THE ROLE OF TRIBUTARIES AND RIVER PLUMES AS NURSERY AREAS FOR YELLOW PERCH AND ROUND GOBIES IN LAKE MICHIGAN

Final Report

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Project Overview

Inter-annual recruitment variability influences management of Lake Michigan fish populations. Heterogeneous habitats in Lake Michigan likely contribute to this variability, yet the mechanistic influence of these habitats on recruitment is thus far poorly understood. River plumes are locations with highly variable and diverse habitats for young fish in Lake Michigan, and therefore may play an important role in recruitment dynamics for important species such as yellow perch and round gobies. However, due to the complex nature of the aquatic environment near tributaries, novel approaches must be used to collect samples and measurements that can help shed light on these areas.

We hypothesized that tributaries and river plumes are important environments for young yellow perch and round gobies in Lake Michigan. These habitats likely provide favorable environments for larval fish growth because of their unique thermal, light, nutrient, and biological properties. Our objectives and methods to address this hypothesis were:

1) Describe the physical, chemical and biotic conditions within river plumes in comparison to adjacent non-plume areas.
2) Estimate the movement of larval fish from tributaries into Lake Michigan and compare densities, diets and growth rates of larval and juveniles yellow perch, alewife and round gobies in river mouths, river plumes and adjacent non-plume areas.
3) Evaluate the extent to which later stage yellow perch, round gobies and alewife utilized tributaries and river plumes as early life habitats.

Summary of Project Findings

Physical plume dynamics

- Spatial extent of plumes differs greatly among sites and dates.
- Plumes can be tracked using measures of conductivity or water isotopes.
- Majority of plumes were fairly small.
- During spring and summer, the relatively large plume in St. Joseph almost always traveled along shore, was positively buoyant and had a lift-off point in the river channel. This plume rarely exceeded 2 km^2 and residence time of the plume was consistently <1 day.
- During late spring and summer, vertical extent of plumes was limited (within 2m of surface). However, in early spring and late fall, plumes can be negatively buoyant.
- Trail Creek plume was much smaller and on several occasions water flowed from Lake Michigan into Trail Creek Harbor.

River mouth and plume physico-chemical characteristics

- During late spring and summer, river mouths were consistently warmer, more turbid and had higher nutrient concentrations, chlorophyll and conductivity than nearshore Lake Michigan.
- Environmental conditions (temperature, water clarity, nutrient concentrations, chlorophyll, conductivity, etc) at Lake Michigan sites near rivermouths (particularly near St. Joseph) tended be more similar to environmental conditions in the river mouth than sites further from river mouths.
- Environmental conditions at sites in Lake Michigan near St. Joseph tended to be more variable relative to sites near Trail Creek.
- Due to positive buoyancy, sites which were plume influenced tended to have vertical structure in temperature (warmer near surface) and light attenuation (more turbid near surface).
- Within plumes, water quality (e.g., nutrient concentrations) is primarily controlled by mixing of river and lake water. Biological processing has some effect but is minor relative to effect of mixing.

Lower trophic level characteristics

- Zooplankton in both river mouths and nearshore Lake Michigan were dominated by small-bodied animals.
- During late spring and early summer, zooplankton concentrations were highly variable but were on average greater in nearshore Lake Michigan than in St. Joseph and Trail Creek rivermouths.
- Benthic macroinvertebrate densities were greater in rivermouths than nearshore Lake Michigan. However, types of benthic macroinvertebrates were generally similar between the two types of habitats.

Larval yellow perch and alewife

- Larval alewife densities were on average greater in St. Joseph and Trail Creek river mouths than in nearshore Lake Michigan.
- Vice versa, larval yellow perch densities were on average greater in nearshore Lake Michigan than in these river mouths.
- We collected relatively small larval alewife and larval yellow perch.
- Many larval fish had no food in their digestive tracts (perhaps because a) they were very young and in some cases still feeding exogenously and b) prey availability was limited).
- Common diet items included dreissenid veligers, copepod nauplii and diatoms.
- Growth of larval alewife was greater in river mouths than in nearshore Lake Michigan.

Diets and trophic connections of juvenile and small adult fishes

- We analyzed diets, fatty acid content and soft tissue stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$, and $\delta^{18}O$) of yellow perch, round goby and alewife collected in different river mouths and nearshore Lake Michigan habitats.
- Generally fish had similar diets items in digestive tracts across habitats.
- Stable isotope ratios (and to a lesser extent fatty acids) were distinct across habitats for yellow perch and round goby.
- However, more migratory alewife displayed similar isotope ratios across habitats.

Movements and natal origin of juvenile and small adult fishes

- We measured $\delta^{13}C$ and $\delta^{18}O$ isotopic composition in the core and outer edge (representing natal and recent environment) of otoliths from juvenile and adult yellow perch, round goby and alewife collected in different habitats.
- Analysis of water isotopes and $\delta^{13}C$ and $\delta^{18}O$ composition of dreissenid mussel shells from different habitats, demonstrate that isotopic signatures are distinct between river mouth and nearshore lake habitats, justifying their analyses from otolith samples for habitat discrimination.
- Yellow perch showed very limited evidence of movement between river mouths and nearshore Lake Michigan. $\delta^{13}C$ and $\delta^{18}O$ values from both the core and edge of yellow perch otoliths suggested that they had spent their entire life in the habitat of capture.
- Round goby showed strong discrimination between river mouth and nearshore Lake Michigan otolith outer edge $\delta^{13}C$ and $\delta^{18}O$ values, suggesting that they had spent recent life in the habitat of capture. However, there was substantial overlap between otolith core values for gobies collected from different habitats; specifically, many round gobies collected inside river mouths had otolith core composition indicative of early life in Lake Michigan.
- Alewife otolith $\delta^{13}C$ and $\delta^{18}O$ values did not consistently differ among habitats. Interestingly, for this more migratory species, there was clear discrimination between otolith core and edge $\delta^{13}C$ and $\delta^{18}O$ values, with edge values generally indicating recent life in Lake Michigan, while core values suggested at least some contribution from tributary environments.

Summary of Project Products

Student thesis

Completed:

Grimm, E.F. "Characterization and mapping of buoyant river plumes in southern Lake Michigan". M.S. Thesis, Purdue University (C. Troy major advisor).

Forthcoming:

Stein, S.R. PhD Dissertation, Purdue University (T. Höök major advisor)

Essig, R. PhD Dissertation, Purdue University (C. Troy major advisor)

Jameel, M.Y. PhD Dissertation, University of Utah (G. Bowen major advisor)

Presentations

Stein, S. R., Guffey, S., Bowen, G.J., Troy, C.D., and Höök, T.O. 2015. Resource Subsidies for Young Fish in Southern Lake Michigan Rivermouths. Oral Presentation. *75th Midwest Fish and Wildlife Conference*. Indianapolis, Indiana, USA, February 8 – 11.

Stein, S. R., Jameel, Y., Bowen, G.J., Troy, C.D., and Höök, T.O. 2014. The Role of Rivermouths in Young Fish Growth and Resource Utilization in Southern Lake Michigan. Oral Presentation. *American Fisheries Society 143rd Annual Meeting*. Quebec City, Quebec, CA. August 17 – 21.

Jameel, M.Y., G.J. Bowen, T.O. Hook, C.D. Troy, and A. Wilson, "Physical characteristics and biogeochemistry of southern Lake Michigan river plumes" 2014 Ocean Sciences Meeting, Honolulu, HI, February 23-28, 2014.

Bowen G.J., Jameel Y., Hook T., Wilson A. and Troy C. (2013) Terrestrial Inputs to Nearshore Freshwater Ecosystems in Lake Michigan:
Biogeochemical and Ecological Consequences, International Workshop on Aquatic Ecology and Restoration, Shenyang Univ..

Bowen G.J., Good S.P., Jameel Y. and Kennedy C.D. (2013) Multi-scale partitioning of the water cycle with water isoscapes, COST-SIBAE Meeting on Challenges in the Applications of Stable Isotopes Across Disciplines and Scales.

Stein, S. R., A. E. Wilson, G. Bowen, C. D. Troy, and T. O. Höök. 2013. Habitat characterization of southern Lake Michigan river plumes: implications for fish recruitment. American Fisheries Society. Little Rock, Arkansas.

Jameel, M . Y., G. Bowen, A. E. Wilson, T. O. Höök, S. R. Stein, C. R. Roswell, and E. F. Grimm. 2013. Biological and water quality characterization of Lake Michigan plumes. International Association of Great Lakes Research. Purdue University, West Lafayette, Indiana.

Wilson, A. E., S. Stein, E. F. Grimm, C. Roswell, Y. Jameel, C. Troy, G. Bowen, and T. O. Höök. 2013. Do rivers mediate water quality in nearshore areas of Lake Michigan? International Association of Great Lakes Research. Purdue University, West Lafayette, Indiana.

Grimm, E. F., C. Troy, S. Stein, A. E. Wilson, and T. O. Höök. 2013. Characterization and mapping of river plumes in southern Lake Michigan. International Association of Great Lakes Research. Purdue University, West Lafayette, Indiana.

Stein, S. R., C. R. Roswell, E. Grimm, C. D. Troy, G. Bowen, A. E. Wilson, and T. O. Höök. 2013. Habitat characterization of southern Lake Michigan river plumes: implications for fish recruitment. International Association of Great Lakes Research. Purdue University, West Lafayette, Indiana.

Stein, S., C. Roswell, A. E. Wilson, G. Bowen, C. D. Troy, and T. Höök. 2012. Habitat characterization of southern Lake Michigan river plumes: Implications for fish recruitment. International Association of Great Lakes Research. Cornwall, Ontario.

Grimm, E., C. D. Troy, S. Stein, C. Roswell, T. O. Höök, and A. E. Wilson. 2012. Field characterization of river plumes and source water in southern Lake Michigan. International Association of Great Lakes Research. Cornwall, Ontario.

Publications (All Forthcoming):

Stein, S., A. E. Wilson, G. Bowen, C. D. Troy, and T. Höök. Habitat characterization of southern Lake Michigan river plumes: Implications for fish recruitment. *In preparation*. Canadian Journal of Fisheries and Aquatic Sciences.

Stein, S. R., Bowen, G.J., Troy, C.D., and Höök, T.O. Resource Subsidies for Young Fish in Southern Lake Michigan Rivermouths. *In preparation*. Ecological Applications.

Stein, S. R., Bowen, G.J., Troy, C.D., and Höök, T.O. Young Fish Nursery Origins and Habitat Utilization in Southern Lake Michigan Rivermouths. *In preparation*. Journal of Fish Biology.

Essig, R., E. Grimm, C. D. Troy, S. Stein, C. Roswell, T. O. Höök, and A. E. Wilson. Physical characteristics of river plumes in southern Lake Michigan. *In preparation*. Journal of Great akes Research.

Jameel, M.Y., G.J. Bowen, T.O. Hook, C.D. Troy, and A. Wilson. Physical characteristics and biogeochemistry of southern Lake Michigan river plumes. *In preparation*.

Response to Standard GLFT Questions

1. **Briefly summarize the project description as outlined in the original proposal.**

   Inter-annual recruitment variability influences management of Lake Michigan fish populations. Heterogeneous habitats in Lake Michigan likely contribute to this variability, yet the mechanistic influence of these habitats on recruitment is thus far poorly understood. River plumes are locations with highly variable and diverse habitats for young fish in Lake Michigan, and therefore may play an important role in recruitment dynamics for important species such as yellow perch and round gobies. However, due to the complex nature of the aquatic environment near tributaries, novel approaches must be used to collect samples and measurements that can help shed light on these areas.

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   -Evaluate the extent to which later stage yellow perch, round gobies and alewife utilized tributaries and river plumes as early life habitats.

2. **Briefly summarize any significant changes to the work performed in comparison to the plan of work originally proposed and funded. If changes were made, describe how they affected your ability to achieve the intended outcomes for the work**

   The most significant change to our study involved inclusion of alewife when comparing among river plumes, river mouths and nearshore Lake Michigan habitats. (We initially planned to only focus on yellow perch and round goby).

3. **To what extent and how (if at all) did this research project advance scientific knowledge of the issue?**

   See project findings summary above

4. **To what extent and how (if at all) did this project contribute to the education and advancement of graduate or undergraduate students focused on Great Lakes fishery issues?**

   This project supported multiple undergraduate and graduate student researchers. The project has (or will) contribute to 4 separate MS theses or PhD dissertations (see above for list).

5. **To what extent and how (if at all) did this work help you or others on your team build new relationships with others in the research or management communities?**

   Our research team encompassed multiple disciplines and this project brought about communication inter-disciplinary communication (which was not always easy).

   In addition, we coordinated with Indiana Department of Natural Resources staff and NOAA Great Lakes Environmental Research Laboratory staff in conducting our field studies.

6. **To what extent and how (if at all) do the findings have action implications for fishery managers?**

   Findings from this project should help managers define population structure for some fishes in Lake Michigan and can thereby potentially tailor regulations to different stocks (e.g yellow perch stocks in river mouths vs. nearshore Lake Michigan).

   We believe that the main, overall contributions of this study relate to a) mechanistic understandings of physical processes and environmental condition in river mouths and river plumes and b) trophic connections, habitat utilization and performance of young fish in these environments.

7. **Considering the above or other factors not listed, what do you consider to be the most important benefits or outcomes of the project?**

   We believe that the main, overall contributions of this study relate to a) mechanistic understandings of physical processes and environmental condition in river mouths and river plumes and b) trophic connections, habitat utilization and performance of young fish in these environments.

   Given the observed small size of river plumes in Lake Michigan and the tendency for fishes like yellow perch and round goby to remain in a single habitat throughout most of their life, we now believe that river plumes are relatively unimportant to many species of fishes inhabiting the main basin of Lake Michigan.

8. **Was this project a standalone effort, or was there a broader effort beyond the part funded by the GLFT? Have other funders been involved, either during the time of your GLFT grant or subsequently?**

   Stand-alone effort. However, we did receive some support for students via a Graduate Assistantship in Areas of National Need.

9. **Has there been any spin-off work or follow-up work related to this project? Did this work inspire subsequent, related research involving you or others?**

Yes, the methods and findings we developed through this project related to otolith isotopic analyses are now being used in a new GLFT-funded project (Ruetz lead-PI) exploring stock structure and population connectivity of yellow perch in Lake Michigan.

In addition, we are now using the fatty acid methods developed in part through this project for a variety of Great Lakes studies.

10. **List publications, presentations, websites, and other forms of formal dissemination of the project deliverables, tools, or results, including those that are planned or in process.**

    See above

11. **Please, characterize your efforts to share the findings of the research with state, federal, Tribal, and interjurisdictional (e.g., Great Lakes Fishery Commission) agencies charged with management responsibilities for the Great Lakes fishery.**

    We have presented project findings at various conferences and are drafting papers for submission to peer-reviewed journals. In the future, we will seek out opportunities to share project summaries through the Great Lakes Fishery Commission technical meetings.

12. **Please identify technical reports and materials attached to this report by name and indicate whether you are requesting that GLFT restrict access to the materials while you seek publication.**

    All aspects of this research will be incorporated into the publications that are in preparation (see above). We request that GLFT restrict access to the final report to allow us to submit these manuscripts.

13. **Manuscripts. Grantees submitting one or more publications or pending publications in lieu of a stand alone technical report must submit a cover memo that confirms that all aspects of the funded research are incorporated in the published work, and in cases of multiple publications, identifies or crosswalks the grant-funded objectives to the published article containing results.**

    All aspects of this research will be incorporated into the publications that are in preparation.

PROJECT NARRATIVE

Background

Recruitment of fish populations in Lake Michigan varies dramatically on an inter-annual basis, potentially leading to huge changes in population abundances and thereby confounding fisheries management. Recruitment rates are highly dependent on early life processes that determine the number of fish which survive to adulthood. Most fish produce large numbers of eggs, but the vast majority of young fish die during very early life. Therefore, small changes in survival rates during early life can have huge impacts on future population size. Early life survival involves surviving a gauntlet of predators and starvation risks, and thus early life survival is closely linked to growth rates; whereby faster growing individuals are less likely to die from starvation and more likely to avoid gape-limited predators. Several hypotheses have been put forth to explain the primary mechanisms structuring fish recruitment. Many of which are based on the notion that recruitment rates are dependent upon spatial and temporal overlap of young fish, their potential prey and suitable physical-chemical conditions. Young fish, their zooplankton prey and other environmental conditions are highly patchy in space and time, and thereby appropriate spatial overlap among fish-zooplankton-environment may be more the exception rather than the norm (leading to frequent low recruitment levels, and only occasional high yields). In Lake Michigan, the high degree of environmental heterogeneity likely contributes to differential early life survival, and thus recruitment success.

Tributaries and river discharge zones result in some of the most heterogeneous environments in Lake Michigan, representing the convergence of nutrient rich, warm surface water with cold, relatively sterile lake water. Moreover, rivers deliver both abiotic (e.g., sediment) and biotic constituents (e.g., bacteria, phytoplankton, zooplankton, larval fish) from tributary environments into the nearshore zone. These convergence zones undoubtedly concentrate diverse abiotic and biotic constituents, stimulate primary and secondary production, and provide thermally suitable conditions. Therefore, these areas may support high densities and growth rates of larval fish and constitute hot spots for production of young native and non-native fish.

Lower trophic level studies of Great Lakes river mouth and river plumes (Lohrenz et al. 2004, Höök et al. 2007, Vanderploeg et al. 2007, Johengen et al. 2008,) suggest that river plumes in the Great Lakes are warmer, more turbid, nutrient-rich, and have higher zooplankton levels than ambient lake water. Riverine inputs are the primary nutrient source for the Great Lakes (Hall 2000; USEPA), with an observed catalytic effect on lower trophic level organisms. In contrast, while there is strong evidence that rivermouths and plumes in a diversity of aquatic systems, including Lake Michigan, provide unique physical, chemical and biological environments, it is less understood how these environments affect early life dynamics and ultimately recruitment of fishes in the lake. A review by Grimes and Kingsford (1996) provides several examples of how estuarine river plumes may lead to high densities of larval fish and positively affect their early life growth and survival. Moreover, there is evidence that these positive effects of river plumes are not limited to a narrow ontogenetic stage reaping benefits in very large discharge zones. In fact, LePape et al. (2003) demonstrate that plumes may not only positively affect larval fish, but also benefit later stage juveniles. Further, while several studies have focused on the biological effects of large river plumes, e.g., Mississippi (Grimes and Finucane 1991; Grimes 2001) and Columbia (Parnel et al. 2008; Peterson and Peterson 2008), there is also evidence that smaller plumes can

structure local ecological processes (e.g., Schlacher et al.2008). Finally, it is important to note that river plumes are highly dynamic and their effects on young fish are likely to vary among systems and species. In fact, researchers who have compared river plume impacts within entire ichthyoplankton assemblages have suggested taxon and temporal specific responses in terms of how plumes structure distributions (e.g., Thorrold and McKinnon 1995) and feeding (e.g., Rissik and Suthers 1996).

Similar to other areas of the Great Lakes, the role of rivermouths and plumes in production of young fish in southern Lake Michigan remains understudied. Nonetheless, it is known that a diversity of fish species utilize rivermouth and river plume environments in southern Lake Michigan (Madenjian et al. 2002). We focus on three ecologically and economically important species (yellow perch, alewife, and round goby) which are abundant across nearshore habitats throughout the Great Lakes including southern Lake Michigan. Yellow perch are native to Lake Michigan while both alewife and round goby are non-native. These species ubiquity, varying habitat preferences, and life-histories make them meaningful focal populations for this study.

Yellow perch once supported a commercial fishery in the main basin of Lake Michigan, and their recreational harvest has continued, contributing to the seven billion dollar annual Great Lakes recreational fishing economy. In recent decades, yellow perch recruitment has declined in Lake Michigan; however, the specific mechanisms underlying poor recruitment have yet to be fully elucidated. Seemingly, a skewed sex-ratio caused by overharvesting reduced the number of reproducing females, leading to multiple low year-classes in the 1990's (Madenjian et al. 2002). Additionally, dreissenid mussels may consume prey of zooplankton, decreasing zooplankton prey for young yellow perch. Lack of prey availability for planktivorous yellow perch may inhibit their early-life growth, survival, and subsequent recruitment (Dettmers et al. 2003; Marsden and Robillard 2004). In southern Lake Michigan, yellow perch spawn and begin exogenous feeding in nearshore waters (Graeb et al. 2004). Their recruitment is thought to be set early in age-0 (Dettmers et al. 2003) suggesting that biotic and abiotic nearshore conditions influence recruitment of this species.

