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FEATURE

Twenty years of conservation effects assessment in the St. Joseph River watershed, Indiana

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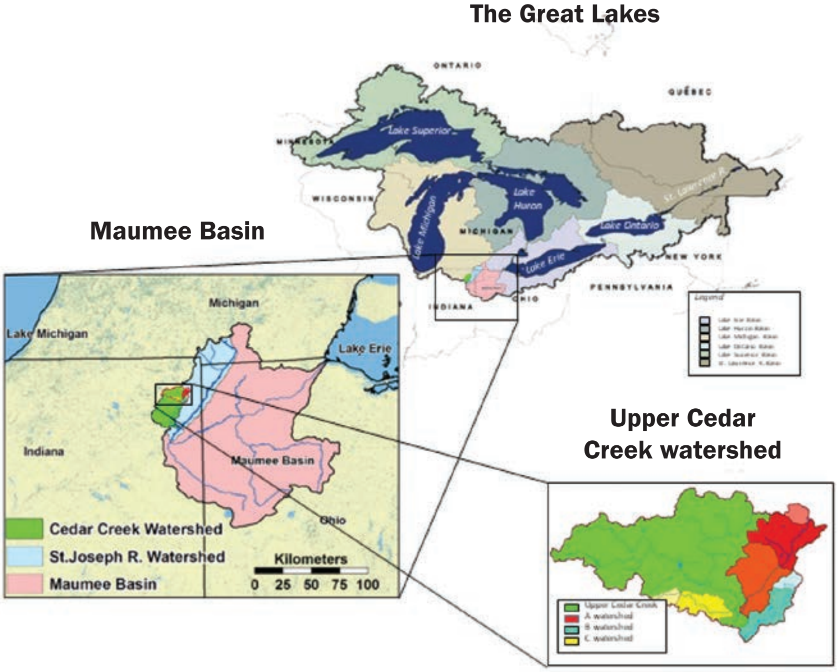
Figure 1

Map of the Great Lakes region, the Maumee River, St. Joseph River, and the Upper Cedar Creek watershed. The USDA Agricultural Research Service (ARS) National Soil Erosion Research Laboratory (NSERL) has been monitoring water, nutrient, sediment, and pesticide losses from agricultural landscapes and evaluating the effectiveness of conservation practices to decrease these losses in the St. Joseph River watershed since 2002.



Lake Erie has a long and storied history with water quality impairment and conservation. Following the passing of the Clean Water Act in the 1970s, total phosphorus (P) loading to the lake substantially decreased through permitting of point sources and through conservation efforts to decrease sediment loss from agricultural fields. While total P losses to Lake Erie have remained relatively stable since the 1990s, dissolved P has increased and resulted in increases in the extent and severity of algal blooms over the past two decades (Smith et al. 2015b). Both agricultural industry and environmental quality are vital to local and regional economies. To achieve a balance between these important resources, there is a critical need to better understand the effect of agricultural practices on crop production and water quality in the national priority Lake Erie watershed.

The St. Joseph River watershed (2,809 km^2 [694,400 ac]) is one of the main tributaries to the Maumee River and Lake Erie (figure 1). Originating in southern Michigan, the St. Joseph River flows to the southwest through northwestern Ohio and northeastern Indiana where it joins with the St. Marys River to form the Maumee River in Fort Wayne, Indiana. The topography of this agricultural watershed (79% agricultural land use) is flat to gently rolling, with many depressional areas and tile drainage. The St. Joseph River contributes 15% to 20% of the water delivered to Lake Erie annually via the Maumee River (Williams and King 2020), serves as the drinking water supply for Fort Wayne, and is a potential hotspot for nutrient loss (Scavia et al. 2016). The USDA Agricultural Research Service (ARS) National Soil Erosion Research Laboratory (NSERL) has been conducting cutting-edge water quality research and testing novel conservation practices for decreasing sediment, nutrient, and pesticide losses in the St. Joseph River watershed since 2002. This article describes the history of the USDA ARS NSERL water quality monitoring in the St. Joseph River watershed; summarizes and highlights key research findings; and outlines the successes, challenges, and future directions of research.

