is based on the mean expenditure per facility for each of the six water use types, applied to all facilities of that type in the basin. The second is based on the mean expenditure of all facilities in each water use category per acre-foot (AF) (1 AF = 0.123 hectare-meter) of raw water used during 2011; volume of water used by each respondent during 2011 was determined via the KDA-managed Water Information Management System (KDAWIMAS 2013). The third projection is based on the mean expenditure by each facility that spent any amount due to zebra mussels in 2011 per AF of raw water used.

Results

Of 203 mailer surveys sent to water rights holders in the Neosho (189) and Walnut (14) river basins, I received 107 responses, a 52.7% response rate. These were similar for each basin: 93/189 = 49.2 % from the Neosho and 8/14 = 57.1% from the Walnut. Of the 107 responses, 100 (49.3% of the 203) provided information beyond simply identifying their water use type, and were used in my analysis. Responses included 46 irrigation, 22 recreation, 18 municipal, 5 industrial, 6 sediment storage, and 3 stock water (Table 1). Eight of the 100 respondents reported zebra mussel related expenditures for 2011, and 92 incurred no such costs for the year. A greater percentage of Walnut Basin respondents (4/8 = 50%) reported spending some amount compared to those in the Neosho Basin, where only 4/100 = 4% reported spending any amount. Taken together, two irrigation, one recreation, two municipal, two industrial, zero sediment storage, and one stock water rights holder reported spending any money due to zebra mussels.

The total reported zebra mussel related annual expenditure for water rights holders during 2011 was $385,806, of which $374,206 (97%) was from the Neosho Basin and $11,600 (3%) was from the Walnut Basin. Neosho Basin respondents who utilized their water rights during the year incurred an average cost of $13.00 per AF used, whereas those in the Walnut Basin spent only $0.18 per AF.

Pooled responses from the Neosho and Walnut basins revealed varying amounts spent among water use types. Industrial water rights holders spent the vast majority of the total ($303,200 = 79%), whereas sediment storage water rights holders incurred no zebra mussel related costs in 2011. The mean expenditure per respondent in each water use category was: irrigation $80 (SD=527.6), recreation $3,409 (SD=15,990.1), municipal $172 (SD=706.1), industrial $75,800 (SD=148,285.4), sediment storage $0 (SD=0), and stock water $333 (SD=577.4) (Table 2).

Mean costs per AF of raw water utilized during 2011 also varied among water use types. Industrial water rights holders spent the most to utilize raw water, at $4.87/AF (n=5, SD=9.0), followed by stock water and irrigation water rights holders with $1.28/AF (n=3, SD=2.2) and $1.08/AF (n=46, SD=7.3), respectively (Table 2). The mean cost/AF incurred by facilities that reported spending any amount on zebra mussels during 2011 varied as well. Irrigation water rights holders were the most affected, at a cost of $49.69/AF (n=2, SD=35.1), and industrial water rights holders spent $12.19/AF (n=2, SD=12.0) (Table 2).

To project potential costs of a more complete infestation of the Neosho Basin, means for each water use type were extrapolated to all water rights holders of that type in the Neosho Basin (Table 3). These projections are based on the mean spent per facility during 2011, mean spent/AF in 2011, and mean spent/AF in 2011 for those who reported any spending. Using the mean cost per facility, a complete infestation, with all water rights users within a category affected equally, would cost water rights holders of the Neosho $864,100 annually, a complete infestation of the Neosho Basin based on the mean spent/AF in 2011 would cost $424,335 annually, and a complete infestation of the Neosho Basin based on the mean spent/AF of facilities who reported spending during 2011 would result in an annual cost to water rights holders of $1,509,055 (Table 3).

Discussion

My economic assessment provides baseline information that will be useful to managers as they inform municipalities, industries, and the general public of the costs incurred by the zebra mussel invasion in Kansas, in general, and in the Neosho and Walnut river basins specifically. Information from my survey will be valuable to managers throughout Kansas who want to plan for the potential economic impacts of the likely spread of zebra mussels in the state. Additionally, the findings of this assessment can be used as a model for future projections of zebra mussel infestations in other Kansas river basins. More broadly, the methods I have developed, i.e., the surveying of surface water rights holders, could be used to develop cost estimates for other regions to base estimates of zebra mussel derived cost on an empirical value, in this case amount of raw water utilized, as suggested by Lovell, Stone, Fernandez (2006).