Alewife also play an important ecological role in the nearshore of Lake Michigan. Alewife population dynamics are strongly influenced by predation by salmonines and by water temperatures (Madenjian et al. 2005). Alewives utilize nearshore areas including tributaries as spawning and nursery habitats in early life. By promoting early hatching and rapid growth, warmer, more productive Great Lakes coastal habitats may be particularly beneficial for this species. For example, Höök (2007) determined that rivermouth habitats such as Muskegon Lake, a drowned rivermouth lake, promoted alewife recruitment by supporting high growth and survival rates relative to nearshore Lake Michigan.

Round goby, a species first detected in the Great Lakes in 1990, utilize rivermouths throughout their lives. However, the relative population-level importance of rivermouths as a nursery habitat for gobies remains unknown. This species has quickly become integrated into several trophic pathways in the Lake Michigan ecosystem. Round goby have become a common prey item for many Great Lakes piscivores, they compete with other benthic fishes, and they are one of the few species that consumes dreissenid mussels (Hensler and Jude 2007; Ruetz et al. 2009). Potentially, environmental conditions in rivermouths may promote round goby recruitment in southern Lake Michigan.

Methods

During 2011 and 2012, we sampled five rivermouths in southeastern Lake Michigan. We sampled at Trail Creek, St. Joseph, Muskegon, and Burns Ditch in 2011. During 2012, we discontinued sampling at Burns Ditch and added Grand River. These five tributaries were chosen because they drain watersheds with differing sizes and land uses. Both the Trail Creek and Burns Ditch watersheds are relatively small and highly developed. St. Joseph and Grand Rivers drain large, primarily agricultural watersheds, and the Muskegon River watershed is primarily forested. Each rivermouth has unique hydrologic characteristics. The Trail Creek rivermouth is partially enclosed by a break wall, and lake water frequently enters the harbor. St. Joseph and Grand Rivers are not restricted in their flow to Lake Michigan while Muskegon River flows into a drowned river mouth lake before reaching Lake Michigan.

At each rivermouth we sampled six fixed sites during 2011 and 2012, hereafter referred to as long-term sites. At Trail Creek and St. Joseph we sampled weekly at each long-term site from mid-May through Mid-August and monthly in September and October during 2011 and 2012. In 2011, we sampled approximately monthly at Burns Ditch from June through September in 2011. We sampled monthly from May through September at Muskegon in 2011. During 2012, we sampled approximately bimonthly from May through October at Muskegon and Grand. Long-term sites included one river site, R, and five lake sites, 1-5 (Figures 1-2). Sites 1-4 were along the 10 m depth contour and site 5 was at an approximately 12 m depth. In 2012, we added additional upstream sampling sites during bimonthly sampling. For a summary of field sampling undertaken as part of this study see Table 1.

River plume characterization

Plume Classification: Daily plume classifications were calculated for 2011-2013 at the St Joseph River and Grand River. Methodologies outlined by Nekouee (2010) and Nekouee et al (2013) were used to classify river plumes. Nekouee proposed six categories to classify the behavior of river plumes within Lake Michigan: radial spreading where the plumes are mostly buoyancy driven because there is no strong wind or alongshore current; offshore spreading where outward cross-shore winds cause the plume to form a trapezoidal shape away from the shoreline; side deflecting where inland cross-shore winds cause the plume to push back towards the shoreline, but are not strong enough to connect to the shoreline; diffuse offshore spreading which is similar to offshore spreading except with stronger winds, diffuse shore impacting which is similar to side deflecting except with strong winds; and shore attached where the alongshore currents are strong enough to dominate the buoyancy, so the plume pushes along the shoreline (Nekouee, 2010) (Nekoueeet al, 2013). In order to accommodate year round classification, negatively buoyant river plumes were added to the original classification chart developed by Nekouee (2010) as seen in Figure 3.

Where:

$b = river\ width\ at\ outlet$

$d = full\ river\ depth\ at\ outlet$

$$\boldsymbol{g' = \frac{\rho_{lake} - \rho_{river}}{\rho_{lake}} = reduced\ gravitational\ acceleration} \qquad \text{Equation 2}$$

$$\boldsymbol{h_0 = h_c = \frac{\left(Q/b\right)^2}{g'^{1/3}} = depth\ of\ river\ plume\ at\ outlet} \qquad \text{Equation 3}$$

$$\boldsymbol{L_b = \frac{g' Q_0}{U_a^3} = plume\ to\ cross\ flow\ length\ scale}$$ Equation 4

$$\boldsymbol{Q_0 = U_0 h_0 b = volume\ discharge\ flux}$$ Equation 5

$Q = full\ river\ discharge\ at\ outlet$

$\rho_{river} = density\ of\ the\ river\ water$

$\rho_{lake} = density\ of\ the\ lake\ water$

$$\boldsymbol{Ri^* = \frac{g' h_0}{W^*} = Richardson\ number}$$ Equation 6

$U = velocity\ of\ the\ river\ water\ at\ outlet$

$U_0 = velocity\ of\ the\ plume\ water\ at\ outlet$

$U_a = depth - averaged\ alongshore\ lake\ velocity$

$$\boldsymbol{W^* = \sqrt{\left| 0.0013 \frac{\rho_{air}}{\rho_{later}} W_{10}^2 \right|} = shear\ velocity\ due\ to\ crossshore\ wind}$$ Equation 7

$W_{10} = crossshore\ wind\ at\ 10\ meters\ above\ lake\ surface$

Data sets used include: Lake Michigan water temperature data from the GLERL CoastWatch system which reports satellite imagery from the NOAA polar-orbiting satellite (NOAA); river streamflow, depth, and temperature are collected from the USGS water quality website (USGS); Lake Michigan water velocity data was collected from the GLERL Nowcast model with 2km grid cells (GLERL); and air and Lake Michigan water temperature was collected from the National Data Buoy Center by NOAA (NOAA).

Plume Size: Water conductivity was used to distinguish river water from lake water for all sites except Muskegon. For each set of field data, the endpoint values of lake conductivity (c_{lake}) and river conductivity (c_{river}) were determined from locations entirely in the lake and river, respectively. Raw conductivities (c) were then scaled to relative conductivities (c_{rel}) with these endpoint values as:

$$c_{rel} = \frac{c - c_{lake}}{c_{river} - c_{lake}}$$ Equation 8

With this normalization, pure river water has a relative conductivity of 1, and pure lake water has a relative conductivity of 0.

Vertical Structure: To capture the vertical structure of the plume, sonde casts were taken starting in the river channel and progressing out through the mouth of the river into the lake. For locations where vertical profiles of relative conductivity were available, the depth of the plume was estimated by several methods. The first method defined the front thickness according to the integral:

$$h_f = \int_{-h}^{0} c_{rel}\, dz$$ Equation 9

This transformation determines the thickness of an equivalent sharp-front relative conductivity profile. It represents the thickness of the plume as an "unmixed" quantity in relation to the ambient water (Geyer et al., 2000). An alternate plume depth, $h_{0.2}$, can be defined by simply defining a threshold value of 0.2 for relative conductivity (see Figure 4).

Residence Time: An estimate of the residence time can be calculated using the plume volume divided by the river discharge rate. The volume of the plume is simply plume area times plume depth. The area of the

plume was calculated from plume maps generated from sonde data. The sonde data was averaged over the top 1.5 meters of the water column to get a relative conductivity point for each sonde cast. From there, linear interpolation and extrapolation was performed between each point to determine the boundary of the plume. Because of the lack of spatial resolution in the sonde data, a more complex averaging formula could not be used. The depth of the plume was assumed as the average h_f value in the plume bounds. The thickness of the plume is controlled by a balance between spreading and mixing and can be assumed to be relatively constant in the far-field (Jay et al., 2010). Once the plume enters the lake, the thickness of the plume decreases rapidly to less than 30% of its initial plume thickness, h_0, within 200 m of the channel mouth (Nekouee, 2010). Therefore, an estimate of plume depth was calculated for each plume map using depth from sonde casts taken in the lake.

Environmental conditions in river mouths and nearshore Lake Michigan

To characterize physical, chemical, and biological conditions, at each fixed site, we used a YSI sonde to measure water temperature and specific conductance every 1.0 m vertically through the water column. To assess the light environment, we measured Secchi depth and recorded ambient light every 0.5 m vertically through the water column with a Licor light meter. We also collected an integrated raw water sample, from the surface to 1.5 m below the surface. At site 5, we collected a bottom water sample with a VanDorn sampler from approximately 2.0 m above the bottom. These water samples were subsequently sent to Auburn University and analyzed for a suite of nutrient and water quality variables (Table XXX) and sent to University of Utah, where water isotopes were measured. To collect zooplankton, we towed a 2.0 m long, 0.5 m diameter, 64 µm mesh plankton net vertically through the water column from approximately 0.5 m above the bottom to the surface at 0.2 m s^{-1}. One to three zooplankton tows were conducted at each site. For counts and biomass estimates, we concentrated one sample, anesthetized zooplankton with bicarbonate, and used 10% sugar buffered formaldehyde for preservation. For the second tow, the sample was concentrated and frozen on ice for isotope analysis, and the third tow, when collected, was frozen on dry ice for fatty acid analysis. We used a petite PONAR to collect benthic invertebrates. For the first tow, we concentrated the sample and preserved the contents in 5% formaldehyde dyed with rose bengal. To preserve subsequent PONAR grabs for isotopes and fatty acids, individual organisms were picked, placed in vials, and frozen on ice or dry ice respectively. We took multiple grabs, usually two to seven, to collect an adequate number of organisms at each site.

In the laboratory, raw water samples were filtered and frozen to prepare them for nutrient analyses. We analyzed water for total nitrogen, total phosphorus, soluble reactive phosphorus, total suspended solids, chlorophyll, and toxins. To subsample zooplankton, we used a splitting wheel to sample 0.125 of the total sample. We then identified and counted zooplankton to coarse taxonomic grouping, to order and family when possible, using a dissecting microscope. We measured up to 20 zooplankters from each taxonomic group in each sample using a mounted camera with Micrometrics and Image J open-source software. We calculated dry masses using published length-weight regressions. Benthic invertebrate samples that were preserved in formalin were rinsed with water and placed in a 4 cm x 5.5 cm tray with water to be identified to order and family taxonomic groups (genus and species when possible) and enumerated. All organisms were placed in glass vials with 70% ethanol, and 20 individuals of each taxon were

photographed under a dissecting microscope with a mounted micrometrics camera. Measurements were taken using Image J open-source software.

Larval fish sampling and analyses

To collect larval alewife and yellow perch, we towed a bongo sampler, a paired ichythyoplankton net with 333 and 500 µm mesh, 0.6 m diameter, 2.0 m length, just below the surface at each of the six fixed sites (Figure 2). The bongo sampler was towed at the surface to collect larvae occupying buoyant plume water. We towed the net for approximately 5 minutes, 20 m behind the boat at 2.0 – 2.5 kts. At sites 1 – 4, we towed the net parallel to shore along the 10 m depth contour, at site 5, we towed toward shore, and at site R, we towed upstream. To estimate volume of water sampled, we attached flow meters (General Oceanics Model 2030R) to the mouth of each net. Samples were concentrated in the field and preserved in 95% ethanol. We sampled larval fish according to the aforementioned sampling design. During May and July 2012 we conducted additional larval fish sampling which included towing a 500µm push net at upstream sites in the four tributaries (Figure 2).Weekly, during June and July of both years, we collected an additional bongo sample at each long-term site at Trail Creek and St. Joseph. These samples were concentrated and preserved in RNA*later*® for RNA:DNA analysis. Upon returning to the lab, samples in RNA*later*® were stored at approximately 4˚C.

In the laboratory, we sorted ichthyoplankton samples and identified larval fish to species under a dissecting microscope (Auer 1982). We used a mounted camera with Micrometrics and Image-J open source software to photograph yellow perch and alewife larvae and to measure total length. To estimate growth, we extracted sagittal and lapillar otoliths from alewife larvae greater than 5.0 mm total length, and yellow perch larvae greater than 6.0 mm total length using a dissecting microscope. Otoliths were mounted on a slide with Crystalbond epoxy. We then used a compound microscope to count daily growth increments to estimate age. Each otolith was interpreted by two independent readers. To estimate age, we added two days to the number of otolith increments (Höök et al. 2007; Roswell et al. 2014). To examine gut contents of yellow perch and alewife larvae, we removed guts of post yolk-sac larvae and opened the gut with a probe under a dissecting microscope. Diet contents were then placed on a slide to be counted and identified to major taxonomic groups using a compound microscope. We photographed and measured diet items with a mounted camera and Image J open-source software.

Larval RNA:DNA quantification: Larval fish samples preserved in RNAlater® were identified and measured (using the aforementioned techniques), and all petri dishes and slides were cleaned with RNase-OFFTM to prevent contamination. RNA:DNA was quantified fluorometrically using methods described in Gorokhova (2005), Höök et al. (2008), and Ryan et al. (2012). To prepare for fluorometric analysis, larvae were placed in tubes with extraction buffer to extract nucleic acids. Whole larvae were manually homogenized with an RNAase free pestle. Samples were then put into a sequence of ultrasound and ice bath treatments and subsequently placed on an orbital shaker for 2 h. DNA and RNA standards and controls were formulated and analyzed alongside duplicate larval fish samples. Each sample was placed in a 96-well microplate, and we added 70uL of the fluorophore. Fluorescence was quantified using a microplate reader and black solid flat-bottom microplates. We added 5 uL of endoribonclease RNase to each well and incubated the plates at approximately 37.5 degrees C for 30 min; then total fluorescence was measured. To determine total fluorescence we used Gen5 (BioTek Instruments, Inc.) microplate data

collection and analysis software. Fluorometry of larval RNA and DNA was compared to standard curve and to published values.

Juvenile and adult fish collection and analysis

To collect fish during 2011 and 2012, at all lake sites and at site R1, we used approximately 30 m long, micromesh (6 mm to 12 mm) gillnets that were set on the bottom for approximately two hours during the day. In the lake, gill nets were set parallel to shore along the 10 m depth contour. At R1, gillnets were set parallel to river flow to minimize interference with boats negating in the channel. During 2012, we added additional upstream fish sampling. At all fixed river sites, we electrofished along three transects parallel to stream flow for approximately ten minutes. We also used beach seines positioned perpendicular to shore along sandy beach areas in the St. Joseph River (site R1) and in Muskegon Lake (near site R2).

Additional young of year and older round goby, yellow perch, and alewife were obtained during 2010 and 2011 as part of a comprehensive Lake Michigan nearshore food web project. The fish were collected by Purdue and the Illinois Natural History Survey. Fish were sampled nearshore (<20 m water depth) with micromesh gillnets set on the bottom for approximately two hours. Upon collection, fish were frozen on ice and stored in a -20ºC freezer in the laboratory until they were analyzed.

Trophic analyses: During 2011, all frozen organisms were kept at -20˚C, and during 2012, the organisms frozen on dry ice in the field were transferred to a -80˚C freezer. Up to 10 fish of each species per sampling site per month were prepared for diet, stable isotope, and fatty acid analyses (2012 only). Fish preparation involved partially thawing fish and recording total length and weight. We also removed stomach or digestive tract (round gobies), extracted sagittal otoliths (see Chapter 3), and removed a white tissue muscle plug from the dorsal mid-section of each fish for FAS (2012 only). Stomachs were frozen at -20˚C in plastic scintillation vials, and muscle plugs were frozen in plastic cryovials at -80˚C. Following processing, fish were weighed and placed in a 70˚C drying oven for at least 48 hours. Dried fish were weighed and homogenized using a commercial blender for subsequent stable isotope analyses.

To examine gut contents, stomach samples were thawed and contents were removed from the gut and rinsed with water into a counting wheel. All organisms were enumerated and identified to order or family under a dissecting microscope and up to 20 organisms of each taxonomic group were photographed and measured using a mounted Micrometrics camera and Image J open-source software.

To prepare homogenized fish samples and a subset of frozen zooplankton and benthic invertebrate samples for stable isotope analyses, we first extracted lipids from each sample. Lipid washing required soaking samples in a 2:1 chloroform:methanol (C:M) solution at 25˚C overnight. After approximately 24 hours, samples were agitated and the C:M solution was decanted. This washing processes was repeated two or three times, until the C:M solution was clear and colorless after the 24 hour soaking period. Lipid washed samples were then allowed to air dry, and they were crushed using a mortar and pestle. A sample of prepared material was then weighed and packed into a tin capsule for isotope analysis. Lipid washed samples were analyzed in duplicate for $\delta^{13}C$, $\delta^{18}O$, $\delta^{15}N$, $\delta^{2}H$ using a Thermochemical Elemental Analyzer coupled to a Delta V mass spectrometer at the University of Utah Stable Isotope Laboratory for Environmental Research (SIRFER, http://sirfer.utah.edu/). The data were normalized to conventional

isotope standards (e.g., Fry 2006) and all isotope values will be presented in notation relative to the standards.

To prepare fish, zooplankton, and benthic invertebrate samples for fatty acid analysis (e.g., Budge et al. 2006), samples were taken from the -80ºC freezer, homogenized with a mortar and pestle, and soaked overnight in a chloroform: methanol solution to extract lipids. After soaking, samples were centrifuged, and the solvent was decanted and evaporated to isolate lipid material. Next, transesterification was conducted with a methanol solution to convert each lipid sample into fatty acid methyl esters (FAMEs). To ultimately prepare samples for analysis on the gas chromatograph, a hexane solution was added. Gas chromatography was then used to analyze samples and results were compared to pre-prepared standards.

At each fish collection site, we collected water samples for $\delta^{2}H$ and $\delta^{18}O$. During the sampling season, water was collected weekly at Trail Creek and St. Joseph and approximately monthly at the other rivermouths. Water samples were collected in clean, glass dram vials that were triple rinsed with lake water and then filled completely to avoid air contamination. Vials were closed and sealed with parafilm.

Otolith analyses: In the laboratory, fish were partially thawed and their length and weight was recorded. We selected up to ten fish from each sampling site per month for otolith analyses. To extract the sagittal otoliths, we cut open the mouth of each fish and removed the upper jaw bones to expose the saccular vestibule. Upon extraction, otoliths were placed in clean microcentrifuge tubes. To sample otolith cores, we mounted otoliths horizontally in epoxy plugs. When the epoxy hardened, we sanded each plug to remove recent otolith growth and to expose one side of the otolith's core. Then the core of each otolith was drilled, and the powder was collected and placed in an acid washed and ashed glass exitainer. For a subset (approximately 20 per species) of juvenile and adult fish, we also collected an isotope core sample and a sample from the outermost growth ring(s) using the aforementioned technique. Additionally, for approximately ten round gobies and ten yellow perch, we used laser ablation to microsample otoliths along a chronological transect at several points from the core to the outer edge. This allows for a narrower temporal scale to examine potential fish movement across habitats. All otolith samples were analyzed for $\delta^{13}C$ and $\delta^{18}O$ using an isotope ratio mass spectrometer at the University of Utah Stable Isotope Laboratory for Environmental Research (SIRFER). In addition, to establish environmental baselines for otolith isotope chemistry, we analyzed water samples for $\delta^{18}O$ using an automated mass spectrometer. We also ground *Dreissenid* shells for $\delta^{13}C$ and $\delta^{18}O$ analyses at the University of Utah.

Results and Discussion

Compared to river plumes described in other areas of the Great Lakes (e.g., Reichert et al. 2010) or in marine systems (e.g., Hickey et al. 2010), river plumes in southern Lake Michigan are relatively small. While the behavior and physical characteristics of individual plumes was variable, some consistent patterns are evident if one considers plumes emanating from large rivers like the St. Joseph and Grand River (Figures 5-10). During 2011-2013, these plumes were consistently at the surface during late spring and during the majority of the summer. Moreover, during these seasons these plumes were usually classified as shore attached or diffuse shore impacting; however, they were occasionally diffuse offshore spreading. In addition, during early spring and late fall, these plumes were frequently negatively buoyant.

