ASSESSMENT OF WATER USE AND INDIRECT WATER REUSE IN A LARGE SCALE WATERSHED: THE WABASH RIVER

by

Maria Julia Wiener

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Loring F. Nies, Co-Chair
Lyles School of Civil Engineering

Dr. Chad T. Jafvert, Co-Chair
Lyles School of Civil Engineering

Dr. Ronald Turco
Department of Agronomy

Dr. Keith A. Cherkauer
Department of Agricultural & Biological Engineering

Dr. Indrajeet Chaubey
College of Agriculture, Health and Natural Resources, Univeristy of Connecticut

Approved by:
Dr. Dulcy Abraham

Dedicated to Federico Antico,

What an adventure! Thank you for walking together…

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ABSTRACT

In the context of climate change, increasing demands for freshwater make it necessary to manage our water resources in a sustainable way and find innovative ways to extend their life. An integrated water management approach needs to consider anthropogenic water use and reuse which represent major components of the current water cycle. In particular, unplanned, or de facto, indirect water reuse occurs in most of the U.S. river systems, however, there is little real-time documentation of it. Despite the fact that there are national and state agencies that systematically collect data on water withdrawals and wastewater discharges, their databases are organized and managed in a way that limits the ability to combine reported water data to perform large scale analysis about water use and indirect reuse. To better document these issues and to demonstrate the utility of such an analysis, I studied the Wabash River Watershed located in the U.S. Midwest. Existing data for freshwater extraction, use, discharge, and river streamflow were collected, curated and reorganized in order to characterize the water use and reuse within the basin. Indirect water reuse was estimated by comparing treated wastewater discharges with stream flows at selected points within the watershed. Results show that during the low flow months of July-October 2007, wastewater discharges into the Wabash River basin contributed 82 to 121% of the stream flow, demonstrating that the level of water use and unplanned reuse is significant. These results suggest that intentional water reuse for consumptive purposes such as landscape or agricultural irrigation could have substantial ecological impacts by diminishing stream flow during vulnerable low flow periods. This research also completed a time series watershed-scale analysis of water use and unplanned indirect reuse for the Wabash River Watershed from 2009 to 2017. Results document the occurrence of indirect water reuse over time, ranging from 3% to 134% in a water-rich area of the U.S. The time series analysis shows that reported data effectively describe the water use trends through nine years, clearly reflecting both anthropogenic and natural events in the watershed, such as the retirement of thermoelectric power plants, and the occurrence of an extreme drought in 2012. Results demonstrate the feasibility and significance of using available water datasets to perform large scale water use analysis, describe limitations encountered in the process, and highlight areas for improvement in water data management.

1. INTRODUCTION

1.1 Problem Statement and Rationale

Proper management of water resources is critical to sustain potable water supplies, food production, manufacturing, energy production, recreation, and the maintenance of natural ecosystems. In the context of population growth, water scarcity, and climate change, the global increasing demand for freshwater makes it necessary to find innovative ways to manage our water resources in a sustainable way (de Vries and Lopez, 2013; U.S. Department of Energy, 2006). In 2012, the National Research Council (NRC) Committee on the "Assessment of Water Reuse as an Approach for Meeting Future Water Supply Needs", analyzed the potential for water reclamation and reuse of municipal wastewater in the U.S. to improve water supply alternatives (National Research Council, 2012). Indirect potable water reuse occurs wherever treated wastewater has been discharged upstream from a source of potable water supply (Asano, 1998; de Vries and Lopez, 2013). This happens in most large U.S. waterways. The extent that treated municipal wastewater effluents contribute to the potable water supply was reported in 1980 by the U.S. EPA (Swayne et al., 1980). The NRC committee concluded that an analysis of unplanned water reuse is critical for understanding the implications of such practices on water resources planning, human health protection, and freshwater ecosystems conservation. This information has particular relevance because of the increasing number of proposed direct water reuse projects, and the recent publication of the EPA Water Reuse Action Plan (U.S. Environmental Protection Agency, 2020) which considers water reuse and recycling to be an important element in an integrated water management approach. If intentional and planned direct water reuse initiatives are put in place, they require an understanding of how changes in water allocation might impact the downstream aquatic ecosystems and water users. Indeed, wastewater and other industrial discharges are key components of the combined human-natural water cycle, and return flows become an important source of downstream water supply.