HISTORY OF WATER QUALITY MONITORING IN THE ST. JOSEPH RIVER WATERSHED

The seeds of the USDA ARS NSERL watershed monitoring program were sown in 1995 when tap water samples from Fort Wayne, Indiana, were tested by environmental groups for common herbicides. At the time, Fort Wayne was pumping 129 million L water d^{-1} (34 million gal water day^{-1}) from the St. Joseph River to serve 250,000 residents. Results of the tap water testing showed herbicide concentrations above US Environmental Protection Agency drinking water standards (Environmental

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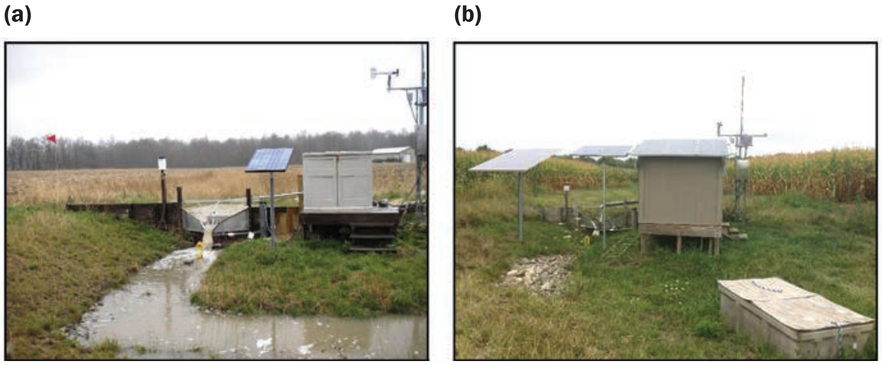
Working Group 1995). While Fort Wayne immediately upgraded its water treatment plant to decrease herbicide concentrations below drinking water standards, local, state, and national stakeholders remained concerned about the presence of low levels of herbicides in surface drinking water supplies. As a result, the US Congress provided new funding known as the Source Water Protection Initiative to the NSERL in 2001 to examine the fate and transport of agricultural chemicals in the St. Joseph River watershed and to assess the effect of conservation practices on pollutant delivery.

In 2002, five watershed monitoring locations (298 to 4,303 ha [736 to 10,634 ac]) were installed by NSERL in the Cedar Creek watershed (707 km^2 [175,000 ac]; figure 1), the largest tributary to the St. Joseph River, to monitor water, nutrients, and pesticides during the growing season. USDA ARS partnered with the USDA Natural Resources Conservation Service (NRCS), USDA National Institute for Food and Agriculture, and other federal agencies in 2003 to create the Conservation Effects Assessment Project (CEAP) (Mausbach and Dedrick 2004). This formally established the St. Joseph River watershed as one of 14 ARS benchmark watersheds to complete in-depth analysis of soil and water quality and quantify the effects of watershed-scale conservation (Duriancik et al. 2008). Since the inception of CEAP, numerous changes and improvements to the NSERL monitoring network have been made including the addition of new watershed monitoring locations, soil moisture monitoring, addition of edge-of-field monitoring of surface runoff and tile discharge, year round monitoring of discharge and water quality, installation of eddy-covariance flux towers to measure gas fluxes to the atmosphere, and addition of telemetry for remote access to monitoring equipment (figure 2). In 2014, monitoring sites also became part of the USDA Long-Term Agroecosystem Research (LTAR) network. Currently, the watershed monitoring includes seven edge-of-field sites (2 to 23 ha [6 to 56 ac]) and five watershed monitoring locations (80 to 19,259 ha [198 to 47,590 ac]). Weather, soil moisture, and hydrology data from 2002 to 2022 along with time-lapse camera images from each of the current monitoring sites can be viewed at https://amarillo.nserl.purdue.edu/ceap/index.php.

Figure 2

Edge-of-field monitoring site in the St. Joseph River watershed in (a) 2005 and (b) 2020. While technology and equipment have improved over the past two decades, long-term data collection from the same research sites is critical for understanding the impacts of agricultural management, conservation practice implementation, and climate on water quality.



Over the past two decades, the St. Joseph River watershed has served as an outdoor laboratory to observe and quantify processes such as nutrient and sediment transport and to develop and test conservation practices. Research findings have been published in more than 80 journal articles (supplemental table S1). More importantly, research results have been used by local, state, and national stakeholders to inform policy, develop conservation practice standards, and provide recommendations for improving water quality. Since 2014, the St. Joseph River watershed has been in the public spotlight when harmful algal blooms in Lake Erie resulted in undrinkable water for 400,000 Ohio residents. Consequently, data generated through the monitoring program have been downloaded more than all the other ARS benchmark watersheds combined via the Sustaining the Earth's Watersheds—Agricultural Research Data System (Sadler et al. 2020).