My survey indicates that expenditures in 2011 due to the zebra mussel invasion in the Neosho and Walnut basins totaled $385,806. The greatest costs were incurred by holders of industrial and recreational water rights, which constituted 79% and 19% of the spending, respectively. O’Neill’s (1997) assessment of economic costs associated with zebra mussels nationwide noted that four Kansas water treatment facilities spent a total of approximately $900 per year, or $225 per facility, from 1989 to 1995, inclusive; this assessment was conducted before any zebra mussel infestations had occurred in Kansas. My 2011 estimate of $385,806 represents a 214-fold (21,434%) increase per facility in 16 years, in the Neosho and Walnut river basins alone.

Many respondents in the Neosho Basin indicated that, although they were not currently spending any money due to zebra mussels, they expected to be compelled to do so in the near future. Municipal water user costs, in particular, will almost certainly grow. In May 2012, the city of Council Grove, Kansas, located in the upper Neosho Basin, was forced to place restrictions on its water users while it cleaned its Council Grove City Lake water intake and outlet facility that was clogged with zebra mussels. In nearby Osage City, Kansas, zebra mussels clogged the pipeline that brought drinking water from Melvern Lake (Marais des Cygnes River Basin), forcing the city to switch its drinking water source to a different lake. Actions like these are likely to become more common as zebra mussels expand their infestation throughout the basin.

Irrigation water rights holders reported low costs from zebra mussels in my survey; however, many of these users commented that they typically engaged in seasonal dewatering of the equipment used with raw water, which could reduce the effects of zebra mussels (Claudi and Mackie 1994). Industrial and recreational water users, for which seasonal dewatering is not a common practice, reported greater overall costs than irrigation, stock water, and sediment storage water rights holders. Seasonal dewatering is likely a potential control for managing zebra mussel infestations.

A much greater percentage of respondents (50%) in the Walnut Basin reported spending than those in the Neosho Basin (4%). Because introduction of zebra mussels to the Walnut Basin took place 5 years prior to infestation of the Neosho, the Walnut had been more completely invaded, and, as a result, a greater proportion of Walnut respondents had incurred zebra mussel related costs. It is reasonable to expect that, as the Neosho Basin is more fully infested, the number of respondents forced to spend will rise to a level similar to that in the Walnut. However, the number of water rights holders in the Neosho Basin (189) compared to the Walnut Basin (14) would result in greater total spending in the Neosho Basin.

By using data from this survey, it is possible to develop projections to forecast possible spending increase in the Neosho Basin and prepare water rights holders for the impending zebra mussel related expenditures. I developed three projections. The first was based on the mean amount spent due to zebra mussels for facilities of each type in the combined Neosho and Walnut basins. Responses from these basins were pooled together, increasing the amount of data used to develop the projected cost. This value was then applied to all facilities of that type in the Neosho Basin. The total of this projection was $864,100 in annual costs to Neosho Basin water rights holders (Table 3). This is the simplest of the projections, and the most easily applied to develop a quick estimate of future costs. However, this model applies costs incurred by facilities of each of the six water use types equally to all facilities of that type, regardless of the size of the facility or amount of raw water utilized annually. Additionally, this projection includes respondents who spent no amount simply because zebra mussels had yet to infest their facilities. Thus, this projection may not be the most accurate method of predicting future costs.

The second projection was based on the mean spent by each water use type to use one AF of water during 2011. This resulted in a projected cost of $424,335 in annual zebra mussel related costs (Table 3). This projection is likely more accurate than the first because it negates differences in facility size by considering the amount of raw water used. However, this includes those facilities spending no amount simply because they had yet to be infested by them, which likely underestimates the mean spent/AF for each water use type. Within the Neosho Basin, respondents spending no amount constituted the vast majority of respondents (96%), thus this effect could be substantial.

The third projection was based on costs incurred by respondents to utilize one AF of raw water among those who reported spending any amount during 2011. This method predicted that zebra mussel related spending in a fully infested Neosho Basin with 100% of facilities affected would cost $1,509,055 annually (Table 3). This projection negated differential facility sizes by basing estimates on AF utilized rather than number of facilities, and averted underestimation due to inclusion of non-infested facilities. Thus, although this may be the most complex projection to develop, it may prove to be the most accurate of the three. This projection assumes that all facilities will be affected by zebra mussels, however in my assessment of the more fully infested Walnut Basin, only 50% of facilities reported zebra mussel related costs. It is likely that not all facilities within a river basin will be affected by zebra mussels. Thus, knowledge of the extent of the infestation is needed for an accurate projection.

