

Spatial and Temporal Differences in Fish Communities Following Dewatering of an Irrigation Canal

Samuel Wallick¹, Melissa R. Wuellner^{1*}, and Keith D. Koupal²

Abstract - Nebraska has >400 irrigation canals in operation, but few studies have examined fish communities in Great Plains canals to date. Our objective was to compare fish communities longitudinally and annually in 1 Nebraska irrigation canal following annual drawdown. Three isolated pools were sampled annually from 2018 to 2020 using single-pass backpack electrofishing 1 week following canal dewatering. Thirty-nine species were captured across all sites and years, but only 36% were captured every year. Patterns in Shannon-Weiner diversity differed between all 3 sites across years (range = 1.29–2.51). Communities were somewhat similar ($\geq 61\%$ species shared) between years. Findings from this study indicate that canal fish communities are diverse and dynamic, but further research is needed to understand the impacts of dewatering on fish community structure.

Introduction

Prairie streams of North America are highly dynamic systems characterized by variable intra- and inter-annual flows and subsequent changes in water quality and fish communities (Franssen et al. 2006). Recent estimates indicate that approximately 84% of endemic Great Plains fishes are declining or are currently extinct due to habitat fragmentation and dewatering (Hoagstrom et al. 2011, Perkin et al. 2015a). The timing, magnitude, duration, and frequency of flow may influence survival, movement, and spawning activity for many prairie fishes (Carlisle et al. 2009, Falke et al. 2010, Humphries et al. 1999). Consequently, fish community dynamics have also been linked to changes in stream flow (Ostrand and Wilde 2002). Alterations to stream flows due to human activities such as channelization, agricultural modifications of waterways (e.g., irrigated channels), and dewatering may alter fish communities directly by affecting fish movement into and out of streams or indirectly by altering habitat (Bunn and Arthington 2002, Cheng et al. 2016, Fischer and Paukert 2008).

Irrigation for agricultural purposes is 1 factor that leads to stream dewatering throughout the world. Nearly 85% of global water consumption is for agricultural production (Gleick 2003). Demand for agricultural water is seasonal; thus, the hydrology of irrigation canals may differ substantially from that of natural streams (King and O'Connor 2007, Stuart et al. 2019, Thorns and Cullen 1998). The filling of canals with water and the resulting flows may cue fish to move into these waterways in order to feed, reproduce, and avoid predation (Stoffels et al. 2014) or escape desiccation of natural rivers during drier months (Cowley et al. 2007). Both native and non-native fish entrainment in irrigation canals have been documented. *Sander canadensis* Griffith and Smith (Sauger), a native species in the Yellowstone River, was found to have relatively high rates of entrainment in an irrigation canal, which accounted for more than half of all non-fishing mortality from 2001 to 2003 (Jaeger et al. 2005). Cowley et al. (2007) noted that the proportion of non-native fish was much higher (54%) in canals than in the mainstem (11%) of the middle Rio Grande River, New Mexico.

¹ Department of Biology, University of Nebraska at Kearney, 2401 11th Avenue, Kearney, NE 68849-1140

² Nebraska Game and Parks Commission, 1617 First Avenue, Kearney, NE 68847 *Corresponding author: wuellnerm@unk.edu

Once canals cease annual operation, these waterways may dry up completely or become a series of disconnected, intermittent pools (Roberts and Rahel 2008). These intermittent pools may then become sinks for those fish left behind, making fish more susceptible to mortality due to reductions in water quality (e.g., dissolved oxygen) or increased competition and predation (Dunning et al. 1992, Pulliam 1998). Some fish may be able to avoid mortality if they are able to move into other connected areas, such as conjoined streams. For example, the mean relative abundance of ten native species and 1 non-native species increased in a conjoined stream after fall irrigation canal dewatering in south central Nebraska (Davis et al. 2022). Thus, which species persist within watersheds of irrigation canals may depend on their ability and cues to move through connected systems.

Previous research on fish entrainment in canal systems has focused largely on salmonids and other recreationally important species (e.g., *Sander vitreus* Mitchell [Walleye]) due to their economic value and migratory habits that may lead to their increased risk of entrainment (Carlson and Rahel 2007). However, some small-bodied fish, including young-of-the-year of larger fishes, may have the ability to move longer distances through stream networks via drift (Hicks and Servos 2017). Further, smaller fish generally have lower swimming abilities compared to larger fish (Langford et al. 2021) and may not be able to escape to more temporally stable streams once irrigation canals cease annual operation. Many fishes native to Great Plains streams are smaller bodied (Falke et al. 2010, Perkin et al. 2015b), and thus, at potentially greater risk of being trapped in dewatered canals on an annual basis.