KEY RESEARCH FINDINGS AND ACCOMPLISHMENTS

Over the past 20 years, research efforts have resulted in significant findings and numerous accomplishments. This section highlights five areas that have had local, regional, and national impact.

Prevalence of Pesticides in Drainage Water Depends on the Specific Compound, Season, and Management Practices. Detection of pesticides in drainage water in the St. Joseph River watershed was found to be highly variable depending on the compound being measured. From 2004 to 2007, atrazine and metolachlor concentrations were consistently above analytical detection limits, while simazine, alachlor, and glyphosate were below detectable limits (Pappas et al. 2008). Indeed, monitoring of glyphosate over seven years from four fields and eight watersheds (~20,000 water samples) showed that concentrations were below detection limits for 99% of water samples collected (Gonzalez, unpublished data). For compounds that were consistently detected, the magnitude of concentration varied seasonally. Atrazine concentrations, for example, were found to be greatest in May and June after application and often exceeded the Maximum Contaminant Level (MCL) (3.0 μg L^{-1}), but were at or near detection limits for the remainder of the year (Pappas and Huang 2008). From 2004 to 2016, atrazine concentrations have remained consistent with no discernable increasing or decreasing trend (Gonzalez, unpublished data). Management practices, however, have the potential to decrease pesticide losses. In-field rainfall simulation experiments have shown that no-till results in greater atrazine and glyphosate runoff losses after application compared to chisel or conventional tillage systems

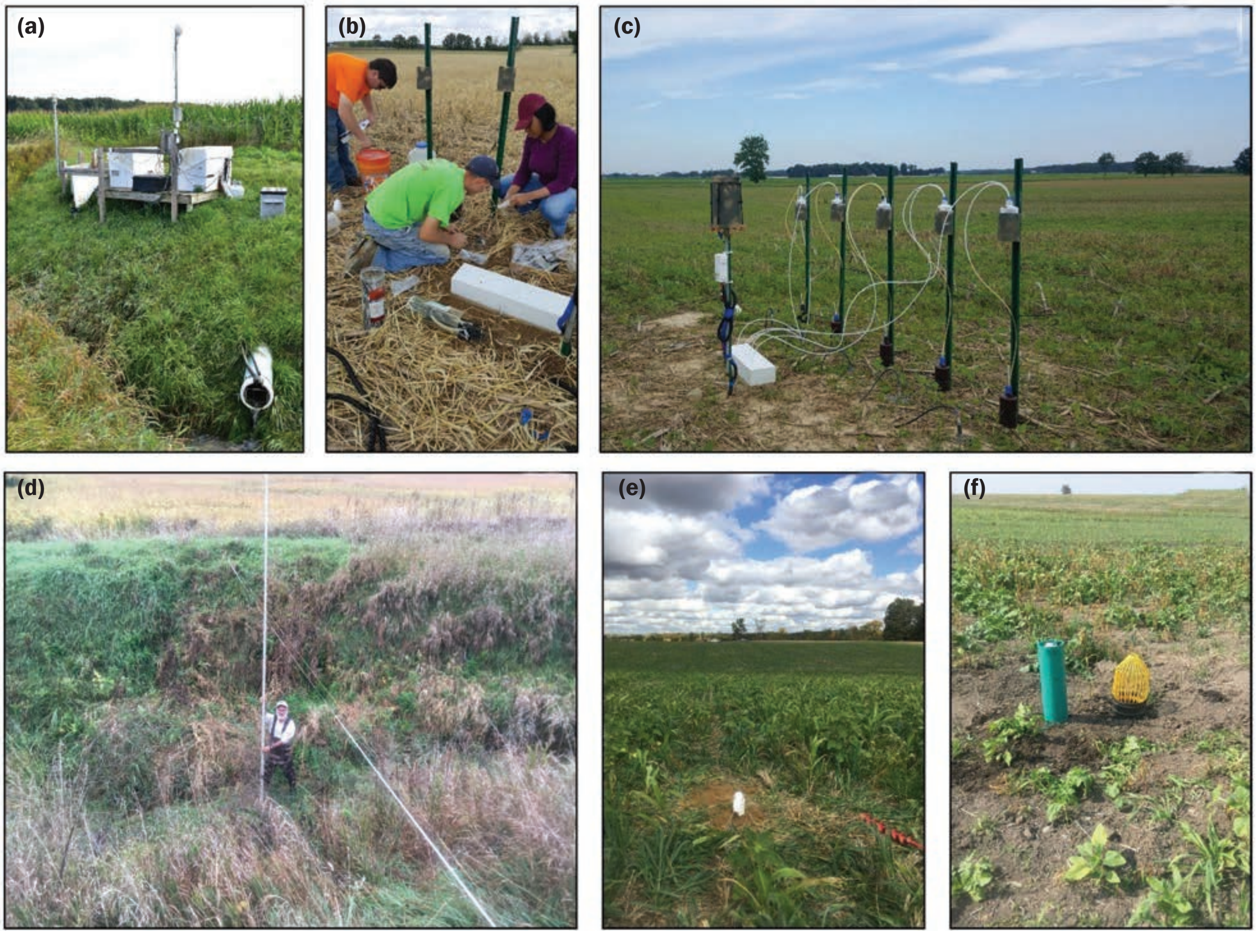
(Warnemuende et al. 2007). When sprayed in no-till systems, pesticides are intercepted by plant residue and not sorbed by the soil and therefore more susceptible to wash off.