We were able to successfully track river water as it entered Lake Michigan using two relatively conservative measures, conductivity and water isotopes. Conductivity-based delineation of river plumes demonstrated that plumes were both horizontally and vertically limited. For example, the relatively large St. Joseph river plume rarely exceeded 2 km^2 and residence time of the plume was consistently <1 day (Table 3; Figures 11-12). Similarly, conductivity measurements demonstrates that during late spring and summer, for a large river, like the St. Joseph, the lift-off point for the plume is generally well within the river channel (Figure 13). In contrast, for a small river, like Trail Creek, the river plume is often undetectable outside of the river mouth (Figure 14), and on several occasions flow appeared to reverse, as conductivity measures in Trail Creek were more similar to Lake Michigan.

Water isotope based delineation of river and lake water revealed similar patterns as conductivity. First, water isotopes were clearly able to differentiate these two types of water (Figures 15-16). Moreover, measurements of water isotopes in Trail Creek demonstrates the potential (and relatively frequent) backflow of water from Lake Michigan into Trail Creek river mouth (Figure 15). The measurement of water isotopes also revealed some interesting phenomenon related to how riverine nutrients are processed once they enter Lake Michigan. That is, within plumes, nutrient concentrations are primarily controlled by mixing of river and lake water. However, within the river plume there also appears to be substantial settling or uptake of riverine phosphorous (see Figure 17).

Given the small size and dynamic nature of southern Lake Michigan river plumes, it somewhat difficult to compare environmental conditions in river plumes in a consistent manner. However, if one considers sites in Lake Michigan which a) are near river mouths (and hence more frequently affected by a plume) versus sites which are further from river mouths and b) are near large rivers (i.e., potentially experiencing a relatively large plume) versus small rivers, some differences are obvious (Figures 18-19). For example, sites in Lake Michigan near river mouths (and especially near the relatively large St. Joseph River) tended to be warmer, more turbid and contain higher concentrations of nutrients, chlorophyll and total suspended solids. In addition, environmental conditions at sites in Lake Michigan near St. Joseph tended to be more variable relative to sites near Trail Creek. Due to positive buoyancy, sites which were plume influenced tended to have vertical structure in temperature (warmer near surface) and light attenuation (more turbid near surface).

It is more straightforward to compare environmental conditions in river mouths versus nearshore Lake Michigan (given that the location of river mouths is fairly constant in space). Not surprisingly, during late spring and summer, river mouths were consistently warmer, more turbid and had higher nutrient concentrations, chlorophyll and conductivity than nearshore Lake Michigan (Figures 20-21). These differences in primary production, temperature and water clarity did not lead to similar differences across habitats for all lower trophic level invertebrates. Zooplankton in both river mouths and nearshore Lake Michigan were dominated by small-bodied animals. During late spring and early summer, zooplankton concentrations were highly variable but were on average greater in nearshore Lake Michigan than in St. Joseph and Trail Creek rivermouths (Figure 22). In contrast, benthic macroinvertebrate densities were greater in rivermouths than nearshore Lake Michigan. However, types of benthic macroinvertebrates were generally similar between the two types of habitats (Figure 23).

While we collected various species of larval fish, we focus on two of the two most common-collected species, alewife and yellow perch. We hardly ever collected our other target larval fish species, round goby, and hence we did not consider habitat differences in densities, diets and growth of larval round goby. Larval alewife densities were on average greater in St. Joseph and Trail Creek river mouths than in nearshore Lake Michigan. Vice versa, larval yellow perch densities were on average greater in nearshore Lake Michigan than in these river mouths (Figure 24). Given that larval alewife are anadromous in their

native range, it is not surprising that their larval densities were greater in river mouths than in nearshore Lake Michigan. Moreover, this is consistent with past studies which also found relatively higher denssities of larval alewife in drowned river mouth lakes connected to Lake Michigan, as compared to nearshore Lake Michigan (e.g., Höök 2005; Höök et al. 2007). Yellow perch, on the other hand, likely spawn in the same habitat occupied by adults, and while there are likely some relatively large yellow perch populations in some drowned river mouth lakes connected to Lake Michigan (e.g., Muskegon Lake), yellow perch are likely not as abundant in truly riverine habitats. For example, the St. Joseph River mouth has riverine characteristics and may not support a very large yellow perch population.

In both habitat types, we generally collected relatively small larval alewife and larval yellow perch. Many of these larval fish had no food in their digestive tracts; perhaps because a) they were very young and in some cases still feeding exogenously and b) prey availability was limited. When larval fish digestive tracts did contain diet items, common contents included small prey such as, dreissenid veligers, copepod nauplii and diatoms. Based on RNA:DNA ratios, growth of larval alewife was greater in river mouths than in nearshore Lake Michigan (Figure 25). This is perhaps surprising since zooplankton prey was generally higher in nearshore Lake Michigan. However, warmer temperatures in river mouths may have contributed to faster growth rates, and greater turbidity in river mouths may have allowed larval alewife to more effectively capture prey and to forage more effectively with less fear of predation.

We used a multi-indicator approach to consider the type of prey and trophic pathways supporting production of small-bodied fishes in river mouths and nearshore areas of Lake Michigan potentially influenced by river mouths. Specifically, we analyzed diets, fatty acid content and soft tissue stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$, and $\delta^{18}O$) of juvenile and adult yellow perch, round goby and alewife collected in different river mouths and nearshore Lake Michigan habitats. We found evidence of size-related prey consumption, e.g., large yellow perch consuming fish and large round goby consuming dreissenid mussels. However, as a whole these fish had similar diets items in digestive tracts across habitats (Figures 26-27).

The use of fatty acids to describe trophic associations is an emerging research approach and is based on the notion that different primary producers synthesize fatty acids in different proportions. As fatt acids are essentially transferred up the foodweb, the relative composition of fatty acids in the tissues of consumers can provide evidence of the trophic pathways supporting their production. Fatty acids turnover more rapidly than stable isotopes and therefore represent trophic connections at an intermediate time scale (relative to more fine-scale diet contents and more broad-scale stable isotopes). Through our analyses, we were able to use a suite of fatty acids to moderately differentiate yellow perch, round goby and alewife among habitats (Figures 28-31). While the three species clearly differed amongst each other in fatty acid composition (Figure 31), within-species differences among habitats were less consistent (Figures 28-30).

In contrast to fatty acids, stable isotopes in soft tissues provide a more long-term indicator of trophic connections and is a more well-established approach. Moreover, we documented consistent across-habitat differences in soft tissue isotope ratios isotope ratios ($\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$, and $\delta^{18}O$). In particular, yellow perch and round goby soft tissue isotope ratios were distinct between fish collected in nearshore Lake Michigan versus fish collected in river mouths (Figures 32-35). This pattern is consistent with yellow perch and round goby spending the preceding several months in the habitats of capture and thereby developing a habitat-specific isotopic signature. In contrast, migratory alewife displayed similar soft tissue isotopic composition across habitats (Figures 36-37). While some alewife collected in the Muskegon Lake system displayed isotope profiles distinct from other alewife, these differences were relatively minor as compared to differences among yellow perch and round goby.

Finally, we measured $\delta^{13}C$ and $\delta^{18}O$ isotopic composition in the core and outer edge (representing natal and recent environment) of otoliths from juvenile and adult yellow perch, round goby and alewife collected in different habitats. Analysis of water isotopes and $\delta^{13}C$ and $\delta^{18}O$ composition of dreissenid mussel shells from different habitats, demonstrate that isotopic signatures are distinct between river mouth and nearshore lake habitats, justifying their analyses from otolith samples for habitat discrimination (e.g., Figure 17). Based on otolith isotopic values, yellow perch showed very limited evidence of movement between river mouths and nearshore Lake Michigan. $\delta^{13}C$ and $\delta^{18}O$ values from both the core and edge of yellow perch otoliths suggested that they had spent their entire life in the habitat of capture. Round goby showed strong discrimination between river mouth and nearshore Lake Michigan otolith outer edge $\delta^{13}C$ and $\delta^{18}O$ values, suggesting that they had spent recent life in the habitat of capture. However, there was substantial overlap between otolith core values for gobies collected from different habitats; specifically, many round gobies collected inside river mouths had otolith core composition indicative of early life in Lake Michigan. Thus gobies may move between habitats during early life, but then remain in a single habitat for a long duration. Alewife otolith $\delta^{13}C$ and $\delta^{18}O$ values did not consistently differ among habitats. Interestingly, for this more migratory species, there was clear discrimination between otolith core and edge $\delta^{13}C$ and $\delta^{18}O$ values, with edge values generally indicating recent life in Lake Michigan, while core values suggested at least some contribution from tributary environments.

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Table 1. Number of field samples collected in A) 2011 and B) 2012. Water included raw water collected for water quality analyses (see table 3). HO water included additional water collected for hydrogen and oxygen isotope analysis. Non-bongo included Neuston net and push net tows for larval fish, and non-gill included electrofishing, beach seining, and hook and line sampling for juvenile fish. Sites labeled X refer to high spatial resolution sampling that was conducted in 2012, where additional sonde, secchi, and HO water samples were collected.

A.

Location	Bongo	Gill Net	Light	PONAR	Secchi	Sonde	Water	Zooplankton
BD MI	14	4	15	23	20	19	17	24
BD RIV	4	4	3	2	4	4	3	5
MK MI	19	9	19	31	20	19	22	24
MK RIV	5	3	4	6	4	4	5	6
SJ MI	94	17	60	39	67	67	66	83
SJ RIV	23	6	11	7	12	12	12	14
TC MI	100	12	71	38	77	75	73	88
TC RIV	30	6	15	7	16	15	16	18
Total	**289**	**64**	**198**	**153**	**220**	**250**	**215**	**262**

B.

Location	Bongo	Non-bongo	Gill Net	Non-gill	Light	PONAR	Secchi	Sonde	Water	HO Water	Zooplankton
GR MI	12		6		5	17	8	8	7	1	18
GR RIV	3	11	2	19	6	32	14	11	14	2	32
GRX							23	23	1	21	
MK MI	14		8		9	23	12	12	18		27
MK RIV	11	4	10	12	9	35	11	11	16		38
MKX		2		9			55	57	1	55	
SJ MI	128	5	8		76	25	77	77	96		95
SJ RIV	30	15		25	21	20	23	22	29	4	35
SJX					3		36	72	3	45	
TC MI	124	3	9		79	32	80	81	95		105
TC RIV	27	5	1	34	19	22	19	19	20		37
TCX							34	47		37	
Total	**348**	**45**	**44**	**99**	**227**	**206**	**390**	**438**	**300**	**164**	**387**

Table 2. Number of water quality samples collected during A) 2011 and B) 2012. TP = total phosphorus, SRP = soluble reactive phosphorus, TN = total nitrogen, TSS = total suspended sediments. During 2012 we did not analyze microcystin and many of the HO water samples were compromised. HO sampling was compiled in table 2b.

A.

Location	Chlorophyll	TP	SRP	TN	TSS	Microcystin	HO Water
BD MI	18	18	18	18	18		18
BD RIV	3	3	3	3	2	2	3
MK MI	23	24	23	24	23	1	17
MK RIV	5	4	5	4	4		4
SJ MI	70	69	68	69	60	20	63
SJ RIV	12	12	11	12	10	8	11
TC MI	75	81	74	81	69		
TC RIV	17	18	17	18	16	5	79
Total	**223**	**229**	**219**	**229**	**202**	**36**	**195**

B.

Location	Chlorophyll	TP	SRP	TN	TSS
GR MI	5	7	5	7	8
GR RIV	10	11	10	11	13
MK MI	15	15	14	15	15
MK RIV	12	13	11	11	12
SJ MI	90	89	90	89	88
SJ RIV	23	21	21	21	20
TC MI	94	88	94	88	92
TC RIV	19	17	17	17	20
Total	**268**	**261**	**262**	**259**	**268**

Table 3. Plume size and residence time calculated using 0.2 relative conductivity threshold for the St. Joseph River.

Date	Q [cms]	g' [m/s^2]	Plume Area [m^2]	Average Plume Depth [m]	Volume [m^3]	Residence Time [hrs]
6/10/11	169	0.013	137,500	1.00	137,180	0.2
6/16/11	126	0.010	964,992	1.27	1,225,332	2.7
6/22/11	120	0.013	1,183,490	0.99	1,172,509	2.7
6/30/11	102	0.006	2,761,935	1.88	5,196,047	14.1
7/7/11	78	0.008	1,813,455	1.57	2,854,342	10.2
7/20/11	67	0.011	803,112	1.13	910,159	3.8
8/2/11	68	0.002	525,882	6.26	3,290,321	13.4
8/11/11	61	0.000	387,550	6.00	2,325,300	10.7
5/1/2012	110	0.005	17,100,000	2.58	4,408,278	11.2
6/6/2012	57	0.008	1,846,600	1.56	2,873,433	14.0
6/13/2012	55	0.007	1,490,016	1.80	2,687,944	13.5
6/20/2012	41	0.014	337,146	0.90	303,830	2.1
7/19/2012	48	0.005	478,750	2.30	1,101,410	6.4
5/24/2012	84	0.016	1,008,950	0.83	836,159	2.8
6/26/2012	39	0.022	1,461,072	0.60	883,074	6.3
7/3/2012	39	0.012	1,506,505	1.04	1,566,801	11.1
7/12/2012	26	0.012	522,000	1.08	563,886	6.1
7/22/2012	33	0.007	701,670	1.67	1,170,758	10.0
7/31/2012	39	0.004	1,327,938	2.99	3,964,515	28.5
8/7/2012	34	0.003	1,155,090	3.67	4,240,088	34.7

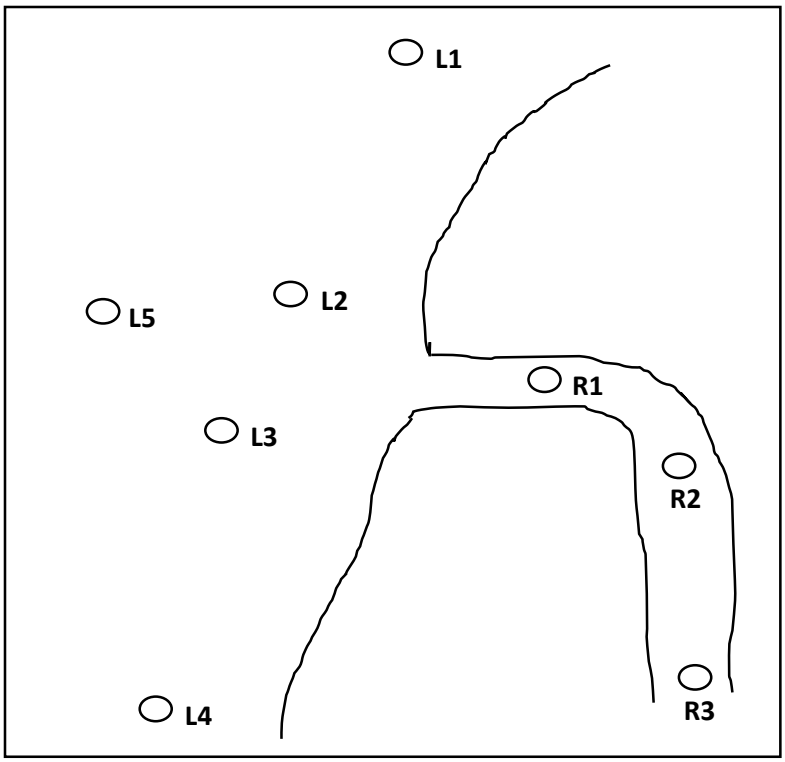

Figure 1. Map of lake and river sampling sites. L1- L4 were along the 10m depth contour, and L5 was at approximately 12m depth.

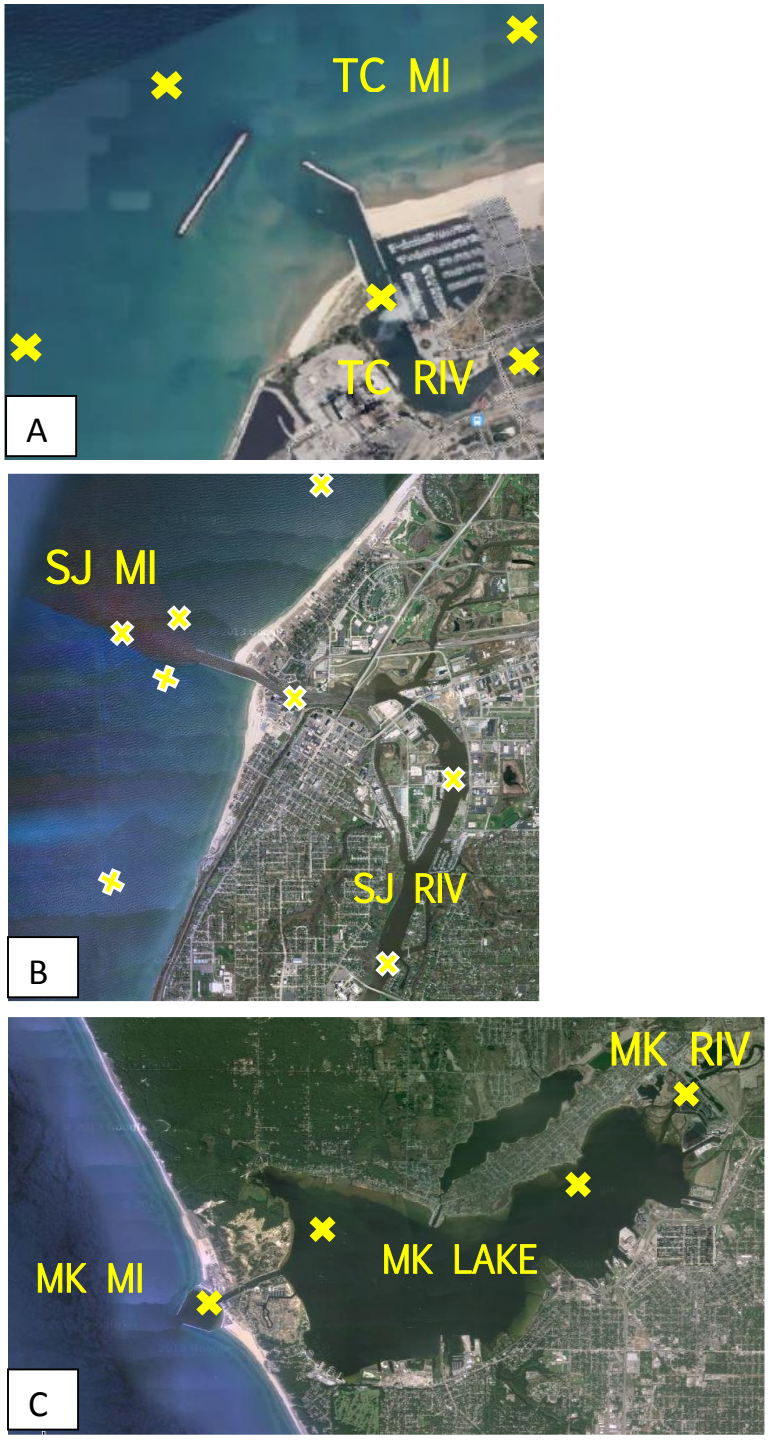

Figure 2. At three rivermouths a) Trail Creek, b) St. Joseph, and c) Muskegon sampling was conducted in the tributary and in Lake Michigan adjacent to the tributary. We sampled at 5 sites in Lake Michigan (shown in figure 1B). The four sites closest to shore were along the 10m depth contour and the farther site was along the approximately 12m depth contour. The two sites farther from the rivermouth were approximately 2km from the mouth. The upstream and Muskegon Lake sites were added to the sampling design during 2012.