For management and enforcement purposes, vast amounts of U.S. fresh water resources data are collected and archived by local, state, and federal departments and agencies. However, there is little coordination of how these data are collected, organized, or stored, leading to an assortment of many heterogeneous data sets (Averyt et al., 2013; National Research Council, 2012; Shaffer, 2009). As a result, sophisticated high performance data analysis for resource management is made difficult, hindering our ability to holistically manage critical water resource needs at the large watershed scale (e.g., the Wabash River, or the Ohio River basin). Quantifying human water use is critical information required for effective water resources planning and management and for evaluating its effect on natural systems. To reduce potential vulnerability to climate change, water resources assessment should include a comprehensive volumetric use analysis (Oki and Kanae, 2006). With improved electronic access to archived water use information and improved computing technologies, more complete and accurate assessments on water use and reuse should be possible. Then, better integrated documentation of the "human water cycle" at larger watershed scales would: (i) Provide relevant information to different stakeholders who influence water resource management decision-making; (ii) aid in the development of national water reuse standards; (iii) expand opportunities for information sharing and public education; and (iv) address issues related to public trust and confidence in policy-maker and regulatory agency decisions related to limited water resources.

The current study was motivated by the dearth of integrated information on water resource use and indirect reuse. Over 30 years ago, the EPA reported (Swayne et al., 1980) that "20 cities with a total population of more than 7 million were determined to have surface water supplies containing 2.3 to 16% wastewater during average flow conditions and 8 to 350% wastewater during low flow conditions". A published update of that report (Rice et al., 2013) states that there was an increase of de facto water reuse for 17 of the top 25 most impacted drinking water treatment plants identified in 1980. Rice et al. estimate there is 7% to 100% de facto reuse under low-flow conditions. One of the limitations of these studies is that they only consider treated wastewater discharged by Waste Water Treatment Plants (WWTPs) and do not account for industrial or other sources of wastewater effluents. Moreover, the de facto water reuse estimation assumes that the WWTP discharge flows are equal to the plants' design flow, which is not an accurate assumption. Most WWTPs seldom operate at maximum capacity. The occurrence of high de facto reuse rates during low flow months raises important questions about the occurrence of anthropogenic compounds. The quality of the water is a major concern for environmental and public health, particularly for the communities that use rivers as major source for potable water supply (Kingsbury et al., 2008; National Research Council, 2012). Findings from the USGS National Water-Quality Assessment (NAWQA) Program, indicate that the Wabash River contained 97 organic compounds related to agricultural and industrial activities located upstream of intake points (Lathrop and Moran, 2010). Most of these chemicals are not regulated under U.S. Environmental Protection Agency (USEPA) federal drinking-water standards. Knowing about emerging contaminants in water resources is important for water quality, human health and treatment needs and also for managing ecosystem health. Rivers and adjacent wetlands require adequate water of good quality to sustain ecological processes and to provide ecosystem services (Postel, 2000). Furthermore, the health of streams depends on maintaining natural flow variability that does not decline below a minimum flow level (Arthington et al., 2006). The increasing trends of de facto water reuse during low-flow months suggest that treated wastewater contributes to the hydrology of the streams in a significant way (Rice et al., 2013).