Tile Drainage and Drainage Ditches Play an Important Role in Nutrient Transport. Research in the St. Joseph River watershed has yielded crucial data revealing the importance of tile drainage to field and watershed nutrient losses (figure 3). Prior to the work in the watershed, the prevailing wisdom was that P loss occurred primarily as the result of erosion and was therefore controlled by surface runoff processes. Comparison of nutrient concentrations and loads in agricultural ditches showed that while total nitrogen (N) and total P losses were likely the result of direct runoff into the ditch, dissolved nutrient concentrations and loads were more closely associated with areas that were hydrologically isolated from the drainage ditch (e.g., closed depressions) (Smith et al. 2008). This suggested that tile drainage was an important pathway for dissolved nutrients from fields to drainage ditches. Further research at both the field- and watershed-scale confirmed these initial findings. Monitoring at four agricultural fields revealed that between 25% and 80% of P loss occurred through tile drains (Smith et al. 2015a). Examining nutrient concentration-discharge relationships within nested watershed monitoring sites during storm events also highlighted the role of tile drainage in nutrient delivery from fields to surface waters (Williams et al. 2018). These research efforts identifying the importance of tile drains for nutrient delivery have been critical for developing strategies to decrease nutrient loss in the western Lake Erie basin and across the US Midwest.

While tile drains have been deemed important for nutrient loss, the physical and chemical processes controlling water and nutrient transport to tile drains are complex. Early work in the watershed observed that peak tile drain discharge occurred within minutes of peak surface runoff discharge suggesting that macropores (e.g., earthworm burrows, desiccation cracks) connect surface run-

Figure 3

Monitoring activities in the St. Joseph River watershed to quantify water and nutrient transport in fields and agricultural drainage ditches. (a) Edge-of-field monitoring of surface runoff and tile drainage, (b) installation of suction cup lysimeters for sampling soil water, (c) suction cup lysimeters with precipitation gauge, (d) surveying an agricultural drainage ditch, (e) groundwater well for monitoring water level and nutrient concentrations, and (f) passive surface runoff device to measure ponding depth and water quality in closed depressions.



off and tile drainage (Smith et al. 2015a). Recent work using stable water isotopes to trace flow pathways to tile drains showed, however, that the rapid increase in tile drain discharge during storm events was largely comprised of "old water," water that had been stored in the soil before the rainfall event and mobilized by the rainfall (Williams and McAfee 2021) (figure 3). Water sources, and ultimately nutrient concentration, is strongly influenced by antecedent wetness conditions (Williams et al. 2022). Dry conditions result in small tile discharge volumes, high but variable nutrient concentrations due to preferential flow, and small loads. Wet conditions, however, are characterized by larger tile discharge volumes, lower but consistent nutrient concentrations due to large groundwater contributions, and large nutrient loads. Process-level insights from the St. Joseph River watershed are being used to inform and improve numerical models. These studies also provide benchmark data for understanding how changing management practices, changing extent/density of tile drainage, and climate interact to deliver water and nutrients to Lake Erie.