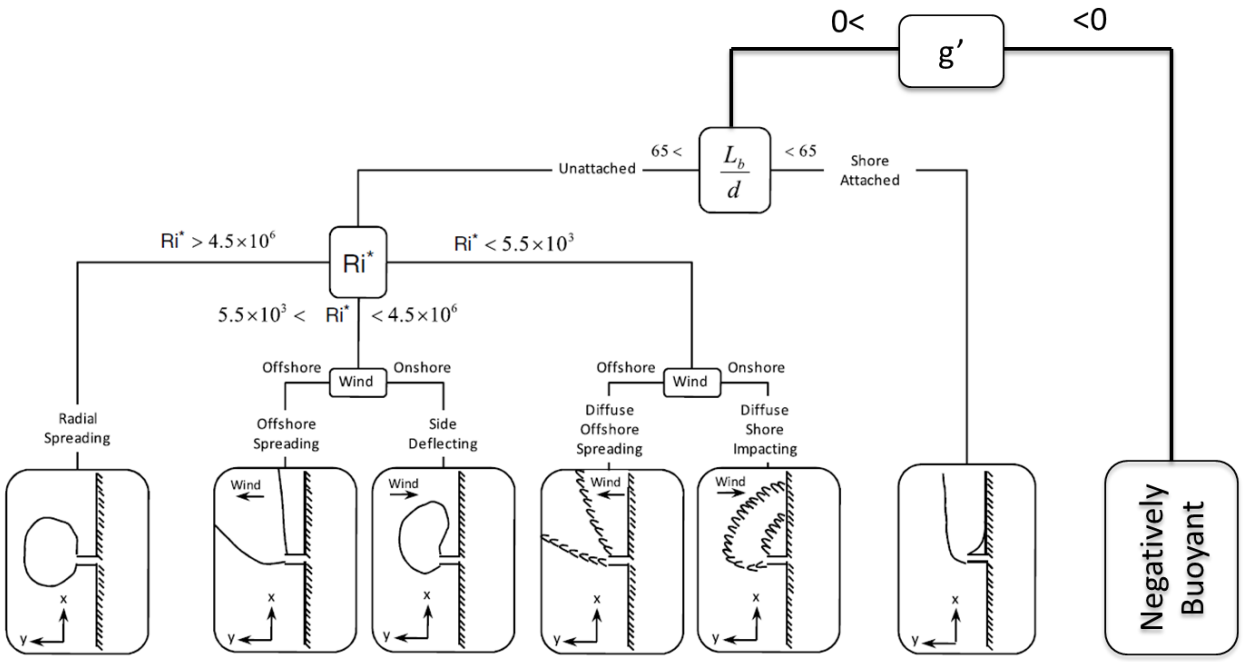

Figure 3. Plume Classification Scheme proposed by Nekouee et al (2013) with the addition of a negatively buoyant classification (Nekouee et al, 2013)

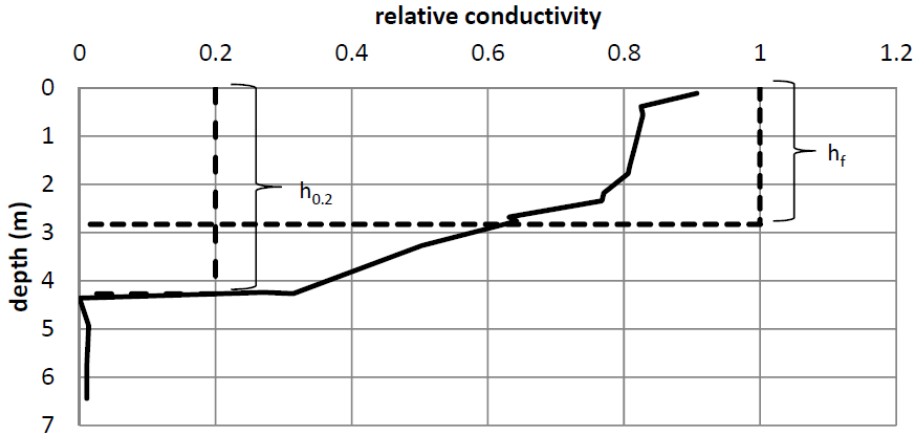

Figure 4. Diagram of plume depth (hf) function versus the plume depth found using c_{rel} =0.2 .

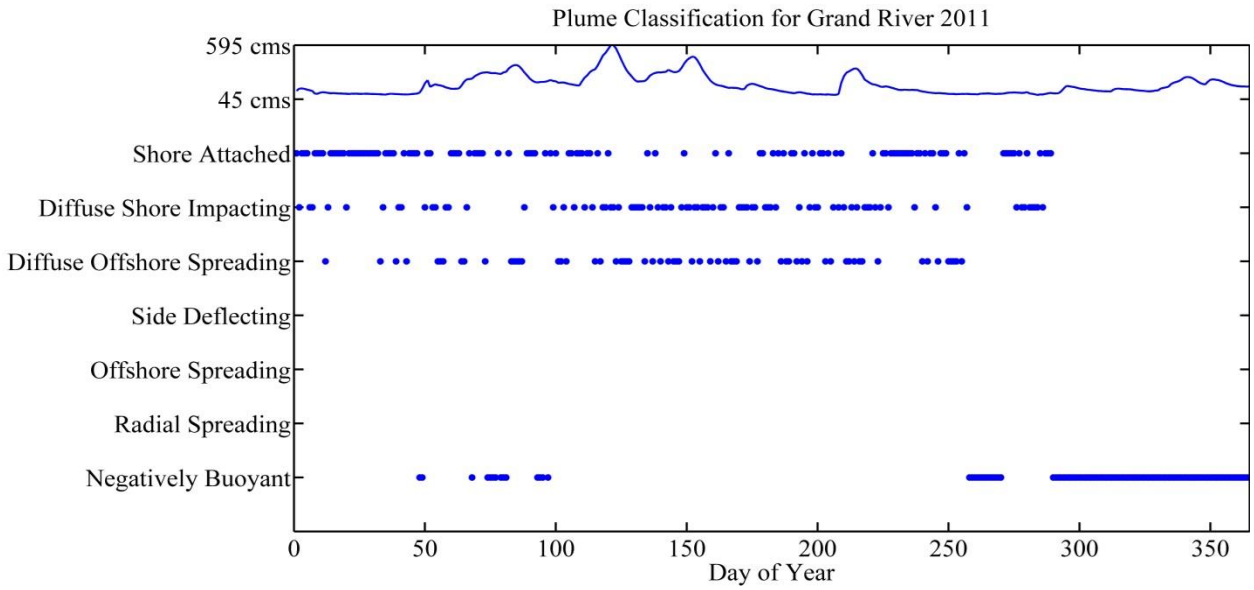

Figure 5. Daily plume classification for the Grand River during 2011. Top line shows hydrograph for the year with a low flow of approximately 45 cms and a peak flow of 595 cms. Peak flow occurs during mid to late April with the majority of storm events occurring during the spring.

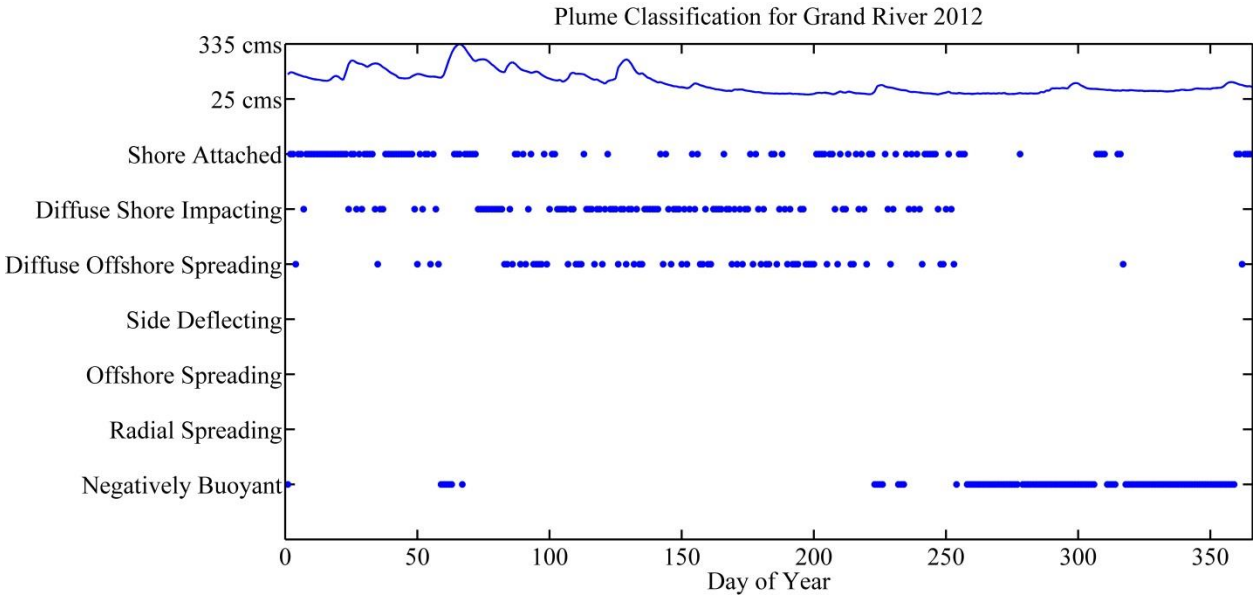

Figure 6. Daily plume classification for the Grand River during 2012. Top line shows hydrograph for the year with a low flow of approximately 25 cms and a peak flow of 335 cms. Peak flow occurs during early March with the majority of storm events occurring during the spring. Streamflow was substantially lower during 2012 compared to 2011 and 2013.

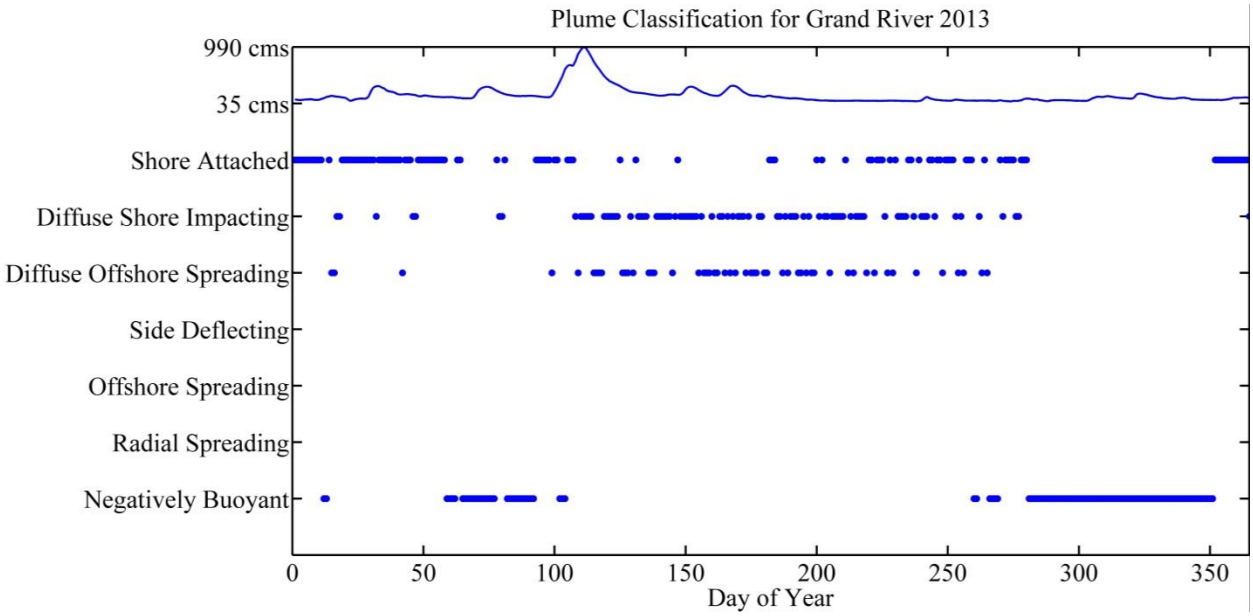

Figure 7. Daily plume classification for the Grand River during 2013. Top line shows hydrograph for the year with a low flow of approximately 35 cms and a peak flow of 990 cms. Peak flow occurs during late April with the majority of storm events occurring during the spring.

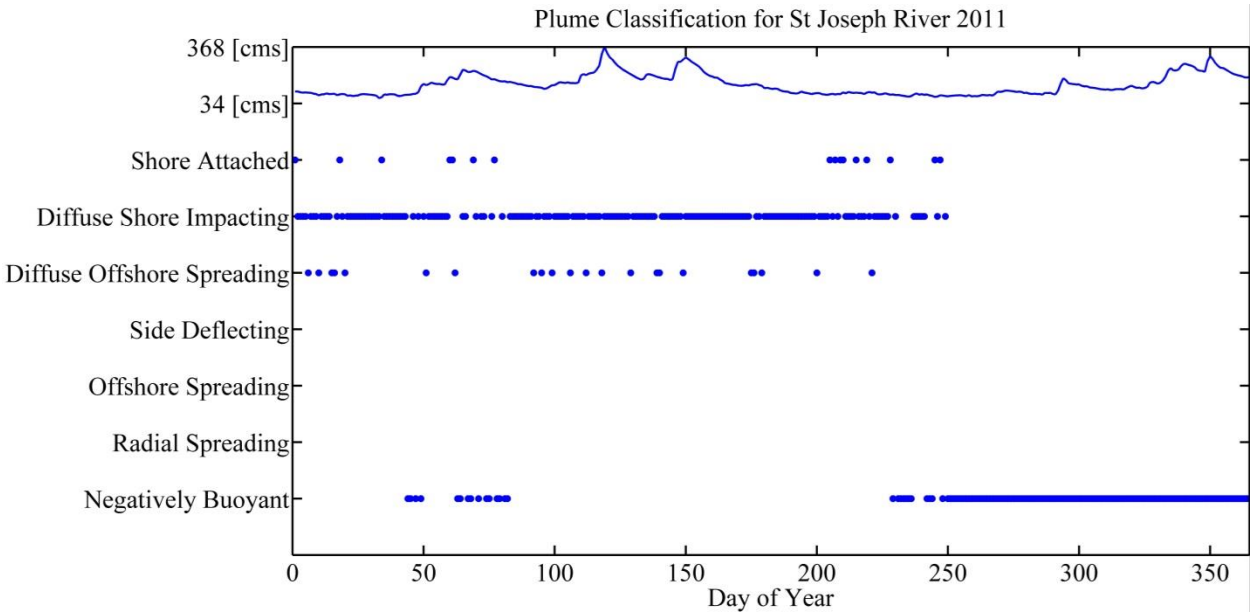

Figure 8. Daily plume classification for the St. Joseph River during 2011. Top line shows hydrograph for the year with a low flow of approximately 34 cms and a peak flow of 368 cms. Peak flow occurs during mid to late May with the majority of storm events occurring during the late spring.

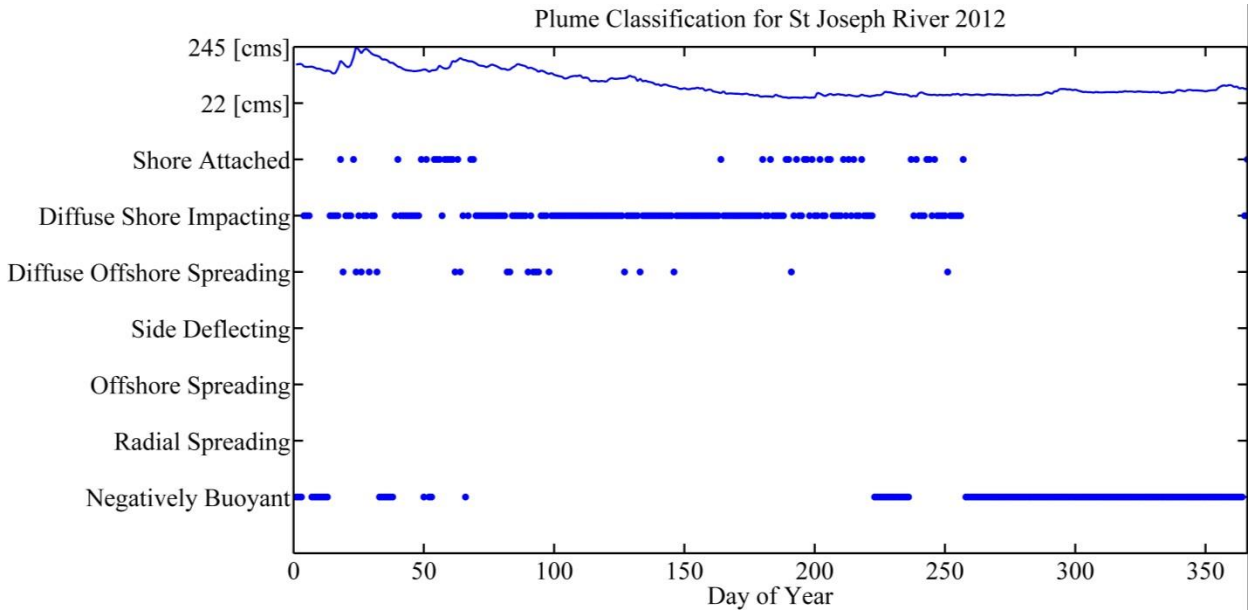

Figure 9. Daily plume classification for the St. Joseph River during 2012. Top line shows hydrograph for the year with a low flow of approximately 22 cms and a peak flow of 245 cms. Peak flow occurs during January. Low overall streamflow for the year resulted from low occurrence of storm events.

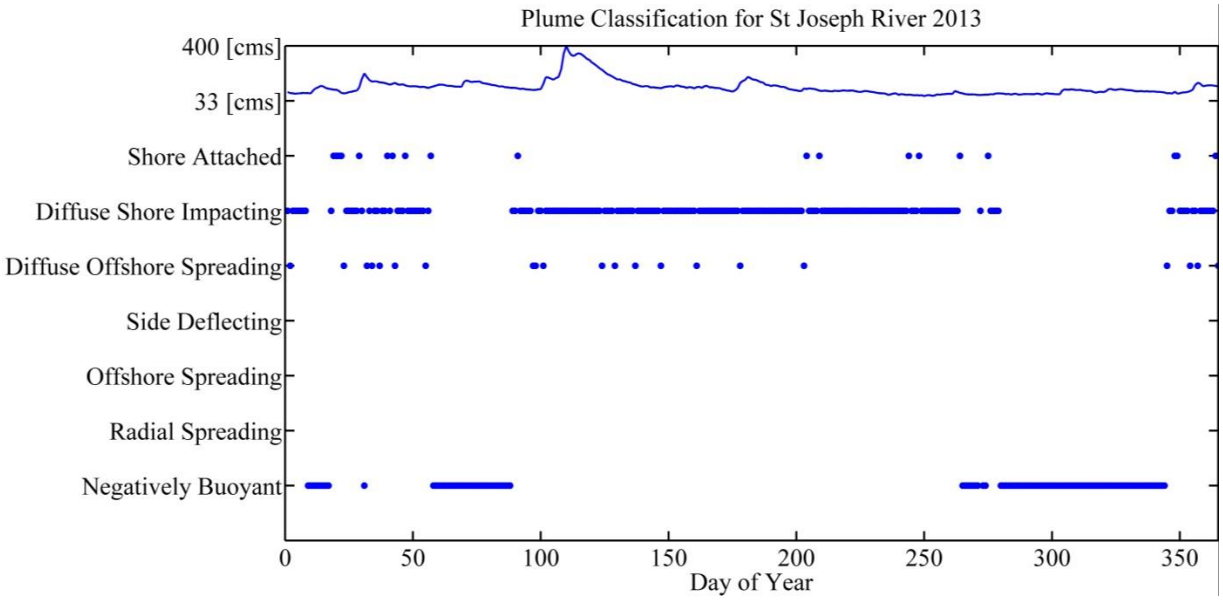

Figure 10. Daily plume classification for the St. Joseph River during 2013. Top line shows hydrograph for the year with a low flow of approximately 33 cms and a peak flow of 400 cms. Peak flow occurs during early May.