Major needs in water resources management include improving water supply and demand characterization, improving monitoring, modeling, integration of regional energy and water resource planning and decision support tools (Hightower, 2011). This study aims to contribute an integrated description and analysis of water extractions, uses and discharges, which will lead to a better understanding of the human water cycle. The Wabash River Watershed was selected to develop and test the methodology proposed, however this research could be applied to other large watersheds, and hopefully scaled up to the Ohio Watershed and ultimately the Mississippi Basin. Finally, this study demonstrates that a radical transformation in the way water data are measured, collected, organized, archived and disseminated is a critical need to achieve holistic watershed scale resources management and research.

1.2 Objectives

The objectives of this research are to:

1) **Understand the occurrence of unplanned indirect water reuse in the Wabash River Watershed:**
    a. Develop a methodology for medium scale (08-04 digit HUC) watershed unplanned indirect water reuse assessment;
    b. Quantify indirect potable water reuse at the 08, 06 and 04 digit HUC watersheds level within the Wabash River Basin, for the year 2007.
    c. Characterize the human-driven water cycle by exploring fresh water withdrawal and point source wastewater discharge volumes, and water use purposes;

d. Develop an integrated geospatial and temporal database to enable large scale water resources management and research;

2) Understand the water use dynamics in the Wabash Watershed over time.

a. Assess water use and unplanned indirect reuse patterns for the 9 year period FY2009-2017

b. Evaluate potential natural and anthropogenic system drivers, such as wet/dry cycles, demographic changes, etc.

c. Develop a set of compiled database, summary figures & tables, and descriptive maps that would serve as water resources management tools for the Wabash Watershed

3) Explore the feasibility of integrating existing databases for large watershed scale analysis

a. Identify reported water data and water data management limitations, and areas for improvement

b. Propose suggestions for integrated, large scale water data collection and management across federal and state agencies

1.3 Chapter Outline

Chapter 2: The Assessment of Water Use and Reuse through reported data: a U.S. case study. This manuscript describes the methodology proposed to assess Indirect Water Reuse (IWR) at specific points in the watershed (gage stations and the watershed outlet) by aggregating reported data of treated point source discharges that occurred upstream those points. It presents results for the year 2007, in a monthly basis, which describe the proportion of water being used and reused in the watershed, with a seasonal trend of larger IWR during low flows. It also includes a water use assessment, by aggregating the reported volumes of significant water withdrawals in the watershed, and an estimation of the water balance of the watershed, by HUC08. **This chapter is reproduced from Wiener, M.J., Jafvert, C.T., Nies, L.F., 2016. The assessment of water use and reuse through reported data: A US case study. Sci. Total Environ. 539, 70–77. https://doi.org/10.1016/J.SCITOTENV.2015.08.114**

Chapter 3: Time Series Analysis of Water Use and Indirect Reuse within a Huc-4 Basin (Wabash) Over a Nine Year Period. This publication follows the methodology already developed to estimate the indirect water reuse at the outlet of the Wabash Watershed for a 9 year period, from FY 2009 to FY2017. This resulted in a time series analysis of point source discharges, indirect water reuse and significant water withdrawals. It shows there is a strong correlation between point source wastewater discharges and significant withdrawals time series data, and suggest that both reported parameters could be used as estimators for water use. **This Chapter is reproduced from: Wiener, M.J., Moreno, S., Jafvert, C.T., Nies, L.F., 2020. Time series analysis of water use and indirect reuse within a HUC-4 basin (Wabash) over a nine year period. Sci. Total Environ. 140221. https://doi.org/10.1016/j.scitotenv.2020.140221.**

Chapter 4: The Future of Measuring, Reporting, and Visualizing Large-Scale Water Data: Insights Gleaned From Existing Methods. This is an opinion article that discusses the current status of water use data in the U.S., in particular with relation to significant water withdrawals and treated point source wastewater discharges reported data. It presents a visionary commentary about the need for real time monitoring and reporting of these data, by federal and state agencies, in the near future. It includes a description of current water data limitations, and suggestions in five major areas for improvement to be considered for rapidly advancing toward better large-scale water data measuring, reporting, managing, and disseminating. **This chapter was submitted for publication in the Journal Water Research's Making Waves.**

Chapter 5: Conclusions & Recommendations. This concluding chapter summarizes the major findings of the research done, and describes some possible ideas as well as recommendations for future follow-up research work.