The Neosho River Basin is in the early stages of zebra mussel invasion, and it is important to continue monitoring to determine the long-term economic impacts of this invasive species. Information on impacts to more fully infested basins such as the Walnut can be used to assist newly infested basins in developing estimations of expected costs for managers. It is important to remember that the facilities impacted by zebra mussels include many that provide some of our most basic utilities and resources, such as electricity generation, municipal drinking water, and irrigated crops and livestock. Additional new costs will constitute a burden on water rights holders and all who directly or indirectly utilize the goods and services rendered by these facilities.

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Table 1. Response rate to zebra mussel surveys sent to water rights holders in the Neosho and Walnut river basins, Kansas, 2011. Multiple-use water rights holders' stated primary purpose was used for analysis; thus, totals for some water use types may exceed the initial number sent.

Water use type	Neosho Basin		Walnut Basin		Total	
	Surveys sent	Responses received %	Surveys sent	Responses received %	Surveys sent	Responses received %
Irrigation	87	42 (48.3%)	9	4 (44.4%)	97	46 (47.4%)
Recreation	48	20 (41.7%)	0	-	50	22 (44.0%)
Municipal	13	12 (92.3%)	3	3 (100%)	19	18 (94.7%)
Industrial	9	4 (44.4%)	2	1 (50.0%)	11	5 (45.5%)
Sediment Storage	9	6 (66.7%)	0	-	9	6 (66.7%)
Stock Water	1	1 (100%)	0	-	3	3 (100%)
Multiple	22	8 (36.4%)	0	-		
Total	189	93 (49.2%)	14	8 (57.1%)	203	100 (49.3%)

Table 2. Mean and total zebra mussel related expenditure per individual facility in Neosho and Walnut basins, Kansas, per facility to utilize one acre-foot (AF) of raw water, and per AF for those facilities that spent any amount during 2011.

Water use type	n	Mean spent per facility	SD	Mean spent per AF used	SD	n	Mean spent per AF used by those spending	SD
Irrigation	46	$80	527.6	$1.08	7.3	2	$49.69	35.1
Recreation	22	$3,409	15990.1	$0.53	2.5	1	$11.66	-
Municipal	18	$172	706.1	$0.06	0.3	2	$1.16	0.8
Industrial	5	$75,800	148285.4	$4.87	9	2	$12.19	12.0
Sediment Storage	6	$0	0	$0.00	0	0	-	-
Stock Water	3	$333	577.4	$1.28	2.2	1	$3.83	-
Total	100	$79,794		$7.82		8	$78.53	

Table 3. Projected total annual spending for a more fully infested Neosho River Basin, Kansas, based on mean expenditures due to zebra mussels per facility in 2011, per facility to utilize one acre-foot (AF) of raw water, and per AF for those facilities that spent any amount.

Water use type	Mean spent/ facility	AF used	Mean spent/ AF used	Mean spent/AF used by those spending
Irrigation	$7,012	5848.8	$6,319	$277,487
Recreation	$170,455	13805.1	$7,315	$160,684
Municipal	$3,100	24030.9	$1,553	$27,293
Industrial	$682,200	85528.3	$408,708	$1,042,268
Sediment Storage	$0	0	$0	$0
Stock Water	$1,333	345.0	$441	$1,322
Total	$864,100	129558.1	$424,335	$1,509,055