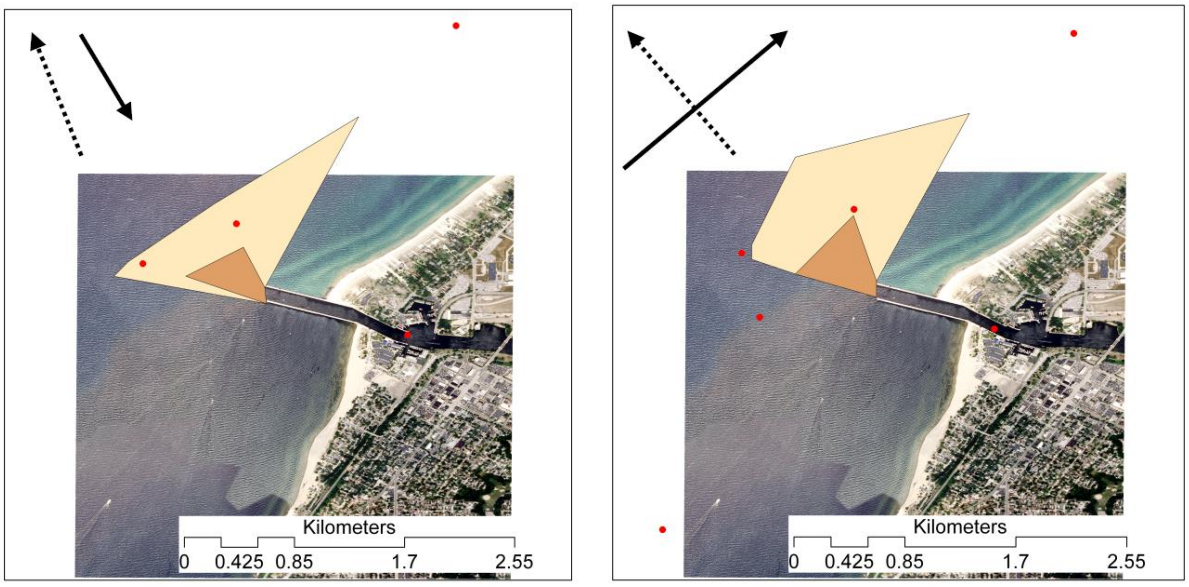

Figure 11. St. Joseph plume maps from July 31st, 2012 (left), and August 7th, 2012 (right). The solid arrow is lake current direction. The dotted arrow is wind direction. Light beige is the 0.2 relative conductivity contour and dark beige is the 0.5 relativity contour.

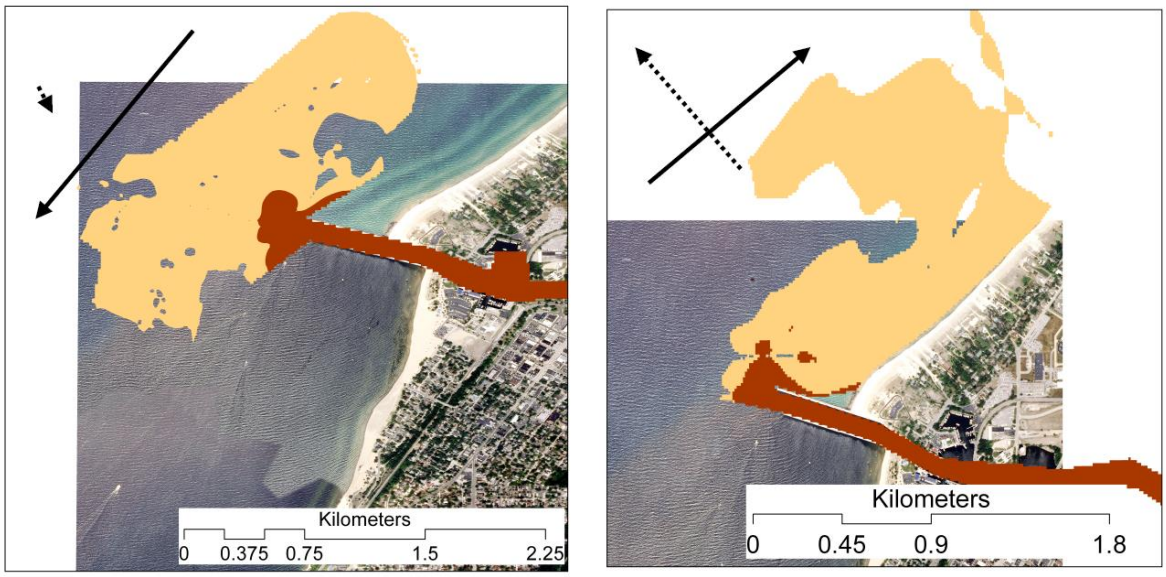

Figure 12. St. Joseph plume maps from June 26th, 2012 (left), and August 7th, 2012 (right). The solid arrow is lake current direction. The dotted arrow is wind direction. Light beige is the 0.2 relative conductivity contour and dark beige is the 0.5 relativity contour.

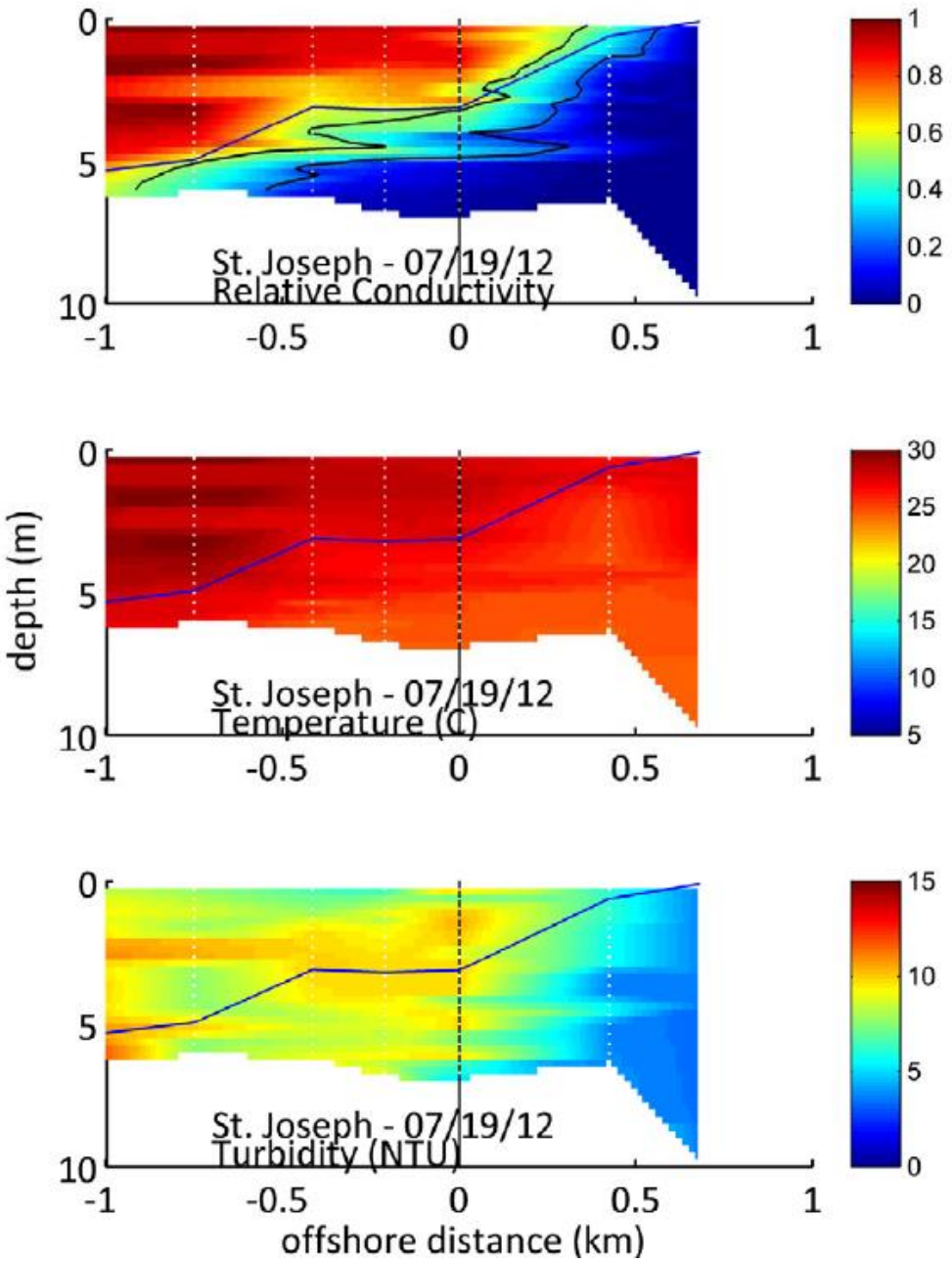

Figure 13. Vertical Transects from St. Joseph on July 19th, 2012. The blue line is plume depth, h_f. The vertical white dotted lines indicate the location of the sonde casts.

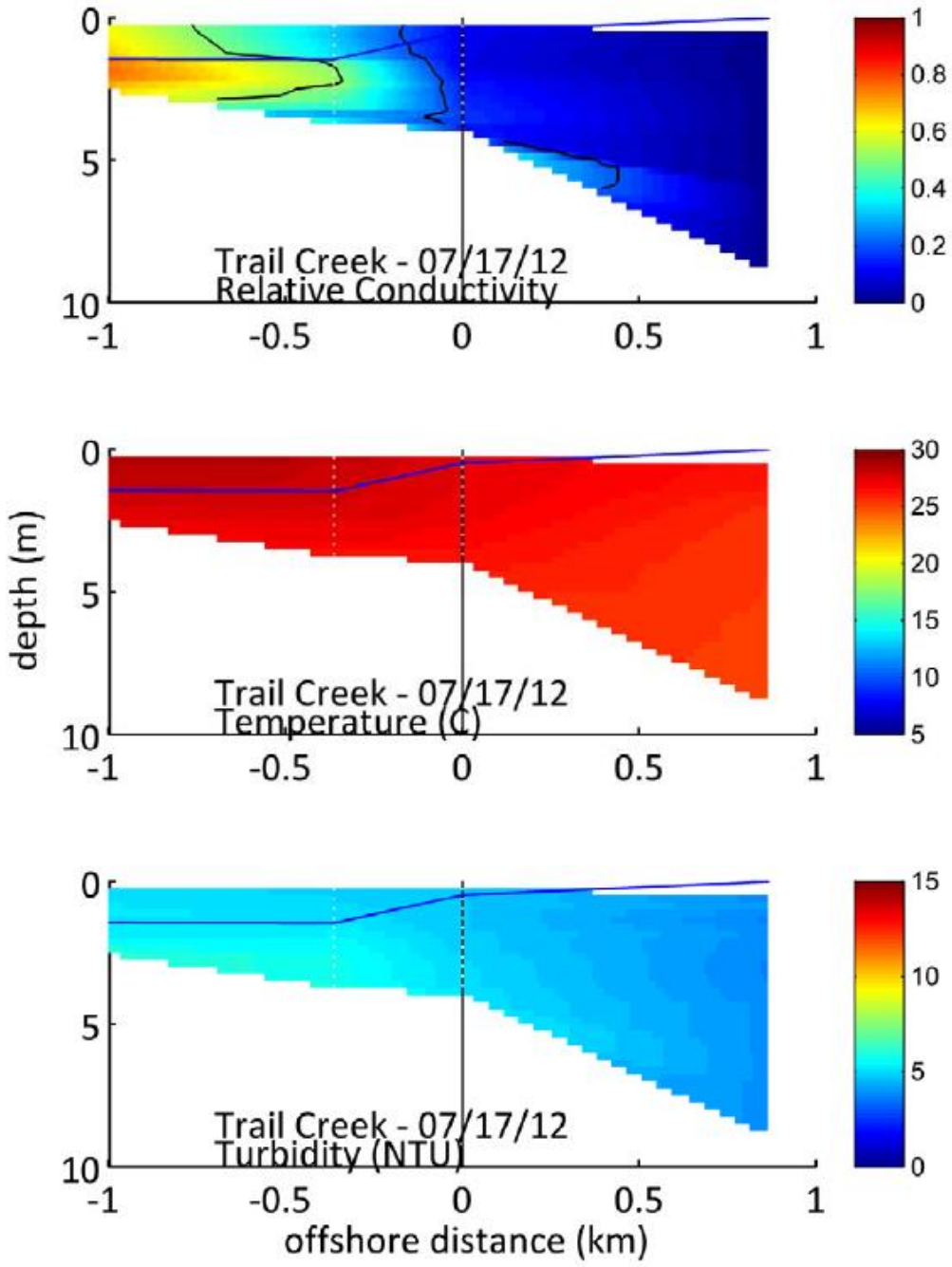

Figure 14. Vertical Transects from Trail Creek on July 17th, 2012. The blue line is plume depth, h_f. The vertical white dotted lines indicate the location of the sonde casts.

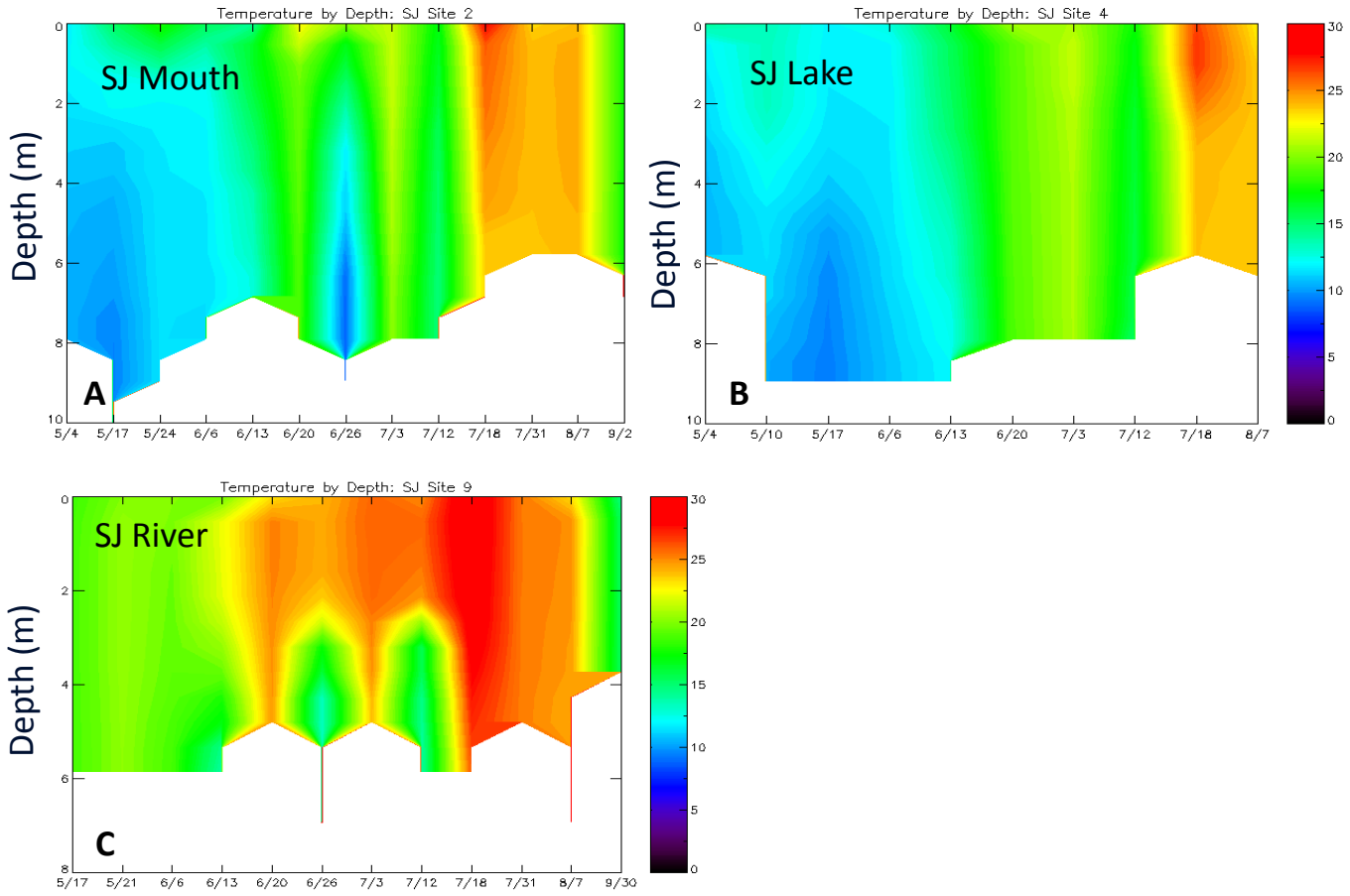

Figure 15. At three sampling sites a) L2, b) L4, and c) R1 we created color plots to display variation in temperature during the sampling season in 2012. The x-axis shows date and the y-axis shows depth in the water column. We interpolated field YSI sonde temperature measurements. During 2012 L2, the site closer to the rivermouth appears to be warmer than L4, the site 2km from the rivermouth.

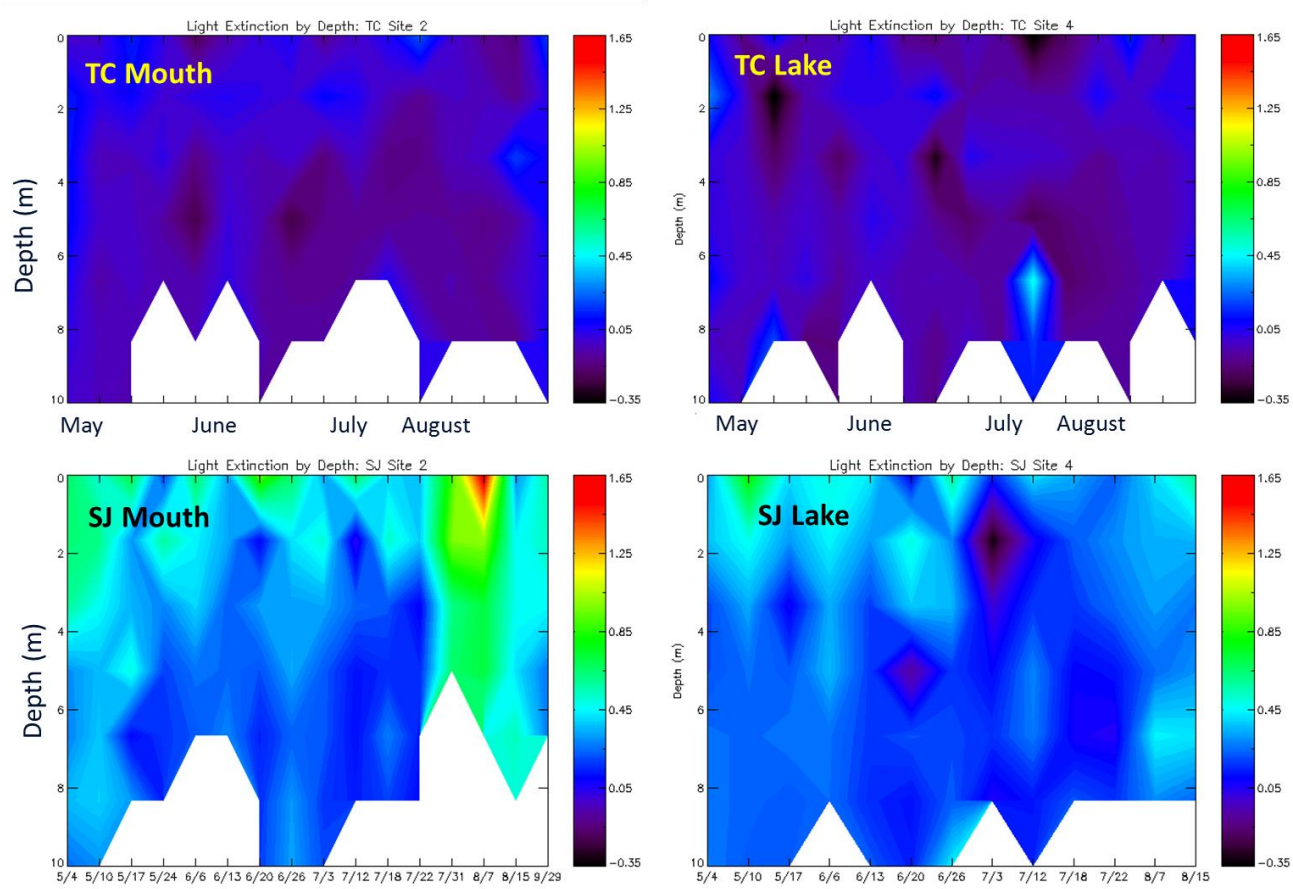

Figure 16. At two sampling sites a) L2 and b) L4, we created color plots to display variation in light extinction during the sampling season in 2012 neat Trail Creek and the St. Joseph River mouth. The x-axis shows date and the y-axis shows depth in the water column. We interpolated depth-specific measures of light level . During 2012 L2, the site closer to the river mouth appears to be more turbid than L4, the site 2km from the river mouth. Moreover, light extinction was consistently greater near St. Joseph as compared to near Trail Creek.