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2. THE ASSESSMENT OF WATER USE AND REUSE THROUGH REPORTED DATA: A US CASE STUDY

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2.1 Abstract

Increasing demands for freshwater make it necessary to find innovative ways to extend the life of our water resources, and to manage them in a sustainable way. Indirect water reuse plays a role in meeting freshwater demands but there is limited documentation of it. There is a need to analyze its current status for water resources planning and conservation, and for understanding how it potentially impacts human health. However, the fact that data are archived in discrete uncoordinated databases by different state and federal entities, limits the capacity to complete holistic analysis of critical resources at large watershed scales. Humans alter the water cycle for food production, manufacturing, energy production, provision of potable water and recreation. Ecosystems services are affected at watershed scales but there are also global scale impacts from greenhouse gas emissions enabled by access to cooling, processing and irrigation water. To better document these issues and to demonstrate the utility of such an analysis, we studied the Wabash River Watershed located in the U.S. Midwest. Data for water extraction, use, discharge, and river flow were collected, curated and reorganized in order to characterize the water use and reuse within the basin. Indirect water reuse was estimated by comparing treated wastewater discharges with stream flows at selected points within the watershed. Results show that during the low flow months of July-October, wastewater discharges into the Wabash River basin contributed 82 to 121% of the stream flow, demonstrating that the level of water use and unplanned reuse is significant. These results suggest that intentional water reuse for consumptive purposes such as landscape or agricultural irrigation could have substantial ecological impacts by diminishing stream flow during vulnerable low flow periods.

Keywords: Indirect water reuse, water withdrawals, wastewater discharges, water data, Wabash River Watershed

2.2 Introduction

The United Nations estimates that 1.8 billion people will be living in countries or areas experiencing water scarcity by 2025, and population growth and climate change will continue to place further stress on freshwater resources, with this occurring with greater frequency and intensity, even in developed countries (UN Water 2007). In many regions, human activities significantly alter the natural water cycle by extracting surface and ground water, distributing it to different locations, and discharging treated wastewater back to waterways (Vörösmarty and Sahagian 2000). To address regional water resource management, both water conservation measures and direct or planned water reuse practices may be implemented. However unplanned, undocumented water reuse is intrinsic to the water cycle and is important to understand in the context of water resource management.

As Dean and Lund (1981) remarked over three decades ago the distinction between the various types of water reuse are somewhat arbitrary. However, the use of treated municipal wastewater generally fall into one of three categories: (1) Direct water reuse, where the effluent from one use becomes the influent (with or without further treatment) to another or the same use; (2) planned indirect water reuse, where the wastewater is returned to a specific water supply environment (i.e., aquifer or wetland) which serves as an environmental buffer before it is extracted for reuse; and (3) unplanned indirect water reuse, where the wastewater is returned to the natural environment (i.e., surface water bodies), with the receiving waterway being the source of water for other uses at one or more downstream locations. When the receiving waters become a drinking water supply source, indirect or de facto potable reuse occurs (U.S. Environmental Protection Agency 2012a), (Asano et al. 2007).

Unplanned indirect water reuse occurs in almost all waterways (Asano 1998, de Vries and Lopez 2013), yet there is little documentation of the practice. The National Research Council (NRC) Committee on the "Assessment of Water Reuse as an Approach for Meeting Future Water Supply Needs" analyzed the potential for water reclamation and reuse of municipal wastewater in the U.S. to improve water supply alternatives (National Research Council 2012). They concluded that an analysis of unplanned water reuse is critical for understanding the consequences of implementing new planned water reuse projects. Indeed, in the United States, there are an increasing number of direct water reuse projects, and these practices may influence the amount and quality of water available to support ecosystem services because municipal wastewater and industrial discharges are often major flows within the combined human-natural water cycle.