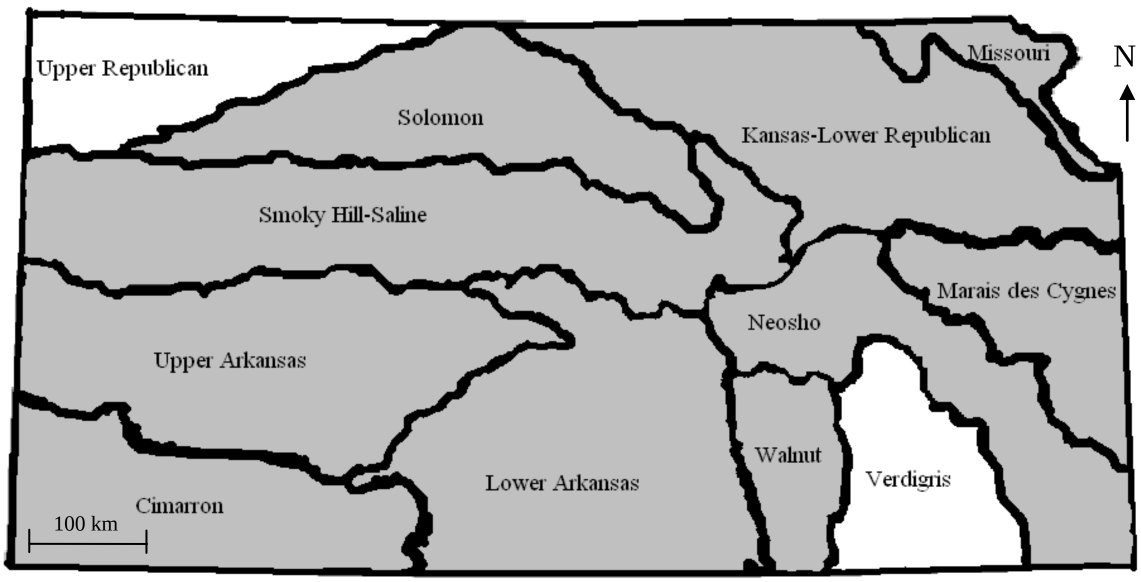

Figure 1. River basins of Kansas. Grey basins were infested with zebra mussels as of October 2013.

Appendix A. Economic survey cover letter sent to Neosho River Basin water rights holders, October 2011.

EMPORIA STATE UNIVERSITY™
1200 Commercial St.
Emporia, KS 66801-5087
USA
620-341-1200
www.emporia.edu

October 17, 2011

Dear Kansas water user:

We are conducting a voluntary survey to estimate the economic impact associated with the spread of zebra mussels in the Neosho River Basin in Kansas, including in operations such as yours. Information from this confidential assessment will be used to help municipalities, industries, and individuals plan for the potential economic impacts of the likely spread of zebra mussels in Kansas, and to independently seek financial assistance for the management and control of zebra mussels in the Neosho River Basin.

Zebra mussels are invasive freshwater mollusks from the Black and Caspian seas of Eastern Europe. They were introduced into the Great Lakes in 1987 by shipping vessels, and have spread quickly throughout the United States. Zebra mussels were first documented in Kansas in 2003 in El Dorado Reservoir. Zebra mussels were discovered in the Neosho River Basin within Marion Reservoir in 2008 and Council Grove City Lake in 2010, and have begun to move downstream into the Cottonwood and Neosho rivers. Adult zebra mussels can reach a maximum size of approximately ¼ inch. They grow in clusters and adhere to hard surfaces such as pipes, trash racks, and filtration screens, and can reach densities such that water can no longer effectively flow through these structures.

I am contacting you in hopes of determining any plans you might have for mitigating the effects of zebra mussels and the costs associated with those efforts. Enclosed you will find a questionnaire. Please answer it to the best of your ability. Any additional comments would be welcomed. Your responses will be kept confidential. I have enclosed a self-addressed, stamped envelope. Please return the questionnaire to me before November 1, 2011. If no response has been received by November 1, 2011, a follow-up letter and additional survey will be mailed. If you have any questions you can contact me by mail at Dept. of Biological Sciences, Campus Box 4050, 1200 Commercial Street, Emporia KS, 66801-5087, by email at bsmith12@emporia.edu, or by phone at 620-341-5101. Thank you very much for your time and assistance.

Sincerely,

Ben Smith

Graduate Research Assistant

Department of Biological Sciences

Encl. 2011 Neosho River Basin Zebra Mussel Economic Survey

Appendix B. Economic survey sent to Neosho and Walnut river basin water rights holders, 2011.

2011 Zebra Mussel Economic Survey

1. Which of the following categories best defines your water usage type? (Please select all that apply.)

- ☐ Municipal
- ☐ Industrial
- ☐ Irrigation
- ☐ Recreation
- ☐ Stock water
- ☐ Sediment storage
- ☐ Other____

2. Are zebra mussels currently present at your facility or intake structures?

- ☐ Yes
- ☐ No
- ☐ Do not know
- ☐ Have not looked

3. Which of the following structures or areas are present at your facility, and where have zebra mussels been detected at your facility? (Please select all that apply.)