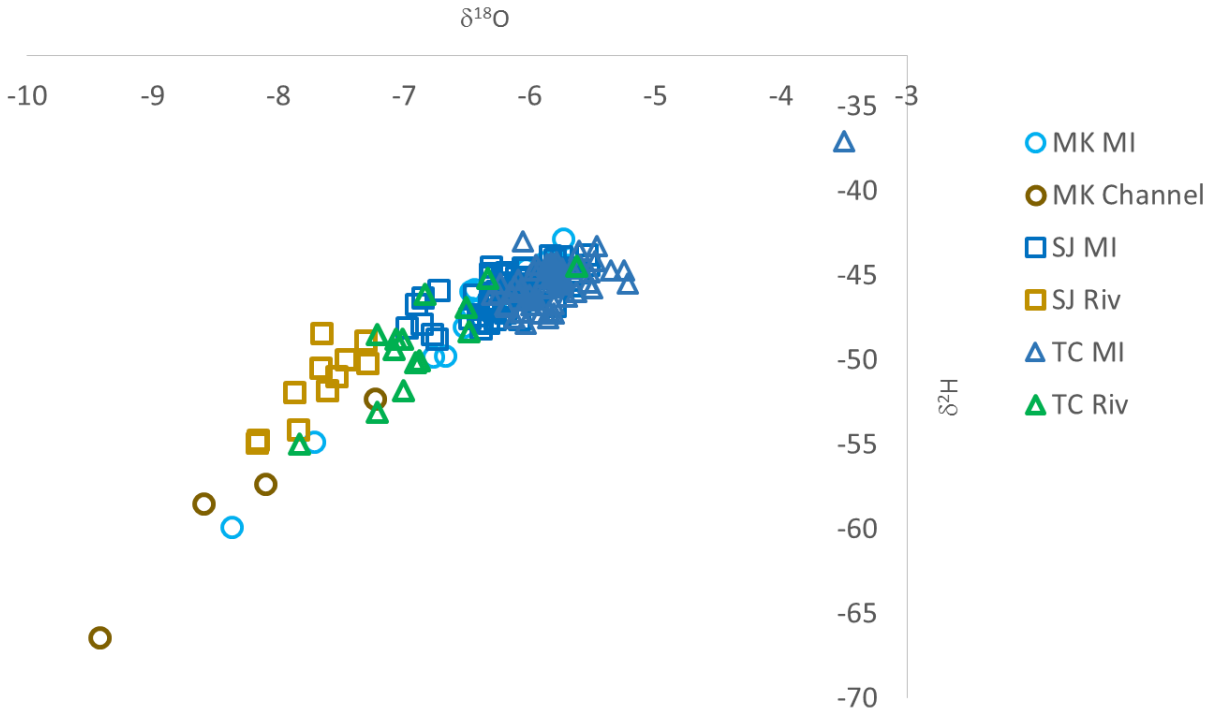

Figure 17. Water isotopes measured for samples collected in nearshore areas and river mouths in southern Lake Michigan during 2011. Note, the differentiation between river mouth and nearshore samples and the occasional samples from Trail Creek River having values similar to lake values (consistent with backflow of Lake Michigan water into Trail Creek).

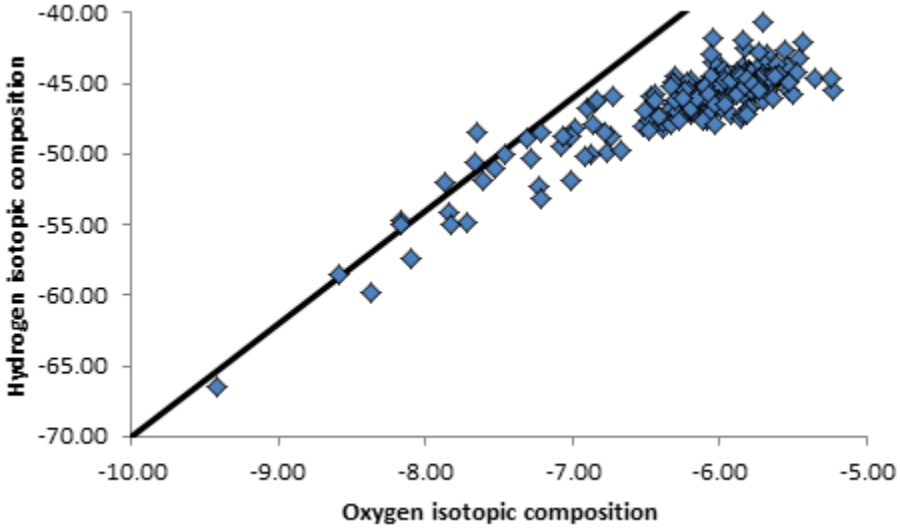

Figure 18. Hydrogen and oxygen isotope ratios of lake, river, and plume water samples. Bold black line shows trend expected for values of un-evaporated surface water. The trend away from that line toward the upper right corner of the plot represents mixing between lake water (upper right) and river inputs (along and close to bold black line).

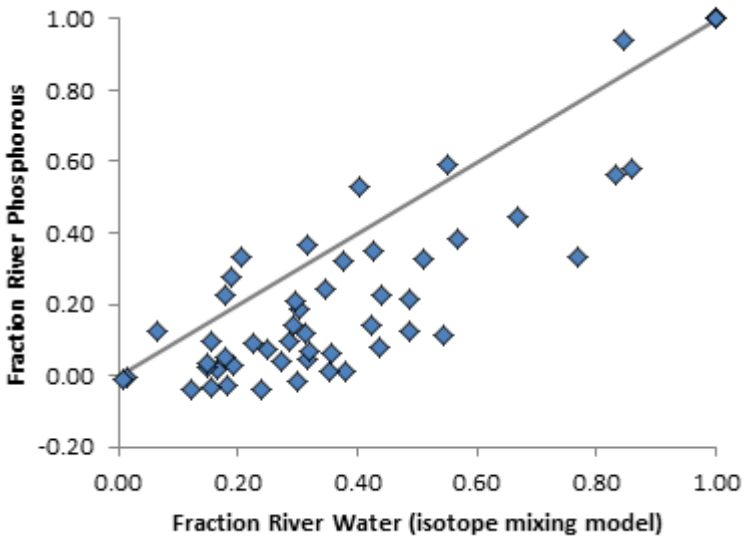

Figure 19. Relationship between total phosphorous concentration and river water fraction for samples from the 2011 St. Joseph rivermouth system. River water fraction was calculated using stable isotope data and a two endmember (river, open lake) mixing model. Fraction river phosphorous indicates the concentration total phosphorous for each sample relative to the measured river water concentration on the same date, corrected for the background concentration of phosphorous in the open lake (~7.5 ug/l). Points near the 1:1 line reflect dilution of riverine phosphorous inputs through mixing with lake water. The substantial cluster of points below the 1:1 line suggest reactive (e.g., primary production) or physical (e.g., particle settling) uptake of phosphorous within the river plume.

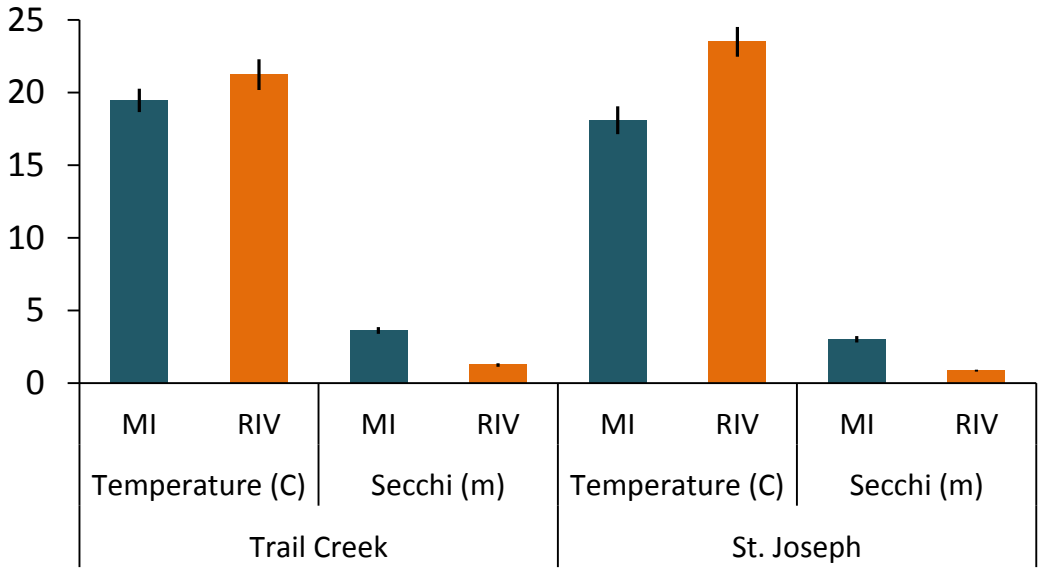

Figure 20. Mean temperature and Secchi depth during April – September 2011 and 2012. River sites were warmer and more turbid than Lake Michigan sites. Error bars indicate standard error.

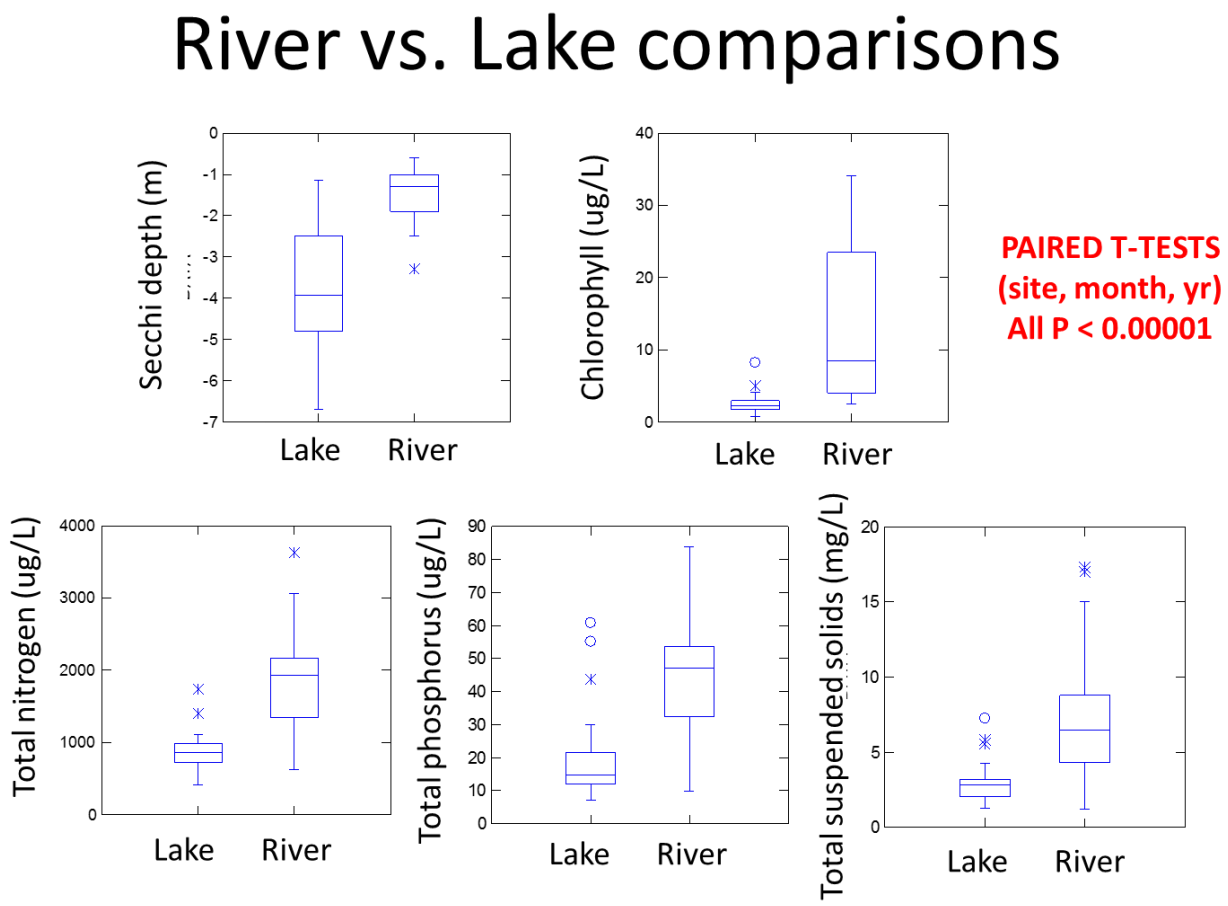

Figure 21. Comparison of wtare quality and nutrient concentrations measured for samples collected in river mouths vs. nearshore Lake Michigan during 2011 and 2012.

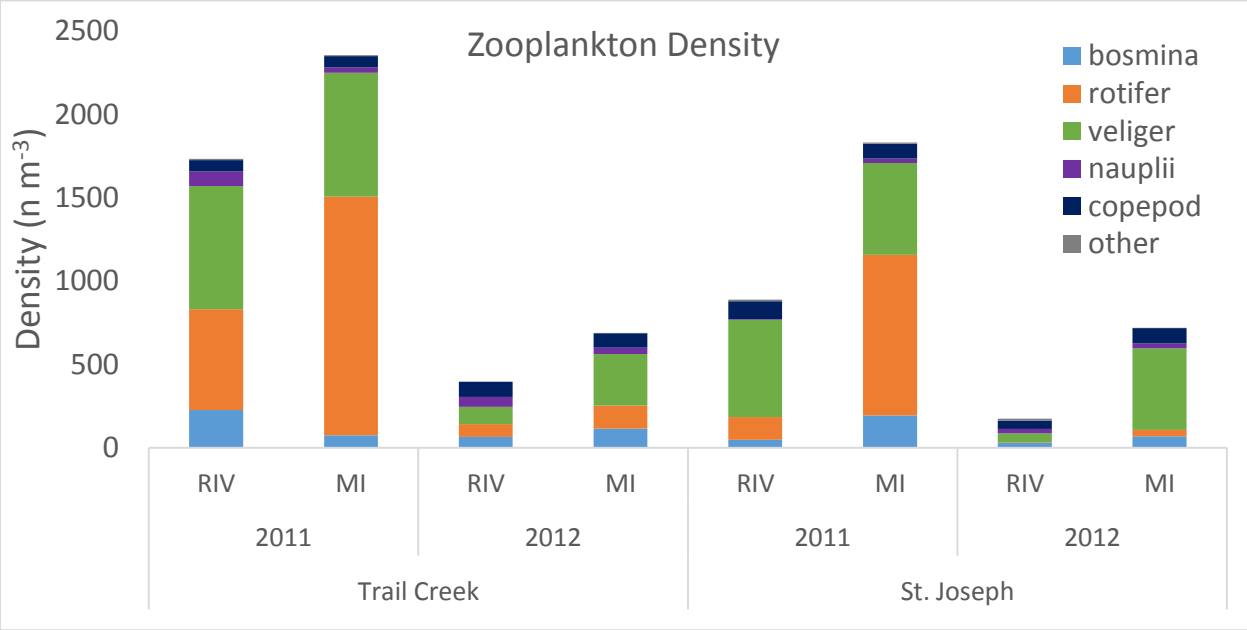

Figure 22. Zooplankton density for Trail Creek and St. Joseph during May through July 2011 and 2012. n = 132 tows.

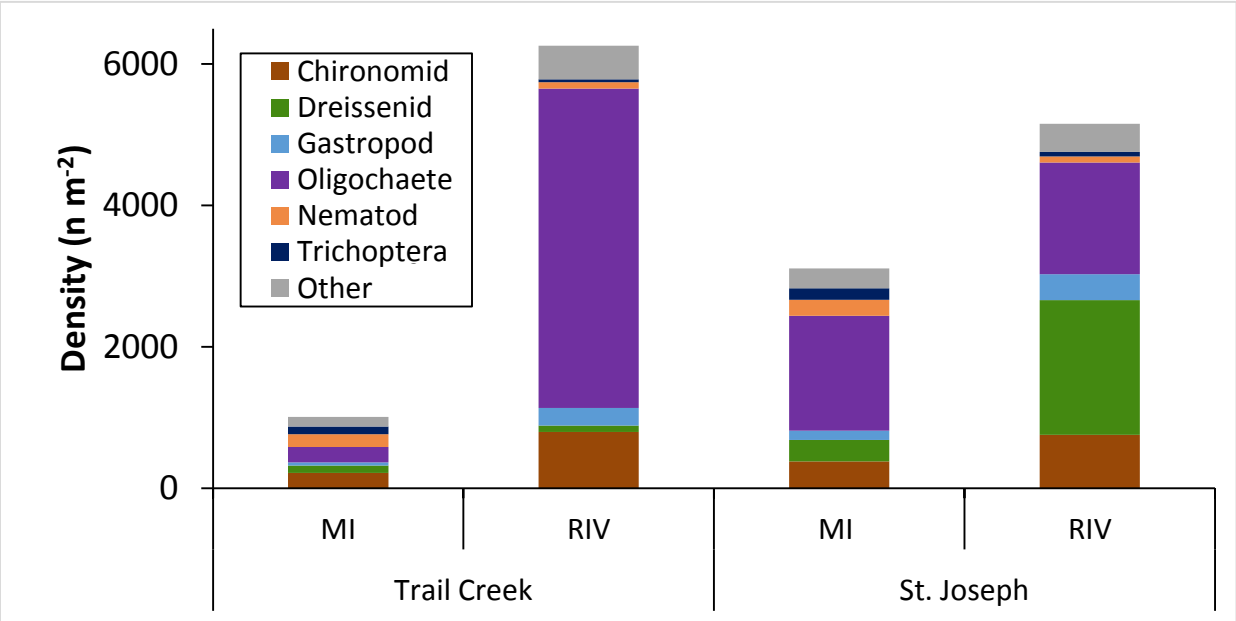

Figure 23. Mean densities of benthic invertebrates, during May – September 2011 and 2012, were greater in the river than in the lake at Trail Creek and St. Joseph.