Canal operation may affect fish communities differently along a longitudinal gradient as well. Longitudinal variations in stream fish communities and populations have been noted across various ecosystems (Jackson et al. 2001, Roberts and Hitt 2010, Schlosser 1987). Larger fishes tend to be found more often in the lower reaches of stream networks (i.e., higher stream orders) than in the upper reaches (Vannote et al. 1980). Longitudinal differences in fish communities and populations differ for a number of reasons, including, but not limited to, differences in trophic dynamics between smaller and larger order streams (Vannote et al. 1980), the availability of diverse habitats (Schlosser 1987), temporal stability of water (Schlosser 1987, Taylor and Warren 2001), and emigration-immigration dynamics between streams and their tributaries (Osborne and Wiley 1992, Robinson and Rand 2005). In canals, longitudinal gradients in fish communities and populations may be further influenced by upstream and downstream water availability at specific locations as canals dewater. Fausch and Bramblett (1991) found that fish species in isolated pools of intermittent canyon streams in Colorado differed markedly, due in part to local flooding events. To date, no study to our knowledge has examined longitudinal differences in fish communities or populations in canals following annual dewatering events.

Nebraska has an estimated 130,000 km of streams (Young et al. 2019), and over 400 irrigation canals are currently in operation (Susan France, Nebraska Department of Natural Resources, Lincoln, NE, USA, pers. comm.). While streams and canals are prevalent in the state, no studies have evaluated fish communities following canal dewatering to date. The objective of this study was to examine differences in fish communities longitudinally and annually in 1 Nebraska irrigation canal following fall drawdown.

Methods and Materials

The Kearney Canal, used primarily for irrigation but also for hydroelectric power generation and recreation, is located in central Nebraska (Buffalo County; Fig. 1). Nebraska Public Power District oversees canal operations and maintains a water allocation of 1.3 m³/s for irrigation and 9.9 m³/s for hydropower generation as part of the oldest water right in the Platte River. The canal begins as a water diversion of the Middle Channel of the Platte River near Elm Creek,

Nebraska, and continues 25 km east into Kearney Reservoir. Kearney Reservoir is completely dry when the canal is de-watered but is approximately 16 ha in size during the power production and irrigation season. Water is pumped from the reservoir through a hydroelectric facility and discharged into the canal below the spillway. Fish migration upstream from the canal into Kearney Reservoir is not likely, as release from the hydroelectric facility includes a 3-m drop in elevation. The canal below the spillway runs 3 km south to its confluence with Turkey Creek, which then rejoins the Platte River approximately 10 km east of Kearney. Habitat within the Kearney Canal above Kearney Reservoir consists of a concrete lined base, uniform depth, and minimal bends. Below the hydroelectric facility, the canal is mostly straight, with only 1 notable bend <0.5 km downstream of the spillway (Fig. 1), wetted widths are fairly uniform (5–7 m), and water margins are riprap fortified. The bottom substrate is integrated with stone and rock and has been hard packed to allow for more efficient water delivery. However, some vertical head-cutting has resulted in bottom undulations that allow for some static pools to persist when de-watered. The canal typically operates between early May and late October each year. However, the canal was dewatered in mid-September in 2020 due to the need for repairs before winter.

The section of the Kearney Canal between the spillway and Turkey Creek was divided into three approximately equidistant (1 km) reaches (upper, middle, and lower). In 2018, the reaches were visually surveyed to identify isolated pools that remained following the annual drawdown, and 1 site was selected from each reach, based on accessibility (e.g., public access, bank slope). Lengths of each site varied; the lower site was the longest (72.0 m), followed by the upper (52.6 m) and the middle sites (44.6 m). No wetted widths were recorded, as these were not used to calculate the length of reach sampled; rather, we sampled the length of the isolated pool available. The pools did maintain similar wetted widths following canal dewatering as they had during the irrigation season. Each of the 3 sites were sampled once per year from 2018 to 2020 1 week following annual drawdown. Each site was enclosed on the upper and lower ends by block nets (1.2 × 20 m, 6.4-mm mesh). In 2018, triple-pass backpack electrofishing depletion without replacement was used in an attempt to estimate population sizes. However, single-pass backpack electrofishing was used in 2019 and 2020, due to unsuccessful depletion efforts in 2018. Only data from the first pass at each site was used from the 2018 sampling for all calculations in order

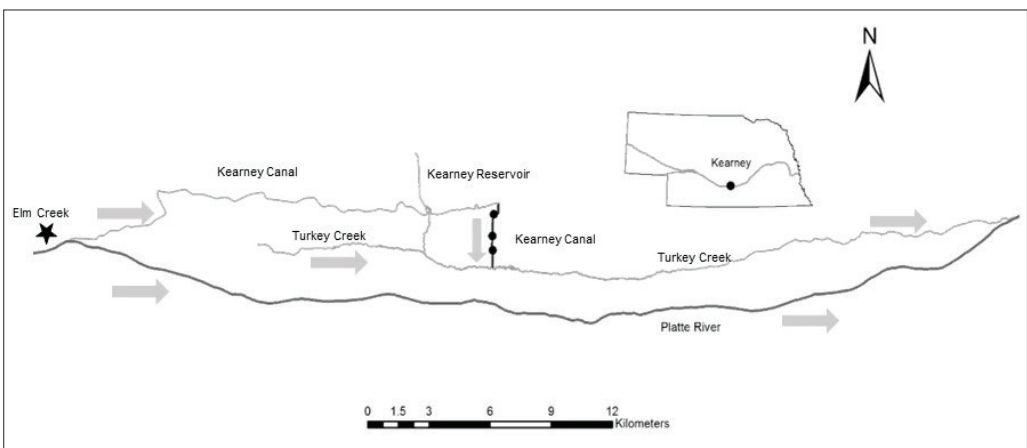


Figure 1. Locations of the three sites within the Kearney Canal sampled for this study. The canal begins near the town of Elm Creek, Nebraska, flows east into Kearney Reservoir, and then joins Turkey Creek approximately 3 km downstream. The study area is represented by the darkened stream segment, and the 3 sites sampled are represented by the black circles. The black square denotes the approximate location of Kearney Reservoir. Gray arrows denote directions of flow.