		Structure Present		Zebra Mussels Present			
A.	Intake structures	Yes	No	No	Adults	Larvae	Unsure
B.	Pump stations	Yes	No	No	Adults	Larvae	Unsure
C.	Trash racks	Yes	No	No	Adults	Larvae	Unsure
D.	Boats	Yes	No	No	Adults	Larvae	Unsure
E.	Barrier systems, filters, screens, etc.	Yes	No	No	Adults	Larvae	Unsure

F.	Filter beds, filtration media	Yes	No	No	Adults	Larvae	Unsure
G.	Forbays	Yes	No	No	Adults	Larvae	Unsure
H.	Discharge lines	Yes	No	No	Adults	Larvae	Unsure
I.	Condenser units	Yes	No	No	Adults	Larvae	Unsure
J.	Chemical injection systems	Yes	No	No	Adults	Larvae	Unsure
K.	Heat exchangers	Yes	No	No	Adults	Larvae	Unsure
L.	Water locks, or gates	Yes	No	No	Adults	Larvae	Unsure
M.	Intake lakes or reservoirs	Yes	No	No	Adults	Larvae	Unsure
N.	Dam structure	Yes	No	No	Adults	Larvae	Unsure
O.	Dock structure	Yes	No	No	Adults	Larvae	Unsure
P.	Public use areas	Yes	No	No	Adults	Larvae	Unsure

OVER

4. Are any of the following occurring at your facility due to zebra mussel infestation? If so, what approximate **annual** cost can be attributed to this? (Please select all that apply)

Place check if applicable		Approximate **annual** cost
☐	Sampling for adults and juveniles	$__________________
☐	Sampling for larvae (veligers)	$__________________
☐	Increase in worker hours	$__________________
☐	Hiring of additional employees	$__________________
☐	Monitoring programs	$__________________
☐	Replacement of facilities, pumps, piping, etc.	$__________________
☐	Lost productivity due to down time	$__________________
☐	Water wasted	$__________________

- Retrofitting of equipment $___________________
- Installation of chemical injection systems $___________________
- Increases in utility or energy costs $___________________
- Redistribution of work $___________________

- Installation of barrier systems, filters, screens, etc. $___________________
- Increase in chemical costs $___________________
- Physical removal of mussels $___________________
- Increases in corrosion of physical infrastructure $___________________

- Reduction in boater usage, or permits issued $___________________
- Reduction in usage of adjoining parks or recreational areas $___________________
- Reduction in fishing permits issued or the quality of fisheries $___________________

5. Does your facility currently have a program or plan for managing zebra mussels? (Please select all that apply.)

- Zebra mussel prevention plan
- Zebra mussel detection plan
- Zebra mussel mitigation plan
- No Plan. If "No," are you currently treating or managing for zebra mussels in any way? (Please explain.)

____

____

6. Currently, at your facility, are you incurring any additional employee salary costs paid for working additional hours managing zebra mussels that have not been captured in the above questions? If so what is the approximate **annual** salary increase for these employees?

$____________________

7. Are you currently, or do you expect to incur any additional costs due to zebra mussels that have not been captured in the above questions? (Please explain.)

____

____

____

____

Thank You!

Dept. Biol. Sciences, Campus Box 4050, ESU, 1200 Commercial Street, Emporia, KS 66801-5087

Appendix C. Economic survey follow-up cover letter sent to Neosho River Basin water rights holders, November 2011.

EMPORIA STATE UNIVERSITY

1200 Commercial St.
Emporia, KS 66801-5087
USA

620-341-1200
www.emporia.edu

November 1, 2011

Dear Kansas water user:

I have not yet received your response to our mailer survey about zebra mussels sent last month. Your participation in this survey is vital in representing the economic burden placed on Kansas water users in the Neosho River Basin by these invasive mollusks. I have enclosed an additional copy, as well as a self-addressed stamped envelope. I hope you will fill out the survey to the best of your ability and return it by November 15, 2011.

To reiterate the goals of this study, we are conducting a voluntary survey to estimate costs associated with the spread of zebra mussels in the Neosho River Basin in Kansas, including in operations such as yours. Information from this confidential assessment will be used to help municipalities, industries, and individuals plan for the potential economic impacts of the likely spread of zebra mussels in Kansas, and to independently seek financial assistance for the management and control of zebra mussels in the Neosho River Basin.

If you have any questions, you can contact me by mail at Dept. of Biological Sciences, Campus Box 4050, 1200 Commercial Street, Emporia KS, 66801-5087, by email at bsmith12@emporia.edu, or by phone at 620-341-5101. Thank you very much for your time and assistance.