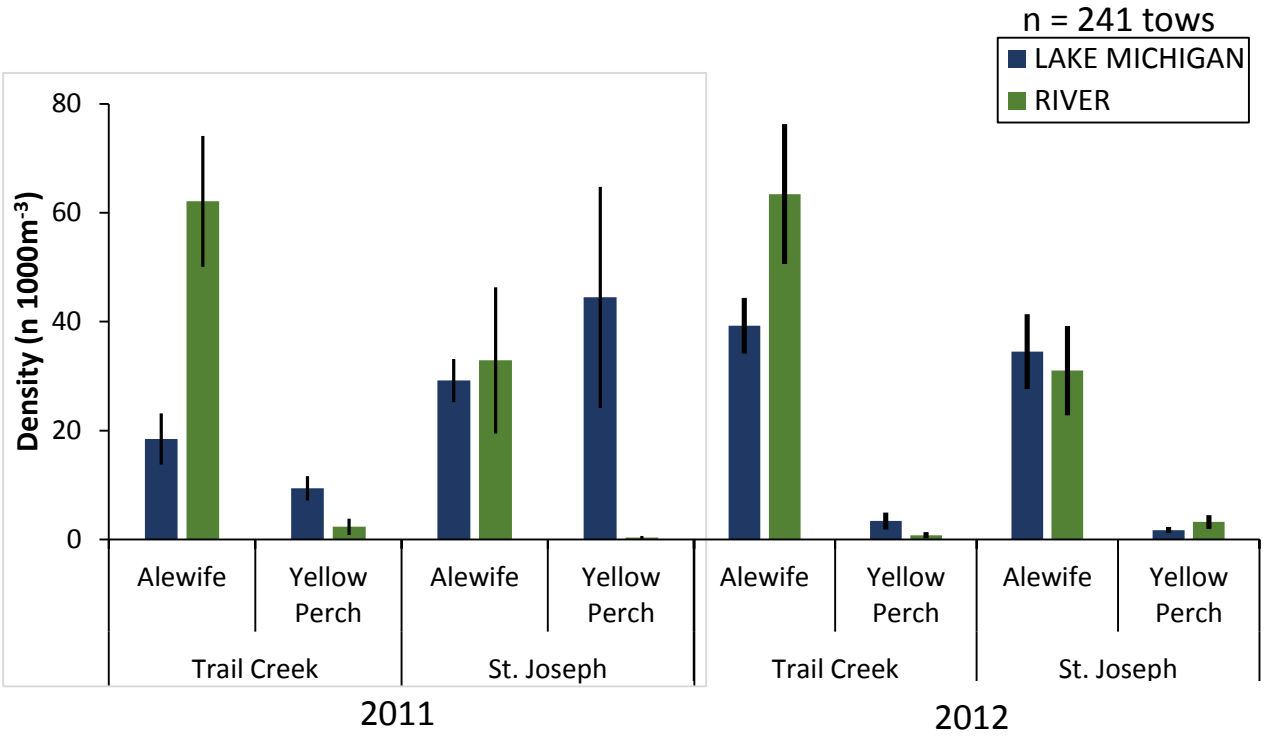

Figure 24. Mean (±SE) densities of larval alewife and yellow perch during May – August 2011 and 2012. Alewife densities were generally higher at river sites while yellow perch tended to be more dense at lake sites.

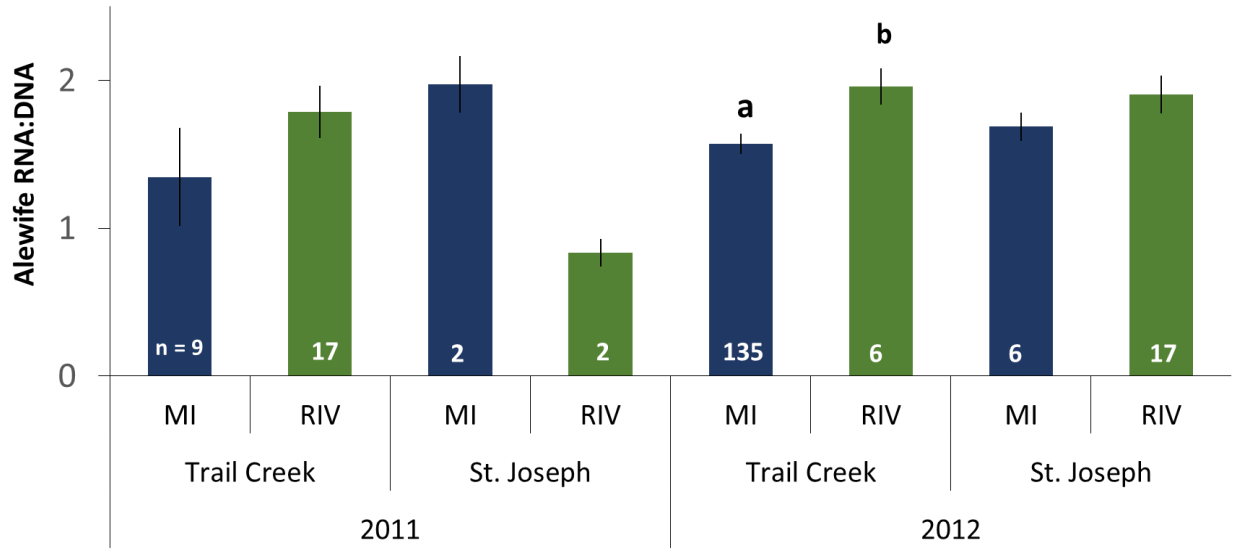

Figure 25. RNA:DNA (mean ±SE) of non-yolk sac larval alewife during May – July 2011 and 2012. a and b indicate a significant difference in means.

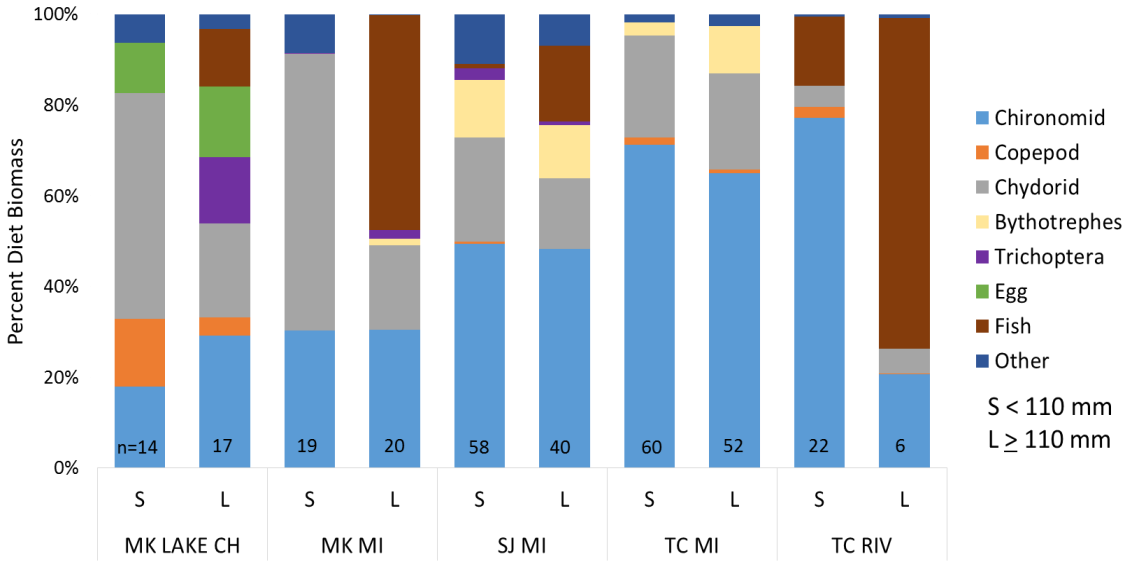

Figure 26. Percent diet biomass of yellow perch stomach contents. Yellow perch consumed a variety of benthic and pelagic prey at all river and lake sites, and they switched to piscivory total length > 110 mm. Overall, yellow perch diets were dominate by chironomid larvae.

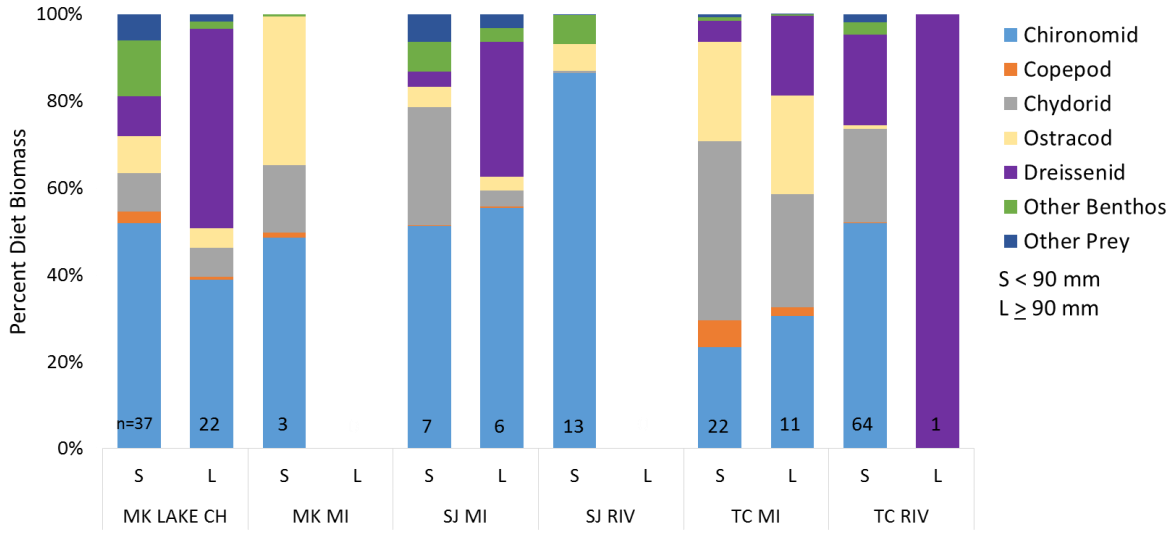

Figure 27. Percent diet biomass of round goby stomach contents. Round goby consumed prey from similar taxonomic groups across river and lake sites. They switched to consuming Dreissenid mussels at larger sizes. Round goby diets were dominated by chironomid larvae.

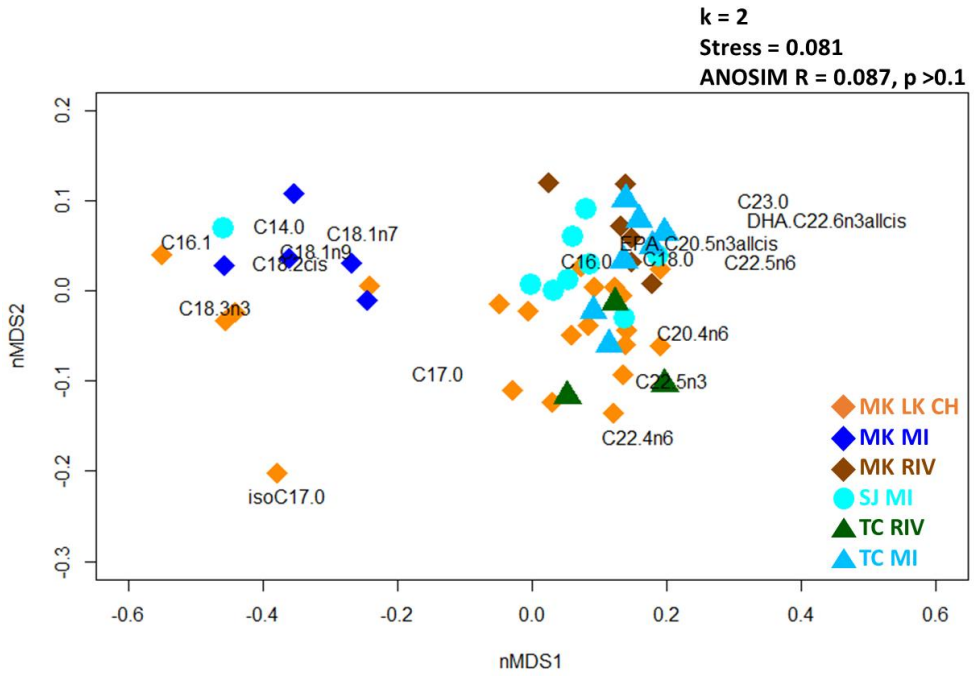

Figure 28. Nonmetric multidimensional scaling (nMDS) displays and ordination of yellow perch (each colored symbol is an individual fish) ordinated with fatty acids (shown as text). Based on their fatty acid signatures, yellow perch collected in Lake Michigan adjacent to Muskegon (MK MI) appear to consume different resources than fish at other sites.

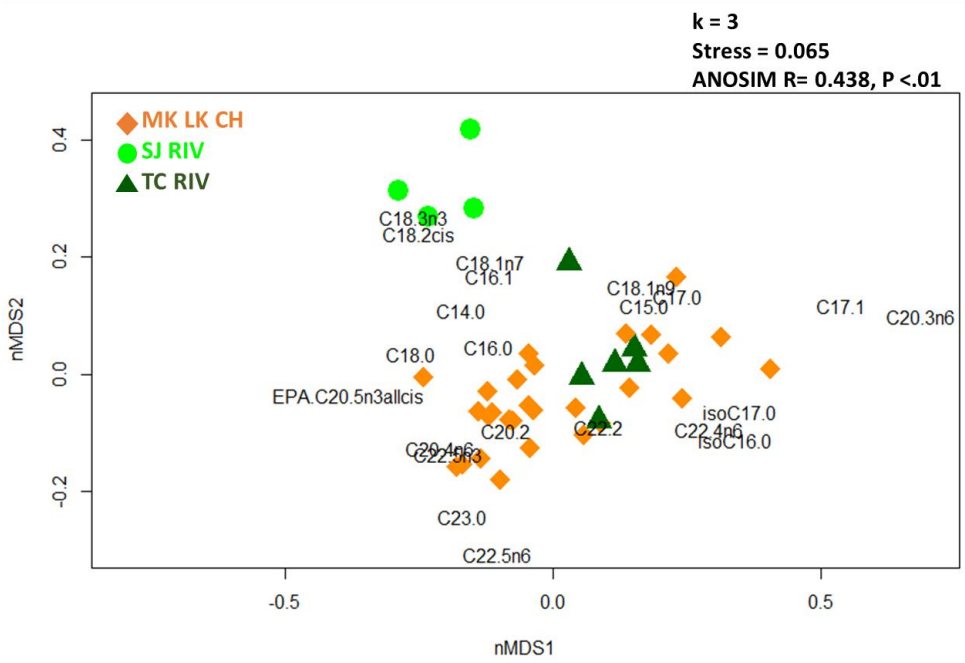

Figure 29. nMDS ordination of round goby (colored symbols) and fatty acids. Round gobies collected in the St. Joseph River appear to be consuming different resources than the other fish.

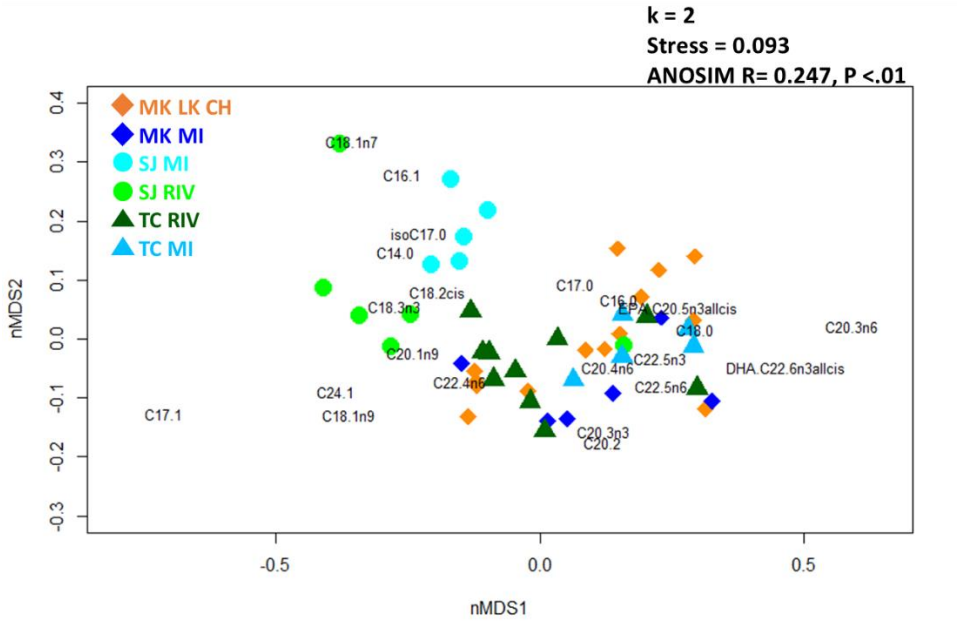

Figure 30. nMDS ordination of alewife (colored symbols) and fatty acids. Alewives collected in the St. Joseph River and Lake Michigan adjacent to St. Joseph appear to be consuming different resources than the other fish.

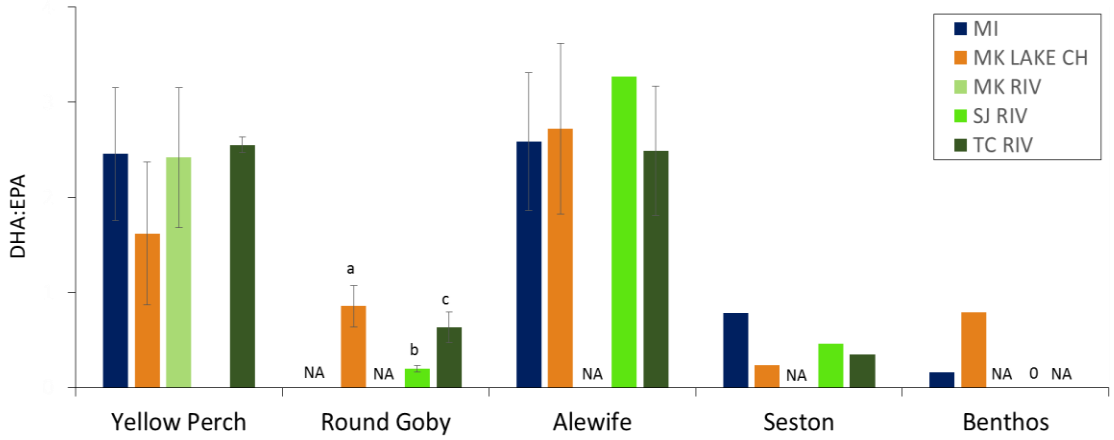

Figure 31. DHA and EPA are two well-studied fatty acids that indicate pelagic and benthic feeding respectively. A higher DHA:EPA indicates more reliance on pelagic prey. Here, alewife and yellow perch seem to be feeding pelagically while round goby appear to consume more benthic prey.

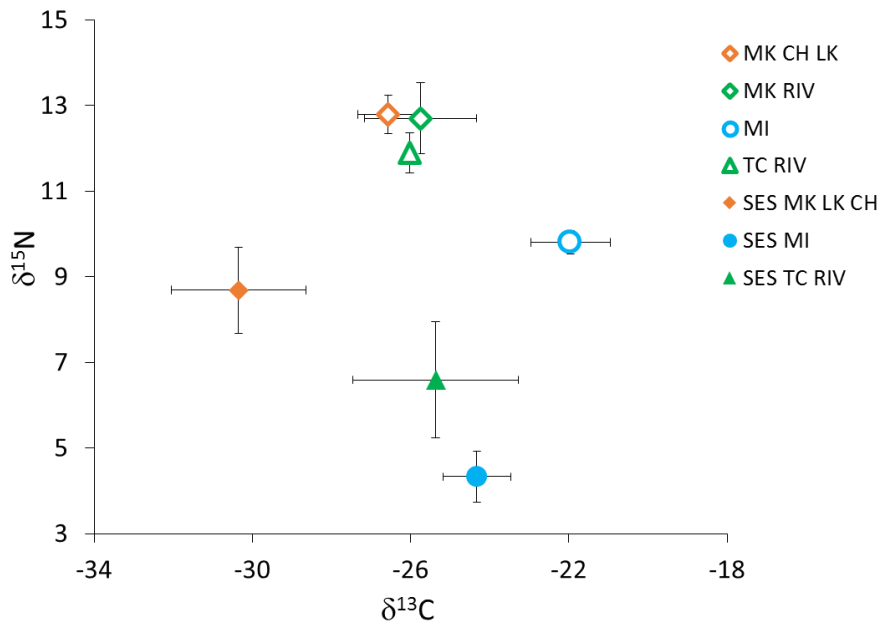

Figure 32. Open symbols indicate carbon and nitrogen isotope values of yellow perch tissue and closed symbols indicate carbon and nitrogen isotope values of seston (unsorted zooplankton samples). Symbols are mean values and error bars show standard error from the mean. Here, yellow perch across all Lake Michigan sites have similar C and N values while river and Muskegon Lake fish have a more riverine signal.