to be comparable to the data for 2019 and 2020. Fish captured at each site were identified to species and counted. No measures of habitat were taken during sampling. Species occurrences at each site and by year were used to calculate richness, Shannon-Weiner diversity (H' ; Shannon 1948), and Pielou’s (J' ; Pielou 1966) index of evenness to identify spatial and temporal patterns. Jaccard’s index of similarity (J ; Jaccard 1901) was calculated between sites within a year and between years by combining data for all sites for that year.

Results

A total of 6029 total fish representing 39 species were captured across all 3 years and all sites (Table 1). The highest number of fish were captured in 2018 ($n = 3003$), and the lowest number of fish were captured in 2020 ($n = 820$). Only 21% of these species were captured at all 3 sites across all 3 years; 13% of species were only captured at 1 site across all three years, and 8% were only captured during 1 year of the study (Table 1). Mean species richness was consistent across all 3 sites from 2018 (19 ± 1 [standard error]) to 2020 (22 ± 2). Species richness for the lower site was the lowest of all sites in 2018 and 2019 but highest among the three sites in 2020 (Fig. 2). Similar to species richness, mean H' (1.54 ± 0.14 v. 2.28 ± 0.13) and J' (0.53 ± 0.05 v. 0.74 ± 0.04) also increased across all three sites from 2018 to 2020. Shannon’s diversity (Fig. 3) and species evenness (Fig. 4) were highest at the middle and lower sites in 2020 and at the upper site in 2019. Fish communities were more similar across all three sites in 2020 than during the other two years (Fig. 5). Additionally, fish communities were somewhat similar between years (J [2018–2019] = 62.2%; J [2019–2020] = 66.7%; J [2018–2020] = 61.1%).

Discussion

Irrigation canals are common features on the landscape of Nebraska, yet no studies have been conducted to evaluate fish communities within these systems to our knowledge. The canal in this study supported a higher-than-expected number of species across all years, including native ($n = 36$) and recreationally regulated ($n = 13$) fishes. Species found over the course of the study also included fishes with small (<130 mm total length; $n = 12$) and larger ($n = 24$) maximum body lengths. All species have been collected previously in the Platte River above and below the Kearney Canal (Hrabik et al. 2015), and more than half (56%) have been collected in Turkey Creek above its confluence with the Kearney Canal (Davis et al. 2022). No species

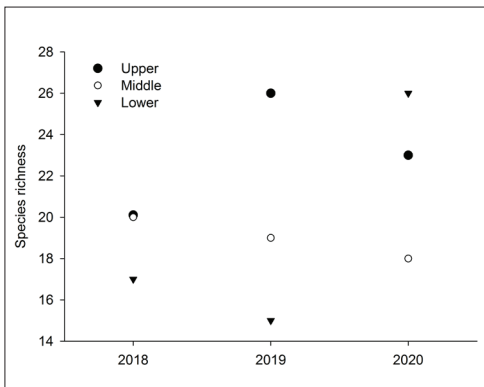


Figure 2. Comparison of fish species richness by site and year in the Kearney Canal following drawdown in 2018 through 2020.

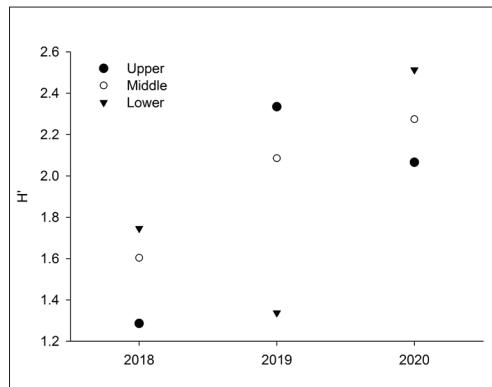


Figure 3. Comparison of Shannon-Weiner diversity (H') by site and year in the Kearney Canal following drawdown in 2018 through 2020.

of concern at the state or federal level were found throughout all years of sampling. Other research around the globe has recognized the importance of irrigation canals as rich sources of fish diversity and potential refugia for threatened fishes (Lakra et al. 2011) and as important ecological corridors for fishes under stress (e.g., dewatering) in nearby rivers and streams (Aspe et al. 2014). The importance of canals to local diversity is likely related to the distance between the location and the diverted river, discharge, and the habitat provided at the location (Aspe et al. 2014). In our study, we were unable to distinguish whether fish were year-round residents of