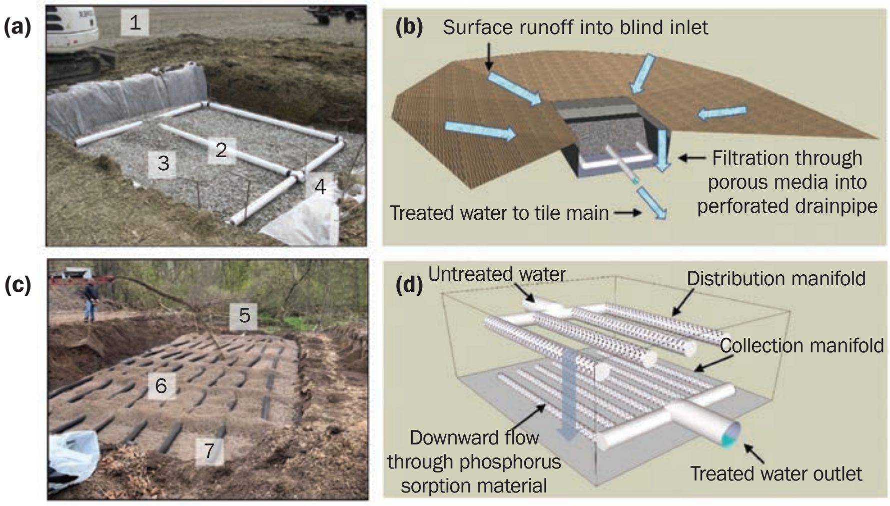
A crucial and often overlooked component of tile-drained landscapes is the drainage ditches, which are the intermediary between tile drains and streams and rivers (figure 3). As man-made elements of the landscape, drainage ditches require maintenance, often in the form of dredging, to ensure adequate removal of water from the landscape. In the St. Joseph River watershed, dredging was shown to increase transport of dissolved nutrients in the short-term (Smith et al. 2006). Vegetation recovery in the months after dredging, however, may serve as a sink for nutrients and decrease transport to downstream waterbodies (Smith and Huang 2010).

Blind Inlets and Phosphorus Removal Structures Decrease Sediment, Phosphorus, and Pesticide Losses from Tile-Drained Landscapes. Decreasing dissolved P losses from fields is a significant challenge as few conservation practices effectively decrease dissolved P. Phosphorus removal structures are landscape-scale filters consisting of a bed of reactive media, referred to as P Sorption Materials (PSMs), designed to remove dissolved P in flowing water from fields with high soil test P levels before it reaches a surface water outlet (figure 4). While they are constructed in a variety of shapes and styles (Penn et al. 2016), P removal structures were first adapted to treat subsurface tile drainage water in western Ohio (Penn et al. 2020), with much of the chart-topping research conducted concurrently in the St. Joseph River watershed. When designed to contain enough PSM to handle an adequate flow rate (i.e., an appropriately sized structure) at a sufficient contact time, P removal structures can remove 30% to 40% of the cumulative dissolved P load over their useful lifetime depending on the type of PSM, field conditions, and design (Penn et al. 2017). Research in the St. Joseph River watershed on P removal structures was recently used to develop USDA NRCS conservation practice standard 782 and is now available for cost-sharing through the Environmental Quality Incentive Program (EQIP). The NSERL has also recently developed software for designing site-specific P removal structures, called P Transport Reduction App (P-TRAP; https://www.ars.usda.gov/nserl/ptrap) (Penn et al. 2021). A series of training modules on designing and constructing P removal structures will be made available on USDA "Ag Learn" and by the American Society of Agricultural and Biological Engineers in January of 2023. Continued research is being conducted to improve cost efficiency and test new applications such as stacking P removal structures with constructed wetlands.

Past glaciation of the St. Joseph River watershed resulted in a landscape dotted with closed depressions or "potholes." To prevent ponding in agricultural depressions following a rain event, open inlets or tile risers have historically been installed at the lowest elevation of the depression. While this can decrease crop water stress, it also delivers runoff water rich in sediment, nutrients, and pesticides directly to the tile drain network. Working closely with local landowners, NSERL scientists adapted and tested a conservation practice called the blind inlet (Smith and Livingston 2013). A blind inlet replaces an open inlet or tile riser and consists of a 3.7 × 3.7 m (12 × 12 ft) framework of perforated drainpipe connected to a tile system that is back-filled with gravel and coarse soil material (figure 4). Blind inlets provide a practical advantage over tile risers in that