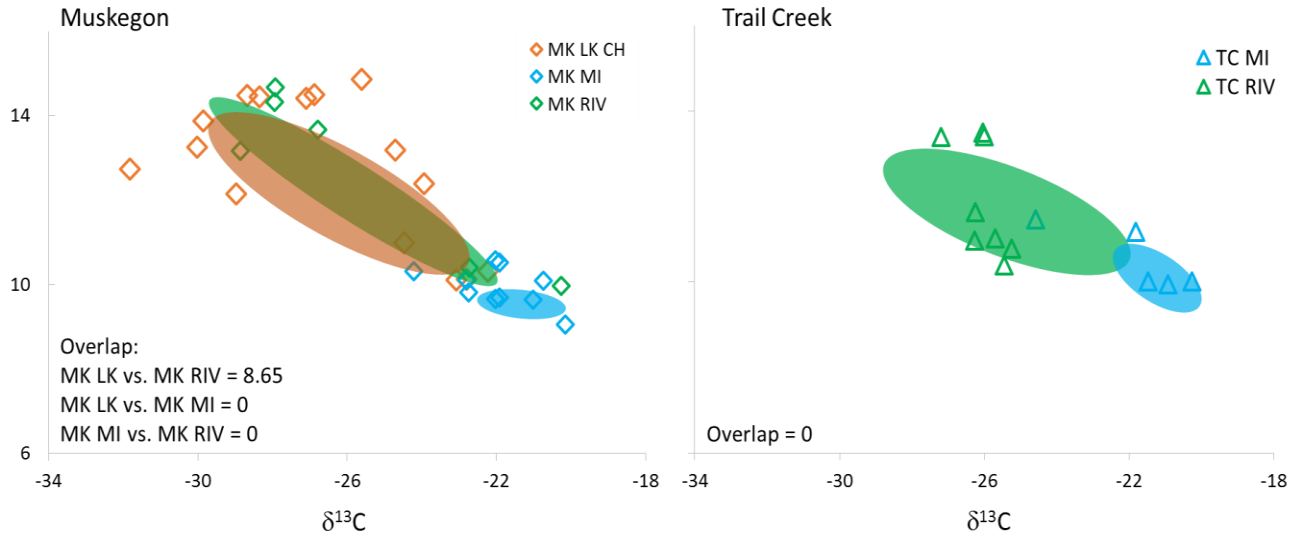

Figure 33. Ovals indicate Bayesian ellipses that depict credible intervals for C and N isotope values of yellow perch tissue. According to overlap calculations, there was no isotopic overlap between Lake Michigan and tributary yellow perch at Muskegon or Trail Creek.

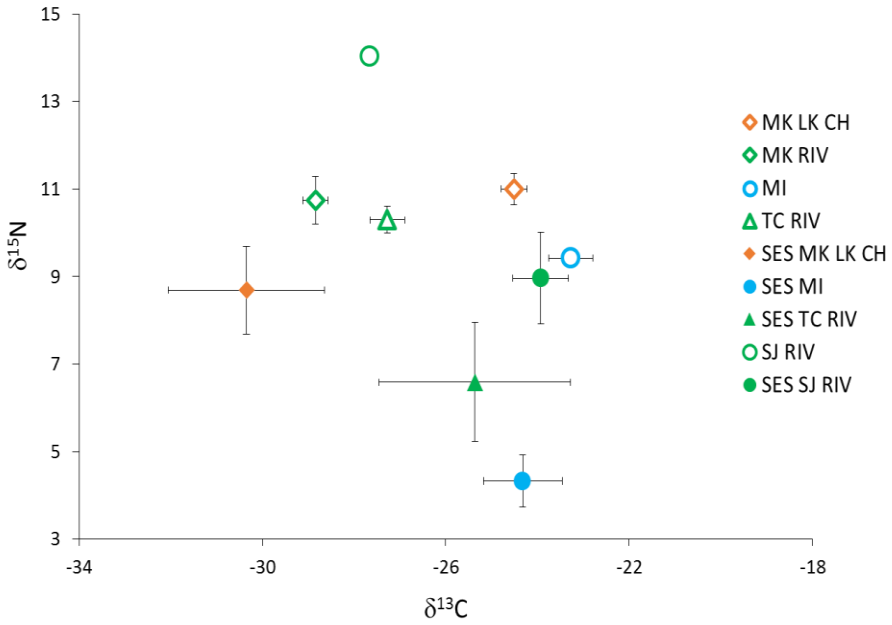

Figure 34. Open symbols indicate carbon and nitrogen isotope values of round goby tissue, and closed symbols indicate carbon and nitrogen isotope values of seston (unsorted zooplankton samples). Round goby isotope values follow a gradient of river to lake signatures indicating resource specialization.

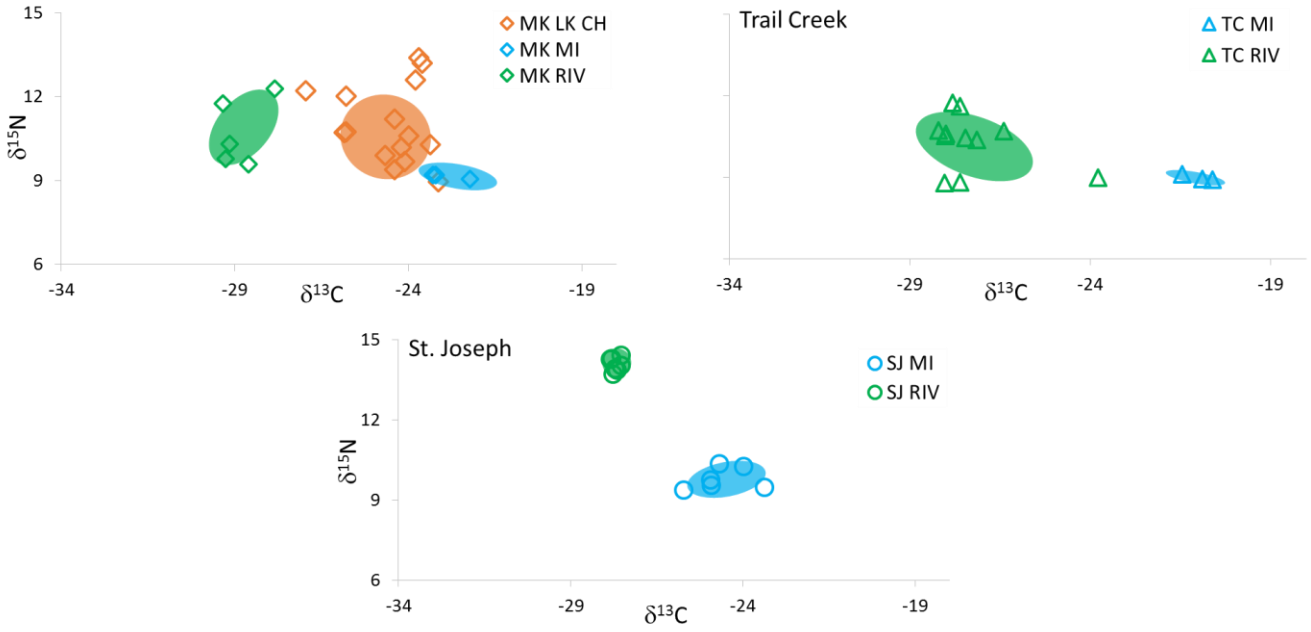

Figure 35. Ovals indicate Bayesian ellipses that depict credible intervals for C and N isotope values of round goby tissue. According to overlap calculations, there was no isotopic overlap in round goby between Lake Michigan and adjacent tributaries at Muskegon, Trail Creek, or St. Joseph.

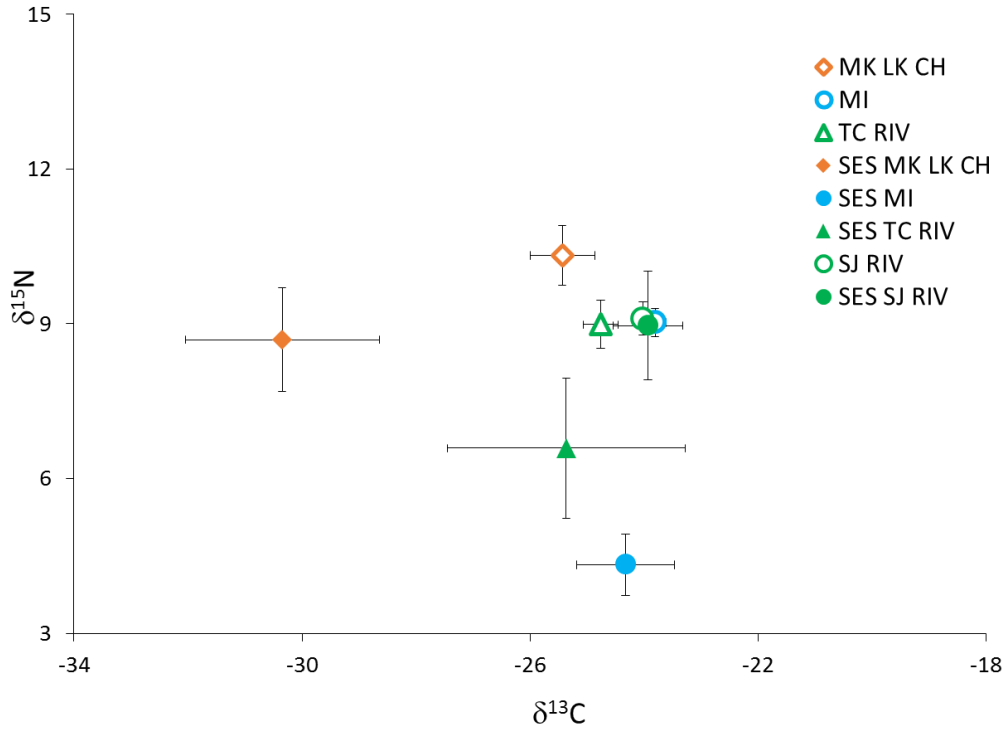

Figure 36. Open symbols indicate carbon and nitrogen isotope values of alewife tissue, and closed symbols indicate carbon and nitrogen isotope values of seston (unsorted zooplankton samples). Alewife C and N isotopes were similar across tributary and Lake Michigan sites.

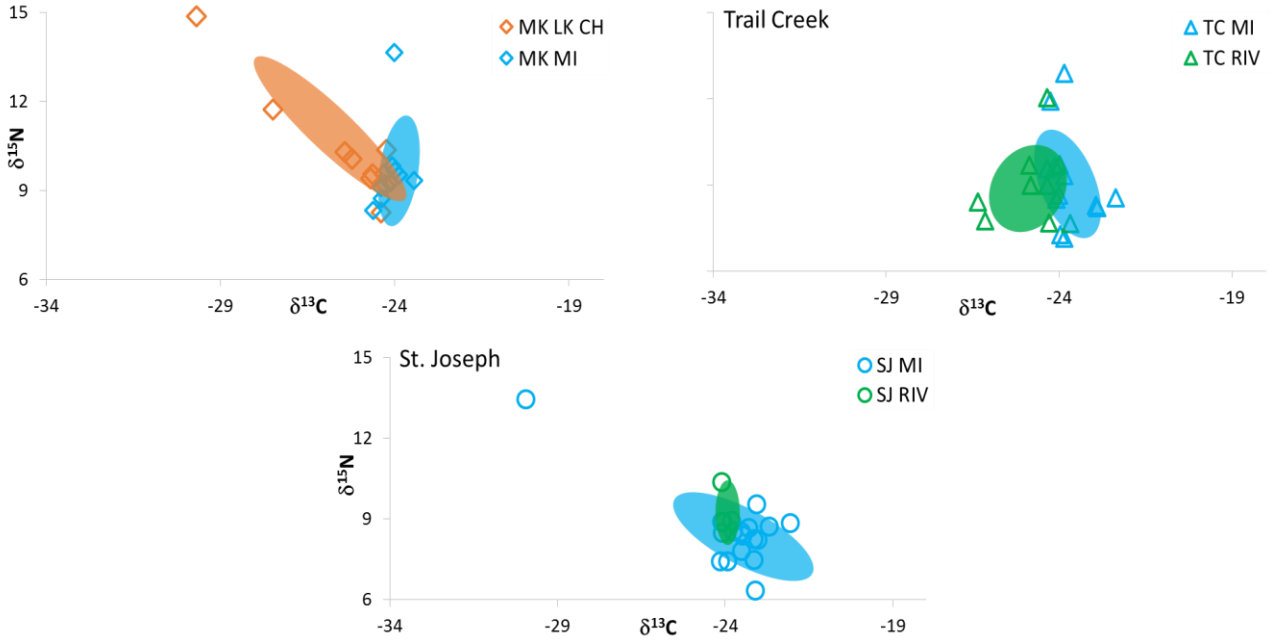

Figure 37. Ovals indicate Bayesian ellipses that depict credible intervals for C and N isotope values of alewife tissue. There was overlap between isotope values in tributary and Lake Michigan fish at all three rivermouths.

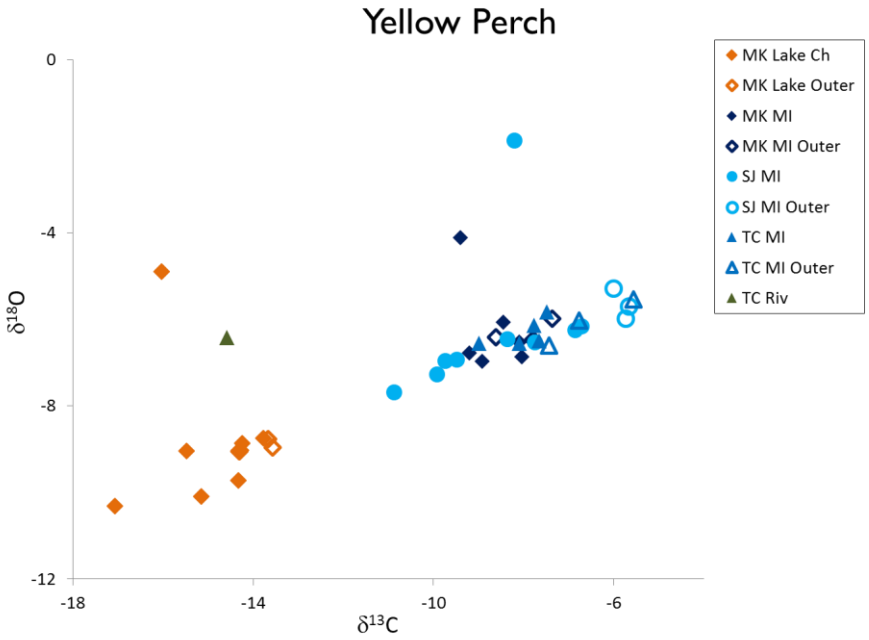

Figure 38. Closed symbols indicate carbon and oxygen stable isotope values from yellow perch otolith cores, and open symbols indicate isotope values from the outer edge of the otoliths. Yellow perch core and outer edge values tended to follow the expected trend from tributary to Lake Michigan sites suggesting that yellow perch did not move considerably between nursery and juvenile habitats.

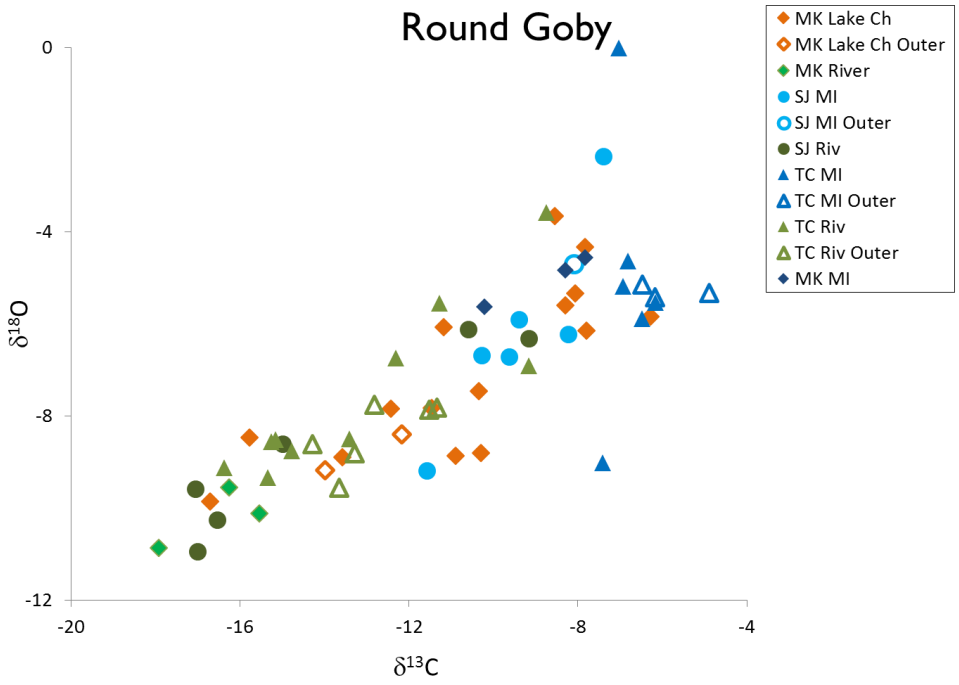

Figure 39. Closed symbols indicate carbon and oxygen stable isotope values from round goby otolith cores, and open symbols indicate isotope values from the outer edge of the otoliths. Round goby core and outer edge values tended to follow the expected trend from tributary to Lake Michigan sites; however, outer edge values differed from core values in some cases suggesting possible movement between habitats during early-life.

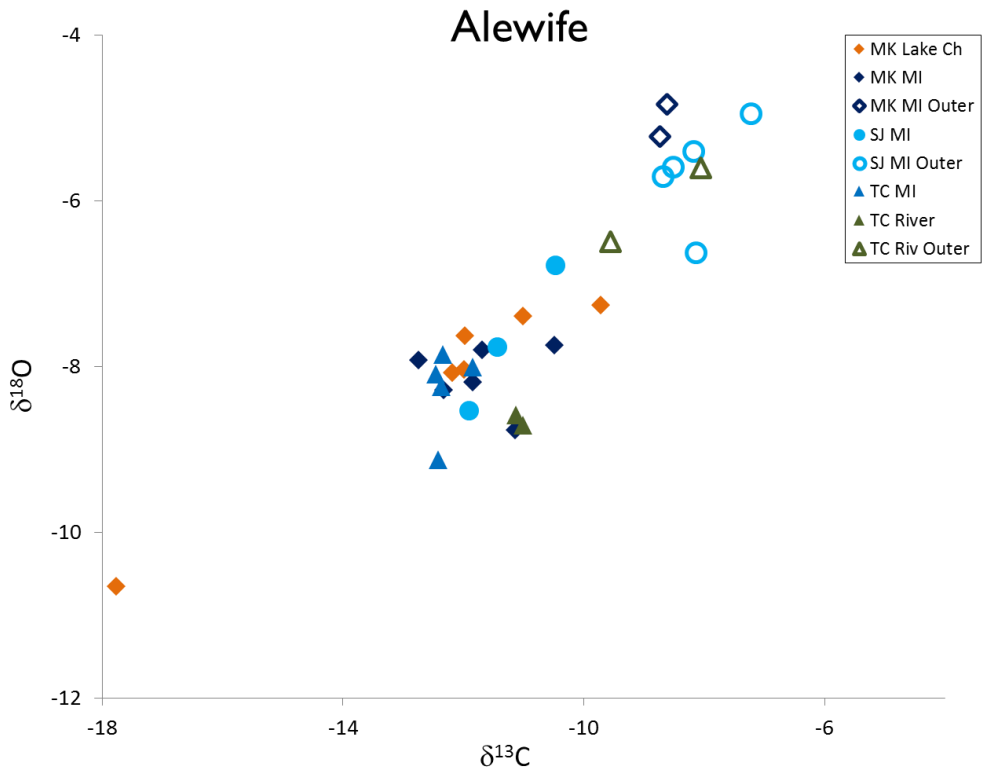

Figure 40. Closed symbols indicate carbon and oxygen stable isotope values from alewife otolith cores, and open symbols indicate isotope values from the outer edge of the otoliths. Alewife core and outer edge values were variable between sites and outer edge values differed from core values suggesting that alewives may utilize different habitats during early-life than as adult fish.