Common name	Scientific name	Upper	Middle	Lower
Bigmouth buffalo	<i>Ictiobus cyprinellus</i> Valenciennes	x, z	x	x, z
Bigmouth shiner	<i>Notropis dorsalis</i> Agassiz			z
Black bullhead	<i>Ameiurus melas</i> Rafinesque	x, y	x, y	
Black crappie	<i>Pomoxis nigromaculatus</i> Lesueur	y, z	x, z	z
Bluegill	<i>Lepomis macrochirus</i> Rafinesque	x, y, z	x, y, z	x, y, z
Brassy minnow	<i>Hybognathus hankinsoni</i> Hubbs			y
Channel catfish	<i>Ictalurus punctatus</i> Rafinesque	x, y, z	x, y, z	x, y, z
Common carp*	<i>Cyprinus carpio</i> Linnaeus	x, y, z	x, y, z	x, y, z
Fathead minnow	<i>Pimephales promelas</i> Rafinesque			y
Flathead catfish	<i>Pylodictis olivaris</i> Rafinesque		y, z	z
Flathead chub	<i>Platygobio gracilis</i> Richardson	x		
Freshwater drum	<i>Aplodinotus grunniens</i> Rafinesque	x, y, z	x, y, z	z
Gizzard shad	<i>Dorosoma cepedianum</i> Lesueur		x	
Goldeye	<i>Hiodon alosoides</i> Rafinesque	y, z	z	
Grass carp*	<i>Ctenopharyngodon idella</i> Valenciennes	z	z	z
Green sunfish	<i>Lepomis cyanellus</i> Rafinesque	x, y, z	x, y, z	x, y, z
Largemouth bass	<i>Micropterus salmoides</i> Lacepède	x, y, z	x, y	x
Longnose dace	<i>Rhinichthys cataractae</i> Valenciennes			x
Longnose gar	<i>Lepisosteus osseus</i> Linnaeus	y, z	z	z
Orangespotted sunfish	<i>Lepomis humilis</i> Girard	x, y, z	x, y, z	x, y, z
Quillback	<i>Carpionodes cyprinus</i> Lesueur	x, y, z	x, y, z	x, y, z
Red shiner	<i>Cyprinella lutrensis</i> Baird and Girard	y, z	x, z	x, y, z
River carpsucker	<i>Carpionodes carpio</i> Rafinesque	x, y, z	x, y, z	x, y, z
River shiner	<i>Notropis blennioides</i> Girard	y		y
Sand shiner	<i>Notropis stramineus</i> Cope	y		x, y
Sauger	<i>Sander canadensis</i> Griffith and Smith	x, y, z	x	z
Shorthead redhorse	<i>Moxostoma macrolepidotum</i> Lesueur	x, y, z	x, y, z	x, y, z
Shortnose gar	<i>Lepisosteus platostomus</i> Rafinesque	x, y, z	z	z
Silver chub	<i>Macrhybopsis storeriana</i> Kirtland			x, z
Smallmouth bass	<i>Micropterus dolomieu</i> Lacepède	z	x, y	x, y, z
Smallmouth buffalo	<i>Ictiobus bubalis</i> Rafinesque	y, z	x, y, z	z
Stoneroller	<i>Noturus flavus</i> Rafinesque	x, z	y, z	x, z
Suckermouth minnow	<i>Phenacobius mirabilis</i> Girard	x		z
Walleye	<i>Sander vitreus</i> Mitchill	x, y, z		x, z
Western mosquitofish*	<i>Gambusia affinis</i> Baird and Girard	x, y	y	z
White bass	<i>Morone chrysops</i> Rafinesque	y	y	y, z
White crappie	<i>Pomoxis annularis</i> Rafinesque	y, z	x	
White sucker	<i>Catostomus commersonii</i> Lacepède	y	y	
Yellow bullhead	<i>Ameiurus natalis</i> Lesueur	x, y	x, y	

Table 1. List of species collected in the Kearney Canal from 2018 to 2020 by site and year (x = species captured in 2018, y = species captured in 2019, z = species captured in 2020). Species are listed in alphabetical order by common name. Asterisks denote non-native species in the state of Nebraska.

the Kearney Canal or moved into the canal from the Platte River at some point during the irrigation season. Understanding fish movement into and out of canals within and between years will provide important information on services and bottlenecks of irrigation systems.