Figure 4

(a) Photograph and (b) conceptual drawing of a blind inlet. In panel a, 1 = upslope contributing area, 2 = perforated tile pipe, 3 = void to be backfilled with gravel or phosphorus sorption material, and 4 = connection to subsurface tile main. (c) Photograph and (d) conceptual drawing of a phosphorus removal structure. In panel c, 5 = inlet to phosphorus removal structure, 6 = phosphorus sorption material, and 7 = distribution manifold.



agricultural operations can be conducted directly on top of the blind inlet. Research has also shown that they act as a landscape-scale filter to reduce sediment and nutrient loads. For example, the longest-running blind inlet (12 years) in the St. Joseph River watershed decreased sediment and total P losses by 40% (Penn et al. 2019) and pesticides by 11% to 69% depending on the specific compound (Gonzalez et al. 2016). Replacing or amending the gravel backfill material with a PSM also allows the modified blind inlet to serve as a P removal structure for dissolved P (Gonzalez et al. 2020). Similarly, amending backfill media with carbonaceous material may further help decrease pesticide losses (Penn et al. 2019). This pioneering work on blind inlets has led to the development of USDA NRCS conservation practice standard 620. Blind inlets are also eligible for funding through EQIP and, as a result, numerous blind inlets have been installed through research and conservation efforts across the US Midwest.

Ecological Assessments Reveal the Importance of Habitat and Water Chemistry to Aquatic Organisms and How Conservation Practices Can Enhance Aquatic Biota Abundance and Diversity. Our research team conducted extensive ecological surveys at 14 sites in the St. Joseph River watershed between 2006 and 2019 (figure 5). Instream habitat, riparian habitat, and water chemistry data from these sites were used to better understand fish, amphibian, macroinvertebrate, crayfish, and freshwater mussel communities. This research is unique because ecological assessments of conservation practices at the watershed scale are limited (Lizotte et al. 2021) and ecologists at only three CEAP watersheds are engaged in these types of studies. Fish community structure in Cedar Creek watershed was strongly influenced by instream habitat (Smiley et al. 2008), with more recent work specifically highlighting the influence of stream hydrology and substrate (Sanders et al. 2020). In contrast, amphibian community and population structure were more strongly correlated with water chemistry than instream habitat (Jordan et al. 2016). Analysis of stream sediment also found evidence of herbicides (i.e., atrazine, metolachlor, simazine) and trace metals (i.e., copper [Cu], zinc [Zn]) at concentrations below sublethal effects benchmarks for macroinvertebrates. Biotic integrity of macroinvertebrates was correlated with sediment nutrient concentrations, sediment herbicide concentrations, and substrate diversity. These results highlight the importance of addressing physical and chemical degradation of stream sediments (Shuman et al. 2020).

Agricultural headwater streams throughout the St. Joseph River watershed support native crayfishes that are keystone species in freshwater ecosystems (Wood et al. 2020). The frequency and severity of crayfish injuries are indicators of crayfish aggression and serve as novel bioindicators of the sublethal impacts of physical habitat quality and water quality. Frequency and severity of crayfish injuries were more strongly influenced by crayfish density than physical habitat quality and water quality (Wood et al. 2020). Additionally, physical habitat quality had greater influence on the frequency and severity of crayfish injuries than water quality. These results highlight the importance of physical habitat quality for native crayfish communities that play a key role in structure and function of stream ecosystems.

The presence of native freshwater mussels in streams is an indicator of high-quality physical habitat and water chemistry. In 2015, 10 mussel species were identified among 6 of 13 sites in the study area. Mussels were found in 2 agricultural ditches, at 3 sites in the Cedar Creek main stem, and at 1 site from in the East Branch of the St. Joseph River (Taylor 2016). Channelization, exposure to contaminants, and riparian habitat degradation are potential reasons for the absence of mussels at the other sites. Comparisons with historical data indicated that mussel species richness did not change between 1988 and 2015 in Cedar Creek, but abundance decreased from 168 to 37 during this period (Taylor 2016). Additionally, mussel species richness and abundance were positively correlated with increasing riparian woody vegetation and negatively correlated with ammonia (NH_3) and total P concentrations. These findings highlight the importance of riparian habitat quality and water quality for mussels in agricultural watersheds.

Figure 5

Students from Purdue University, Fort Wayne, conducting ecological assessments within streams and agricultural ditches of the St. Joseph River watershed to better understand the relationships among habitat, water quality, and aquatic community response variables.