An estimate of the extent that treated municipal wastewater effluent contributes to the potable water supply in the United States was reported in 1980 by the U.S. EPA (Swayne et al. 1980):“20 cities with a total population of more than 7 million were determined to have surface water supplies containing 2.3 to 16% wastewater during average flow conditions and 8 to 350% wastewater during low flow conditions”. An update of that report (Rice et al. 2013) states that there was an increase in de facto water reuse for 17 of the top 25 most impacted drinking water treatment plants identified in 1980. One of the limitations of these studies is that they only considered treated wastewater discharged by Waste Water Treatment Plants (WWTPs) and they did not account for industrial or other wastewater effluents. However, wastewater is defined as “Used water discharged from homes, business, industry, and agricultural facilities” (U.S. Environmental Protection Agency 2012a). Moreover, the de facto water reuse estimation in both cases assumed that the WWTP discharge flows were equal to the plants’ design flow, which is not an accurate assumption, as WWTPs seldom operate at the design capacity. Furthermore, only discharges and not withdrawals were reported, making it impossible to evaluate the entire “human water cycle”.

To provide a more accurate assessment, actual flow data on withdrawals and discharges must be used. For management purposes in the United States, vast amounts of fresh water resources data are collected and archived by local, state, and federal departments and agencies. However, there is little coordination of how these data are collected, organized, or stored, leading to an assortment of many heterogeneous data sets (Averyt et al. 2013a, National Research Council 2012, Shaffer 2009). As a result, sophisticated rapid high performance data analysis for resource management is difficult, hindering our ability to holistically manage critical water resources at large watershed scales (e.g., 8, 4, or 2 digit Hydrologic Unit Code (HUC) scales). At a sub-continental scale, the Mississippi River basin comprises an area of almost 3 million km2, populated by more than 70 million people. Within this watershed the USGS maintains 2,479 gauging stations, while the US EPA maintains data on more than 800,000 facilities that discharge treated water into the river. Despite the river’s ecological and economic value there is no integrated knowledge about the quantity of water used or reused within the watershed.

In order to test the feasibility of such integration and analysis, in this research we have collected, curated, and analyzed all water withdrawals and discharges within the Wabash River watershed that have been reported to Federal and State agencies for the 2007 calendar year. The Wabash River watershed was selected for evaluation because it is used for a wide variety of anthropogenic activities, and as a 4-digit HUC watershed, it is an appropriately large sub-basin within the Mississippi River watershed. It is shared by the states of Indiana, Illinois and Ohio, providing some challenges regarding state agency data integration. It is also an example of a water-rich basin, where water use and reuse are not yet of major concern. Data on water withdrawals, wastewater discharges, and stream flow were collected for the year 2007 because the dataset for this year was the most complete at the initiation of this study. Treated wastewater discharge data are reported to the appropriate regulatory agency as monthly averages, thus our analysis is performed on a monthly time scale.

By retrieving data for the entire watershed from multiple sources and curating within one coherent database, we have developed and describe a simple methodology that can be applied to other watersheds where data on water withdrawals, discharges, and stream flow are archived over time. In the final database, each discharge and withdrawal point is associated with its own set of geographic coordinates. As a result, water reuse can be assessed at any scale within the watershed by aggregating all reported data on treated wastewater flows and withdrawals upstream from any point in the watershed. This study shows that in addition to simply collecting data on water availability and use, the appropriate organization and dissemination of these data are necessary to effectively and sustainably manage all available water resources (de Vries and Lopez 2013, Gleick 1998, U.S. Department of Energy 2006).