While we were unable to sample the Kearney Canal during operation due to high flows, sampling fish that remained following canal dewatering provided some important information on which species use this canal during at least a portion of the year and may be affected by annual canal water cycles. Identifying the characteristics of fish species that remained at a given site can inform managers regarding the physical and chemical factors of canals influencing their likelihood of being sinks for some species and not others. Important characteristics of the fish to consider include, but are not limited to, fish age, body size, body shape, and guild. Previous research has noted that small fish, particularly young-of-the-year, may be more likely to be stranded following dewatering events than older fish, and smaller fishes that are stranded are subjected to higher levels of intraspecific competition that may decrease their short-term survival (Saltveit et al. 2001). Morphology (e.g., body shapes, fin forms) influences swimming ability, and some morphological characteristics have been linked to the likelihood of fish being stranded in dewatered conditions (Bradford 1997, Nagrodski et al. 2012, Wolter and Arlinghaus 2003). Some reproductive guilds such as pelagic spawners have experienced declines in Great Plains streams due to reduced hydrologic flows over decades (Perkin et al. 2015a, 2015b). Many canals lack diverse habitat (e.g., flow and substrate) and are disturbed systems by nature; lotic systems lacking in habitat diversity but heavy in human disturbance tend to support more generalist feeders (Rahel and Hubert 1991, Bramblett et al. 2005). Although we did not directly examine fish age or size, morphological characteristics, or reproductive, feeding, or tolerance guilds in our study, we did note some important relevant patterns in our fish communities across all 3 sites. First, more than half (59%) of our species would be considered small-bodied at their maximum sizes (e.g., most cyprinids) or were represented by young-of-the-year (e.g., many centrarchids, some ictalurids). Additionally, many of our species in the Kearney Canal are typical of other Great Plains lotic communities, with more fusiform body shapes, generalist food habits, and moderate to full tolerance (Bramblett et al. 2005). Further research and analyses are needed to understand the characteristics of fishes that more likely remain in canals following dewatering and how dewatering impacts community structure and distribution of reproductive and feeding guilds over time.

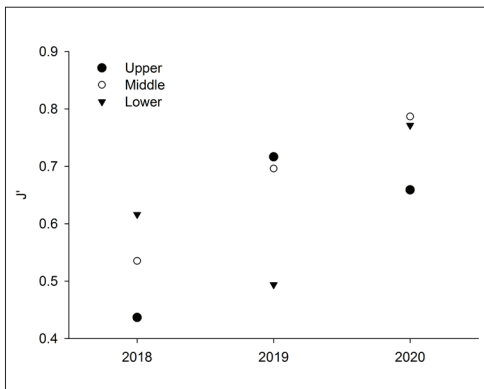


Figure 4. Comparison of species evenness (J') by site and year in the Kearney Canal following drawdown in 2018 through 2020.

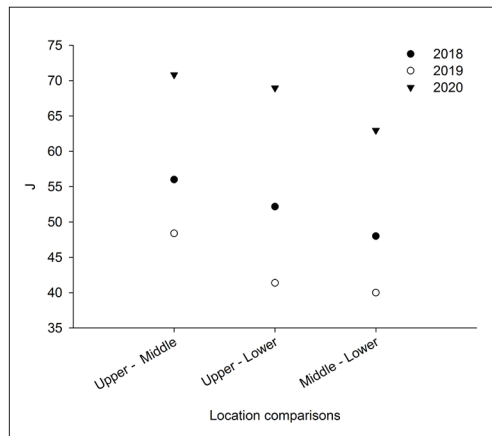


Figure 5. Jaccard's index of fish community similarity (J) between sites by year in the Kearney Canal following drawdown in 2018 through 2020.

In addition, environmental characteristics at landscape and site-specific scales may lead to increased rates of fish stranding. Characteristics that operate at larger scales to influence fish stranding include cooler water temperatures (Saltveit et al. 2001), longer wetted periods (Irvine et al. 2009), and the rate of dewatering (i.e., faster reductions in water increase stranding potential; Hunter 1992). The habitat within each location may also influence what fishes are found at specific sites following canal dewatering. While we did not measure habitat characteristics as part of this study, we did note some basic morphological differences between sites. For example, the upper site has the deepest and longest pool located at a substantial bend in the canal. In contrast, the middle and lower sites had straight channels with only some variation in water depth. Pool area and depth influence the persistence of available water during drier periods (Capone and Kushlan 1991), and fish may be able to use pools as refugia when canals are dewatered. However, fish may not always be selective at choosing pools during stream drying, and the persistence of fish within individual pools may be influenced by the presence and abundance of competitors and predators also stranded at those same locations (Magoulick 2000). Given the level of similarity in fish communities between sites, the generalist nature of many species collected, and the time of year of collection (i.e., several months after spawning), it is possible that many species in our study are not choosing habitats as water in the canal recedes. Rather, fish may just become stranded randomly at locations that have water, and deeper pools have more area to support more fish, at least temporarily. Further research is needed to understand the movement of fish in relation to canal dewatering and to identify characteristics of fish and habitat that may lend to the persistence of fish when canals are dewatered.