Despite degraded habitat and exposure to physical and chemical contaminants, agricultural headwater streams in the St. Joseph River watershed support an unexpected abundance and diversity of aquatic biota. Future use of effective conservation practices will be needed to conserve biotic integrity within the watershed. Results from these ecology research studies suggest that future conservation strategies within agricultural watersheds in the midwestern United States should incorporate conservation practices capable of (1) improving and/or conserving riparian habitat quality; (2) improving and/

or conserving instream habitat quality; and (3) reducing nutrient and herbicide concentrations in the water and sediment.

Computer Simulation Modeling at Field and Watershed Scales Shows the Impact of Conservation under Current and Future Climates. The St. Joseph River watershed has provided valuable hydrologic and pollutant datasets that have allowed for modeling conservation practice effects under current and projected future climates. Numerous computer simulation modeling studies have been conducted by both NSERL and Purdue University over the past 20 years. These include studies examining the applicability of the Soil and Water Assessment Tool (SWAT) (Vazquez-Amabile et al. 2006), the Annualized Agricultural Non-Point Source Pollution (AnnAGNPS) (Heathman et al. 2008), and the Agricultural Policy/Environmental eXtender (APEX) (Francesconi et al. 2014) models, identifying gaps and improving models (Van Liew et al. 2017), and conducting management practice scenario simulations with current and future climate inputs (Wallace et al. 2017b).

Modeling efforts were initially focused on predicting pesticide concentrations and loads. The SWAT model was applied to the St. Joseph River watershed and accurately predicted the timing and magnitude of atrazine concentrations in the watershed (Vazquez-Amabile et al. 2006). These results permitted a nonpoint source risk analysis to be completed, which highlighted areas of the watershed that were at greater risk for atrazine losses. Given the increase in harmful algal blooms in Lake Erie, more recent modeling work has shifted to nutrient loading. For example, Wallace et al. (2017a) used hydrology and water quality data from Cedar Creek to examine changes in flow, sediment, and nutrient losses under projected climate change effects using SWAT. Findings indicated that surface flow was projected to decrease significantly (9% to 22%) toward the end of this century, while predicted tile drain flow would increase (20% to 26%). Atrazine, dissolved N, total N, and total P losses were not projected to change relative to the baseline period (1961 to 1990); however, dissolved P losses were predicted to increase. Under extreme precipitation events and temperatures, both surface (10% to 140%) and tile drain flow (up to 70%) could substantially increase in the Cedar Creek watershed by the end of the century (Mehan et al. 2019).

Quantifying the impact of conservation practices both individually and in combination on water quality is critical for developing strategies to decrease nutrient, sediment, and pesticide losses. This is especially important for understanding and adapting to the effects of climate change. Hydrology and water quality data from the Cedar Creek watershed were therefore used with the SWAT model to assess grassed waterways, vegetative filter strips, no-tillage, and blind inlets under projected future climate scenarios (Wallace et al. 2017b). Predicted changes in average annual dissolved N losses ranged from −5% to +14%, with grassed waterways or combined management practices being the most effective at decreasing dissolved N loads. Dissolved P and total P loss changes ranged from −10% to +41% and <1% to 60%, respectively. Nutrient management or combined conservation practices were predicted to be the most effective at decreasing dissolved P losses, while no-till or combined practices were predicted as the most effective at decreasing total P losses. These results show that conservation practices can decrease nutrient losses; however, projected future climates also likely impact conservation effectiveness due to greater discharge volumes.

DEVELOPING AND MAINTAINING PARTNERSHIPS FOR SUSTAINED SUCCESS

The longevity of the research and monitoring within the St. Joseph River watershed and the accomplishments highlighted above can be attributed to the support and collaboration of local partners. All NSERL monitoring sites are privately owned; thus, developing strong relationships with landowners has been critical to our sustained success. In the initial stages of working in the watershed, close collaboration with the St. Joseph River Watershed Initiative and the Allen and Dekalb county (Indiana) soil and water conservation districts (SWCD) and local USDA NRCS staff facilitated relationships with a core set of landowners within the watershed, many of which we still work closely with after 20 years. Over the years these partnerships have been maintained through mutual interests in environmental stewardship, clear communication, and data sharing. Of particular importance to sustaining partnerships has been aligning landowner and stakeholder needs and/or questions with research objectives. Indeed, the consensus is that the researchers have learned equally, if not more, from the local stakeholders than they have learned from the science. USDA NRCS recently produced a video documenting the partnership among landowners, SWCDs, USDA NRCS, and USDA ARS within the St. Joseph River watershed and the broader Western Lake Erie Basin as we work together toward developing solutions for improving water quality (https://www.youtube.com/watch?v=-LB8qg97pfw&t). Collaboration across ARS benchmark watersheds through CEAP and the LTAR network has further expanded and broadened the relevance of data collected in the St. Joseph River watershed to regional and national spatial scales. For instance, data have recently been used in combination with other ARS benchmark watersheds to develop national-scale soil moisture tools and products (Lui et al. 2022) and to evaluate the Soil Vulnerability Index (Baffaut et al. 2020). Partnerships at local, regional, and national levels have therefore provided a strong basis for past accomplishments and are poised to drive research questions and conservation implementation into the future.