Sincerely,

Ben Smith

Graduate Research Assistant

Department of Biological Sciences

Encl. 2011 Neosho River Basin Zebra Mussel Economic Survey

Appendix D. Economic survey cover letter sent to Walnut River Basin water rights holders, November 2011.

EMPORIA STATE UNIVERSITY™
1200 Commercial St.
Emporia, KS 66801-5087
USA
620-341-1200
www.emporia.edu

November 16, 2011

Dear Kansas water user:

We are conducting a voluntary survey to estimate the economic impact associated with the spread of zebra mussels in Kansas, including in operations such as yours. Information from this confidential assessment will be used to help municipalities, industries, and individuals plan for the potential economic impacts of the likely spread of zebra mussels in Kansas, and to independently seek financial assistance for the management and control of zebra mussels in the state.

Zebra mussels are invasive freshwater mollusks from the Black and Caspian seas of Eastern Europe. They were introduced into the Great Lakes in 1987 by shipping vessels, and have spread quickly throughout the United States. Zebra mussels were first documented in Kansas in 2003 in El Dorado Reservoir. Adult zebra mussels can reach a maximum size of approximately ¼ inch. They grow in clusters and adhere to hard surfaces such as pipes, trash racks, and filtration screens, and can reach densities such that water can no longer effectively flow through these structures.

I am contacting you in hopes of determining any plans you might have for mitigating the effects of zebra mussels and the costs associated with those efforts. Enclosed you will find a questionnaire. Please answer it to the best of your ability. Any additional comments would be welcomed. Your responses will be kept confidential. I have enclosed a self-addressed, stamped envelope. Please return the questionnaire to me before December 1, 2011. If no response has been received by December 1, 2011, a follow-up letter and additional survey will be mailed. If you have any questions you can contact me by mail at Dept. of Biological Sciences, Campus Box 4050, 1200 Commercial Street, Emporia KS, 66801-5087, by email at bsmith12@emporia.edu, or by phone at 620-341-5101. Thank you very much for your time and assistance.

Sincerely,

Ben Smith

Graduate Research Assistant

Department of Biological Sciences

Encl. 2011 Zebra Mussel Economic Survey

Appendix E. Economic survey follow-up cover letter sent to Walnut River Basin water rights holders, December 2011.

EMPORIA STATE UNIVERSITY™
1200 Commercial St.
Emporia, KS 66801-5087
USA
620-341-1200
www.emporia.edu

December 1, 2011

Dear Kansas water user:

I have not yet received your response to our mailer survey about zebra mussels sent last month. Your participation in this survey is vital in representing the economic burden placed on Kansas water users by these invasive mollusks. I have enclosed an additional copy, as well as a self-addressed stamped envelope. I hope you will fill out the survey to the best of your ability and return it by December 15, 2011.

To reiterate the goals of this study, we are conducting a voluntary survey to estimate costs associated with the spread of zebra mussels in Kansas, including in operations such as yours. Information from this confidential assessment will be used to help municipalities, industries, and individuals plan for the potential economic impacts of

the likely spread of zebra mussels in Kansas, and to independently seek financial assistance for the management and control of zebra mussels.

If you have any questions, you can contact me by mail at Dept. of Biological Sciences, Campus Box 4050, 1200 Commercial Street, Emporia KS, 66801-5087, by email at bsmith12@emporia.edu, or by phone at 620-341-5101. Thank you very much for your time and assistance.

Sincerely,

Ben Smith

Graduate Research Assistant

Department of Biological Sciences

Encl. 2011 Zebra Mussel Economic Survey

I, Benjamin R. Smith, hereby submit this thesis/report to Emporia State University as partial fulfillment of the requirements for an advanced degree. I agree that the Library of the University may make it available to use in accordance with its regulations governing materials of this type. I further agree that quoting, photocopying, digitizing or other reproduction of this document is allowed for private study, scholarship (including teaching) and research purposes of a nonprofit nature. No copying which involves potential financial gain will be allowed without written permission of the author. I also agree to permit the Graduate School at Emporia State University to digitize and place this thesis in the ESU institutional repository.

____
Signature of Author

____
Date

____
Zebra Mussels in the Neosho River Basin:
Ecology and Economics

____
Signature of Graduate School Staff

____
Date Received