While the fish communities at each site of this study were fairly similar between years across all three sites, the longitudinal patterns of species richness, diversity, and evenness differed each year. Lotic fish communities often follow a general longitudinal pattern of species richness and diversity (Vannote et al. 1980, Oberdorff et al. 1993), and these patterns can be more consistent when water levels at specific sites are relatively stable. For example, Fausch and Bramblett (1991) found that fish species composition and relative abundance remained relatively constant over time within deep, complex pools of intermittent canyon tributaries of the Purgatory River, Colorado. In our study, hydrological patterns were variable between years. In July 2019, a 500-year flood event that took place in the city of Kearney three months prior to canal drawdown. This rapid and short-term event connected multiple discrete bodies of water that each had fish. Abundance of fish and species richness have been shown to increase due to flooding, especially when floods help fish to bypass barriers that exist when flows are normal (Franssen et al. 2006). Thus, we expected that the lower site (the site most connected to the flood event) would have higher richness and diversity after that event. Instead, both were lowest at that site in that year. Perhaps the flood event cued fish to leave the Kearney Canal to seek refugia elsewhere (Marshall et al. 2016). Previous research on Turkey Creek which connects to the Kearney Canal (see Fig. 1) has indicated that fish may move between these two systems when canal operation changes (Davis et al. 2022), so it may be possible that the fish at that lowest site moved into 1 of four locations: Turkey Creek, upstream in the canal, a manmade lake adjacent to the canal, or the Platte River downstream. One year later, the Kearney Canal was dewatered over a month earlier (September 2020) than normal (late October in 2018 and 2019). Air and, thus, water temperatures were warmer at the time of fish sampling in 2020 compared to other years. This was the only year in our study that species richness and diversity were highest at the lower site compared to the upper site. Previous research has noted the influence of lower water temperature on fish stranding for salmonids (Saltveit et al. 2001). Warmwater fishes may move at greater rates when water temperatures are warmer (Todd and Rabeni 1989), but no studies to our knowledge have linked warmwater fish movement to stranding. Further

research is needed to understand how hydrological patterns before dewatering and the timing of dewatering influence fish communities in irrigation canals once operation ceases.

Overall, this study provides some of the first research on the potential impacts of irrigation canal operation on fish communities following annual dewatering. Water demand for irrigation is expected to increase around the world (Gleick 2018, Hedden and Gido 2020); thus, impacts to fish communities will be ongoing. Further, irrigation canals may provide some additional recreational opportunities (e.g., recent development of the Kearney Canal Whitewater Park; Davis et al. 2022) that could also influence water management into the future. Understanding how fish communities respond to anthropogenically-induced changes to flow can be used to support reproduction, growth, and survival of native species (Cowley et al. 2007) and manage or control the spread of non-native species (Brown and Ford 2002, Hopper et al. 2020, Rogosch et al. 2019). In all, identifying how fish communities in irrigation canals change spatially and temporally can help inform water and fisheries managers in maintaining society's needs for water while simultaneously supporting fish communities.

Acknowledgements

We thank the Nebraska Game and Parks Commission for their aid in the field and use of equipment. Appreciation is extended to Gabrielle Buttermore, Thyme Cooke, Riley Couch, Will Frisch, Abby Kessler, Josh Kreitman, Tony Long, Brian Mason, Nicole Mittman, the students of BIOL 472/872 in fall 2019, and a number of University of Nebraska-Lincoln students for their assistance in field collections throughout this study. Special thanks are extended to the Nebraska Public Power District for granting permission to access the canal sites on an annual basis. We appreciate the comments and edits provided by B.J. Schall and two anonymous reviewers. This research protocol was approved by the University of Nebraska Institutional Animal Care and Use Committee (Project #080817).

Literature Cited

- Aspe, C.A. Gilles, and M. Jacqué. 2014. Irrigation canals as tools for climate change adaptation and fish biodiversity management in southern France. *Regional Environmental Change* 16:1975–1987.
- Bradford, M.J. 1997. An experimental study of stranding of juvenile salmonids on gravel bars and inside channels during flow decreases. *Regulated Rivers: Research and Management* 13:395–401.
- Bramblett, R.G., T.R. Johnson, A.V. Zale, and D.G. Heggem. 2005. Development and evaluation of a fish assemblage index of biotic integrity for northwestern Great Plains streams. *Transactions of the American Fisheries Society* 134:624–640.
- Brown, L.R., and T. Ford. 2002. Effects of flow on the fish communities of a regulated California River: Implications for managing native fishes. *River Research and Applications* 18:331–342.
- Bunn, S.E., and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30:492–507.
- Capone, T.A., and J.A. Kushlan. 1991. Fish community structure in dry-season stream pools. *Ecological Society of America* 72:983–992.
- Carlisle, D.M., J. Falcone, D.M. Wolock, M.R. Meador, and R.H. Norris. 2009. Predicting the natural flow regime: Models for assessing hydrological alteration in streams. *River Research and Applications* 26:118–136.
- Carlson, A.J., and F.J. Rahel. 2007. A basinwide perspective on entrainment of fish in irrigation canals. *Transactions of the American Fisheries Society* 136:1335–1343.
- Cheng, S.T., E.E. Herricks, W.P. Tsai, and F.J. Chang. 2016. Assessing the natural and anthropogenic influences on basin-wide fish species richness. *Science of the Total Environment* 572:825–836.
- Cowley, D.E., R.C. Wissmar, and R. Sallenave. 2007. Fish assemblages and seasonal movements of fish in irrigation canals and river reaches of the middle Rio Grande, New Mexico (USA). *Ecology of Freshwater Fish* 16:548–558.