DISENTANGLING CO-VARYING TRENDS REMAINS A CHALLENGE FOR WATERSHED-SCALE CONSERVATION EFFECTS ASSESSMENT

Much of the research documenting conservation practice benefits has been conducted at the field scale despite significant investment in watershed-scale monitoring (supplemental table S1). This phenomenon is not unique to the St. Joseph River watershed and has been noted across nearly all the ARS benchmark watersheds (Tomer and Locke 2011). Field research projects benefit from single landowners, well-defined management practices and treatments, and relatively short residence times. As a result, conservation effects can be directly measured over relatively short time intervals (months to years). Scaling to larger watersheds is often complicated by multiple landowners, lesser known or unknown management practices, and relatively long residence times, which make it difficult to discern trends in watershed-scale data. Concomitant changes in management practices (e.g., fertilizer inputs, crop rotations), conservation practice implementation, legacy sediment and nutrient loss, and climate (e.g., rainfall amount, intensity) at larger spatial scales persist as a challenge for directly measuring conservation benefits. Conservation effects assessment has therefore relied on modeling scenarios to parse out the effects of these factors on water quality outcomes. To help meet nutrient reduction goals in the Lake Erie region and elsewhere, addressing the challenge of measuring conservation effects at the watershed scale has been and will continue to be a top research priority.

LONG-TERM DATASETS SET THE STAGE FOR TESTING NEW HYPOTHESES AND RESEARCH QUESTIONS

Twenty years of data collection have allowed us to benchmark process understanding and quantify the impact of conservation practices on water quality. At the same time, it has shown us that our original research questions were more complex than we initially assumed. The questions of "Why do you need to collect more data?" and "Haven't you already learned everything?" often arise from a broad spectrum of stakeholders. Observational data collected from long-term experimental watersheds form the foundation of scientific hydrology and sustainable management (Hewlett et al. 1969). Thus, as the time-series extends, new research questions emerge, and the watershed becomes a research platform that attracts others, providing a focus for interdisciplinary research (Tetzlaff et al. 2017). Long-term datasets provide crucial context for understanding climate change, for example, and more focused research-driven hypothesis testing. They also provide ground-truth data that help constrain model results across various spatial and temporal scales. The answer to the questions posed above is therefore "We are just getting started."

With 20 years of research and data collection in the rearview mirror, we plan to leverage long-term datasets to tackle both ongoing and newly emerging research questions. Two priority issues within the Lake Erie region currently include climate change and legacy nutrients. Thus, we plan on using datasets of precipitation and hydrology from nested monitoring locations in combination with other regional long-term datasets to understand the impacts of past and future periods of drought and extreme wetness. Separating the effect of climate from that of management practices on water quality at the watershed scale remains a research priority. Quantifying legacy nutrient losses and their contributions to watershed loadings relative to newly or recently applied nutrients is also at the forefront of research questions to be addressed. Understanding the relative contributions of legacy versus newly applied nutrients will be extremely valuable for improving nutrient management and planning in the Lake Erie region. Further, testing and improving conservation practices such as P removal structures will continue to be one of the primary objectives of research within the St. Joseph River watershed, with new research efforts focused on understanding the effects of conservation systems (e.g., stacked practices) on sediment and nutrient loss. Finally, evaluating, improving, and developing models and tools for assessing and predicting sediment and nutrient loss using long-term and newly collected datasets will be an essential component of research efforts. The benefits of long-term data collection in the St. Joseph River watershed have accrued in nonlinear and unexpected ways over the past two decades. We expect the value of the research and datasets to continue to grow over the next 20 years as new insights and discoveries are uncovered.

SUPPLEMENTAL MATERIAL

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2023.1204A.

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