2.3 Materials and Methods

2.3.1 Study Area

The Wabash River basin area is 85,237 square kilometers, shared by the States of Ohio (OH), Indiana (IN), and Illinois (IL) (Geological Survey (U.S.) 1975) (Figure SI-1). This is a 4 digit HUC (HUC04) area, formed by 2 major basins, the main Wabash River basin and the Patoka-White River basin, each of which is subdivided into smaller sub-basins (or cataloging units), totaling to 24 8-digit HUC (HUC08) sub-basins (Seaber et al. 1987) (Table SI-1). Historically, this watershed has been water rich with trends of increasing stream flows (Zhang and Schilling 2006). Due to land use changes, annual river flows in the Mississippi River basin have increased 31-41% from 1940 to 2003 and water availability has not been a major issue. However, severe droughts such as the one experienced during the summer of 2012 (Schnoor 2012) highlight the need for understanding how water is being used and reused in the watershed. A more detailed characterization of the watershed and the methods used to integrate the data is included in the supplementary information (SI).

2.3.2 Fresh Water Withdrawals

Data on water withdrawals from surface and well sources is collected at the state level (Shaffer 2009). In the state of Indiana, the Department of Natural Resources (DNR) maintains the Significant Water Withdrawal Facility (SWWF) database which provides information on facilities that withdraw more than 100,000 gallons (0.378 m3) of ground and/or surface water in one day (Indiana Department of Natural Resources). Completeness of Indiana's SWWF data for 2007 was estimated to be over 99.5% (A. Mann, personal communication, April 1, 2013). Data on significant withdrawals in the state of Ohio were obtained from the Ohio Department of Natural Resources, Division of Soil and Water Resources, Water Withdrawal Facilities Registration Program (Ohio Department of Natural Resources Division of Soil and Water Resources 2012). Data from the State of Illinois were not complete. The Illinois Water Inventory Program (IWIP) compiles annual information on water withdrawals, use, and returns. Data from public wells and intakes are considered to be public information, however data from commercial and industrial facilities are kept confidential (Illinois State Water Survey 2012). Therefore, the only data that were available were the annual withdrawals for public supply from surface and groundwater sources. As a result, commercial and industrial water withdrawals in Illinois were estimated from the corresponding publicly accessible National Pollutant Discharge Elimination System (NPDES) data for each facility. It was assumed that all water discharged through an NPDES permit was previously extracted from a source in the same watershed. Due to the resolution of the data (typically monthly averages) water consumption rates could not be estimated with accuracy.

Because the available data from Indiana and Ohio and estimates made for Illinois only account for major withdrawals, minor extractions were assumed to be mostly private well withdrawals for self-supply. These were estimated by considering population numbers in each

HUC08, and information from the USGS on estimated self-supply use rates in the U.S. for 2005 (Kenny 2009) (Table SI-5). More detailed information about the management of withdrawal databases is included in the SI.

2.3.3 Treated Wastewater

Discharge monitoring and permit data on municipal and industrial point source discharges were obtained from the Discharge Monitoring Report (DMR) Pollutant Loading Tool database (U.S. Environmental Protection Agency 2012b), which uses data from EPA's Permit Compliance System (PCS) and Integrated Compliance Information System for the National Pollutant Discharge Elimination System (ICIS-NPDES). Data completeness for 2007 reports reached 92.0% for Indiana, 83.0% for Ohio and 80.3% for Illinois (U.S. Environmental Protection Agency 2012b). Detailed information about the DMR database and data management is included in the SI.

2.3.4 Stream Flow

The USGS National Water Information System (NWIS) database provides historical data on stream flow measured at numerous USGS gaging stations (GS) (U.S. National Water Information System 2002). Seven stations within the watershed were selected due to their proximity to the discharge point of the major sub-basins (Figure 2.1 b). Average monthly flows measured at those stations were retrieved. Because there is no GS at the confluence of the Wabash and Ohio River, it was necessary to estimate the streamflow at this point. This flow was estimated as the sum of the flow measured at the last GS on the Wabash River main stream stem (USGS 03377500, Wabash at Mt. Carmel) and the flow contributions by streams (sub-basins) that flow into the Wabash, downstream from the last GS (Table SI-3).