S. Wallick, M. R. Wuellner, and K. D. Koupal

- Davis, J.L., K.D. Koupal, M.R. Wuellner, and B. Roberg. 2022. Impact of irrigation canal operation on the fish assemblage and biomass of a connected stream. *Great Plains Research* 32:29–37.
- Dunning, J.B., B.J. Danielson, and H.R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. *Oikos* 65:169–175.
- Falke, J.A., K.R. Bestgen, and K.D. Fausch. 2010. Streamflow reductions and habitat drying affect growth, survival, and recruitment of brassy minnow across a Great Plains riverscape. *Transactions of the American Fisheries Society* 139:1566–1583.
- Fausch, K.D., and R.G. Bramblett. 1991. Disturbance and fish communities in intermittent tributaries of a western Great Plains river. *Copeia* 1991:659–674.
- Fischer, J.R., and C.P. Paukert. 2008. Historical and current environmental influences on an endemic Great Plains fish. *American Midland Naturalist* 159:364–377.
- Franssen, N.R., K.B. Gido, C.S. Guy, J.A. Tripe, S.J. Shrank, T.R. Strakosh, K.N. Bertrand, C.M. Franssen, K.L. Pitts, and C.P. Paukert. 2006. Effects of floods on fish assemblages in an intermittent prairie stream. *Freshwater Biology* 51:2072–2086.
- Gleick, P.H. 2003. Water use. *Annual Review of Environment and Resources* 28:275–314.
- Gleick, P.H. 2018. Transitions to freshwater sustainability. *Proceedings of the National Academy of Sciences of the United States of America* 115:8863–8871.
- Hedden, S.C., and K.B. Gido. 2020. Dispersal drives changes in fish community abundance in intermittent stream networks. *River Research and Applications* 36:797–806.
- Hicks, K.A., and M.R. Servos. 2017. Site fidelity and movement of a small-bodied fish species, the rainbow darter (*Etheostoma caeruleum*): Implications for environmental effects assessment. *River Research and Applications* 33:1016–1025.
- Hoagstrom, C.W., J.E. Brooks, and S.R. Davenport. 2011. A large-scale conservation perspective considering endemic fishes of the North American plains. *Biological Conservation* 144:21–34.
- Hopper, G.W., K.B. Gido, C.A. Pennock, S.C. Hedden, B.D. Frenette, N. Barts, C.K. Hedden, and L.A. Bruckerhoff. 2020. Nowhere to swim: Interspecific responses of prairie stream fishes in isolated pools during severe drought. *Aquatic Sciences* 82:1–15.
- Hrabik, R.A., S.C. Schainost, R.H. Stasiak, E.J. Peters. 2015. *The Fishes of Nebraska*. University of Nebraska–Lincoln.
- Humphries, P., A.J. King, and J.D. Koehn. 1999. Fish, flows and flood plains: Links between freshwater fishes and their environment in the Murray-Darling River system, Australia. *Environmental Biology of Fishes* 56:129–151.
- Hunter, M.A. 1992. Hydropower flow fluctuations and salmonids: A review of the biological effects, mechanical causes and options for mitigation. Washington Department of Fisheries Technical Report No. 119, Olympia, WA. 58 pp.
- Irvine, R.L., R. Oussoren, J.S. Baxter, and D.C. Schmidt. 2009. The effects of flow reduction rates on fish stranding in British Columbia, Canada. *River Research and Application* 25:405–415.
- Jackson, D.A., P.R. Peres-Neto, and J.D. Olden. 2001. What controls who is where in freshwater fish communities — The roles of biotic, abiotic, and spatial factors. *Canadian Journal of Fisheries and Aquatic Sciences* 58:157–170.
- Jaccard, P. 1901. Distribution of the Alpine flora in the Dranse's Basin and some neighbouring regions. *Bulletin de la Societe vaudoise des Sciences Naturelles* 37:241–72.
- Jaeger, M.E., A.V. Zale, T.E. McMahon, and B.J. Schmitz. 2005. Seasonal movements, habitat use, aggregation, exploitation, and entrainment of saugers in the lower Yellowstone River: An empirical assessment of factors affecting population recovery. *North American Journal of Fisheries Management* 25:1550–1568.
- King, A.J., and J.P. O'Connor. 2007. Native fish entrapment in irrigation systems: A step towards understanding the significance of the problem. *Ecological Management and Restoration* 8:32–37.
- Lakra, W.S., U.K. Sarkar, V.K. Dubey, R. Sani, and A. Pandey. 2011. River inter linking in India: Status, issues, prospects, and implications on aquatic ecosystems and freshwater diversity. *Reviews in Fish Biology and Fisheries* 21:463–479.
- Langford, M.T., D.Z. Zhu, A. Leake, and S.J. Cooke. 2021. Hydropower intake-induced fish entrainment risk zone analysis. *Canadian Journal of Civil Engineering* 48:284–297.

S. Wallick, M. R. Wuellner, and K. D. Koupal

- Magoulick, D.D. 2000. Spatial and temporal variation in fish assemblages of drying stream pools: The role of abiotic and biotic factors. *Aquatic Ecology* 34:29–41.
- Marshall, J.C., N. Menke, D.A. Crook, J.S. Lobegeiger, S.R. Balcombe, J.A. Huey, J.H. Fawcett, N.R. Bond, A.H. Starkey, D. Sternberg, S. Linke, and A.H. Arthington. 2016. Go with the flow: The movement behavior of fish from isolated waterhole refugia connecting flow events in an intermittent dryland river. *Freshwater Biology* 61:1242–1258.
- Nagrodski, A., G.D. Raby, C.T. Hasler, M.K. Taylor, and S.J. Cooke. 2012. Fish stranding in freshwater systems: Sources, consequences, and mitigation. *Journal of Environmental Management* 103:133–141.
- Oberdorff, T., E. Guilbert, and J.C. Lucchetta. 1993. Patterns of fish species richness in the Seine River basin, France. *Hydrobiologia* 259:157–167.
- Osborne, L.L., and M.J. Wiley. 1992. Influence of tributary spatial position on the structure of warmwater fish communities. *Canadian Journal of Fisheries and Aquatic Sciences* 49:671–681.
- Ostrand, K.G., and G.R. Wilde. 2002. Seasonal and spatial variation in a prairie stream-fish assemblage. *Ecology of Freshwater Fish* 11:137–149.
- Perkin, J.S., K.B. Gido, K.H. Costigan, M.D. Daniels, and E.R. Johnson. 2015a. Fragmentation and drying ratchet down Great Plains stream fish diversity. *Aquatic Conservation: Marine and Freshwater Ecosystems* 25:500–516.
- Perkin, J.S., K.B. Gido, A.R. Cooper, T.F. Turner, M.J. Osborne, E.R. Johnson, K.B. Mayes, and C. Nilsson. 2015b. Fragmentation and dewatering transform Great Plains stream fish communities. *Ecological Monographs* 85:73–92.
- Pielou, E. 1966. The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology* 13:131–144.
- Pulliam, H.R. 1998. Sources, sinks, and population regulation. *American Society of Naturalists* 132:652–661.
- Rahel, F.J., and W.A. Hubert. 1991. Fish assemblages and habitat gradients in a Rocky Mountain–Great Plains stream: Biotic zonation an additive patterns of community change. *Transactions of the American Fisheries Society* 120:319–332.
- Roberts, J.H., and N.P. Hitt. 2010. Longitudinal structure in temperate stream fish communities: evaluating conceptual models with temporal data. *American Fisheries Society Symposium* 73:281–299.
- Roberts, J.J., and F.J. Rahel. 2008. Irrigation canals as sink habitat for trout and other fishes in a Wyoming drainage. *Transactions of the American Fisheries Society* 137:951–961.
- Robinson, J.L., and P.S. Rand. 2005. Discontinuity in fish assemblages across an elevation gradient in a southern Appalachian watershed, USA. *Ecology of Freshwater Fish* 14:14–23.
- Rogosch, J.S., J.D. Tonkin, D.A. Lytle, D.M. Merritt, L.V. Reynolds, and J.D. Olden. 2019. Increasing drought favors nonnative fishes in a dryland river: Evidence from a multispecies demographic model. *Ecosphere* 10:1–19.
- Saltveit, S.J., J.H. Halleraker, J.V. Arnekleiv, and A. Harby. 2001. Field experiments on stranding in juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) during rapid flow decreases caused by hydropeaking. *River Research and Applications* 17:609–622.
- Schlosser, I.J. 1987. A conceptual framework for fish communities in small warmwater streams. Pp. 17–24. In W.J. Matthews and D.C. Heins (Eds.). *Community and Evolutionary Ecology of North American Stream Fishes*. University of Oklahoma Press, Norman, OK, USA. 310 pp.
- Shannon, C.E. 1948. A mathematical theory of communication. *Bell System Technical Journal* 27:379–423.
- Stoffels, R.J., K.R. Clarke, R.A. Rehwinkel, and B.J. McCarthy. 2014. Response of a floodplain fish community to river-floodplain connectivity: Natural versus managed reconnection. *Canadian Journal of Fisheries and Aquatic Sciences* 71:236–245.
- Stuart, I., C. Sharpe, K. Stanislawski, A. Parker, and M. Mallen-Cooper. 2019. From an irrigation system to an ecological asset: Adding environmental flows establishes recovery of a threatened fish species. *Marine and Freshwater Research* 70:1295–1306.
- Taylor, C.M., and M.L. Warren. 2001. Dynamics in species composition of stream fish assemblages: Environmental variability and nested subsets. *Ecology* 82:2320–2330.

S. Wallick, M. R. Wuellner, and K. D. Koupal

- Thorns, M., and P. Cullen. 1998. The impact of irrigation withdrawals on inland river systems. *Rangeland Journal* 20:226–236.
- Todd, B.L., and C.F. Rabeni. 1989. Movement and habitat use by stream-dwelling smallmouth bass. *Transactions of the American Fisheries Society* 118:229–242.
- Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:130–137.
- Wolter, C., and R. Arlinghaus. 2003. Navigation impacts on freshwater fish assemblages: The ecological relevance of swimming performance. *Reviews in Fish Biology and Fisheries* 13:63–89.
- Young, A.R., M.E. Burbach, L.M. Howard, and S.O. Lackey. 2019. Nebraska statewide groundwater-level monitoring report 2018. Nebraska Water Survey Paper Number 86. Institute of Agriculture and Natural Resources, University of Nebraska—Lincoln, Lincoln, NE, USA. 24 pp.