2.3.5 Water use and indirect reuse

All data on water withdrawals and wastewater discharges were selectively quality controlled, reorganized, filtered by use-category and by location (i.e., HUC08) to determine the annual and monthly volumes of water extracted and discharged, respectively, within each HUC08 and above each selected GS (Figure 2.2). The fraction (or percent) of indirect water reuse was calculated as the sum of all NPDES permitted discharges from all facilities (reported on a monthly basis) above a GS, divided by the average monthly stream flow measured at the respective GS.

$$B(X) = (\sum (Di)) / F(X) \quad (1)$$

where Di is point discharge i located upstream from point X where a GS occurred, F(X) is the monthly average stream flow at point X, and B(X) is the fraction of indirect water reuse at point X. Estimates of indirect water reuse were determined at those GSs shown on Figure 2.1 b.

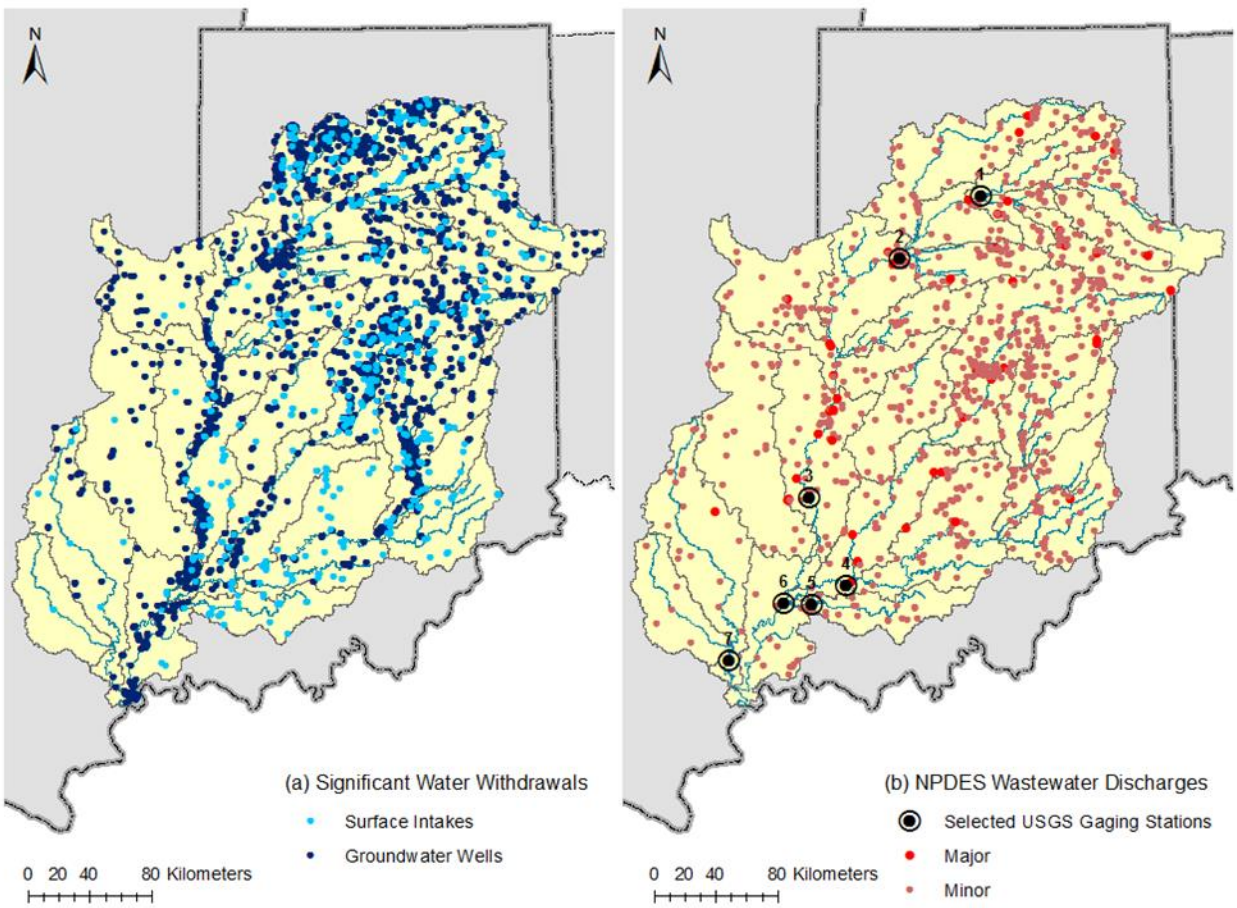

Figure 2.1. Wabash River Watershed (a) Reported Intake and Well significant water withdrawals (more than 100,000 gal/day (0.0043 m3/s)), (b) Reported NPDES wastewater discharges, from Major (more than 100,000 gal/day) and minor facilities, and USGS gaging stations selected as reference to the water reuse calculation

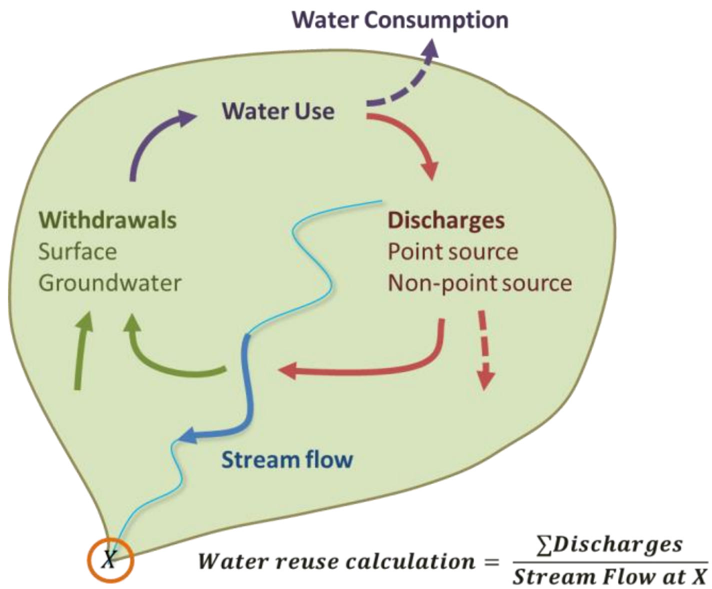

Figure 2.2. Summary of the water use and reuse analysis. Solid lines represent the variables considered: Surface and groundwater withdrawals to determine Water Use along the watershed, and point source wastewater discharges to complete the water balance. The current analysis does not account for Water Consumption and non-point sources discharges (dashed lines). At a specific point down a watershed, water reuse is estimated by calculating the ratio between total discharges upstream that point and the stream flow volume at that specific location

2.4 Results

2.4.1 Water Use -Withdrawals

The data for all large surface water and groundwater extractions aggregated by water use category, the estimated significant withdrawals for Illinois, and the estimated self-supply volumes were organized and aggregated to provide an estimate of total annual withdrawals within each HUC08 basin **(Table 2.1).** During 2007, it is estimated that an average of 3,690 MGD (161.66 m^3/s) was withdrawn from the watershed. The major use of this water was for energy production (EP), accounting for 73% (2,666 MGD (116.80 m^3/s)) of all extractions, almost all of which came from surface waters. The second largest extraction category was public supply (PS) accounting for 13% (480 MGD (21.02 m^3/s)), contributed by both surface (43%) and ground (57%) water resources.

Based on reported discharge data, we assumed that approximately 201 MGD (8.82 m^3/s) was withdrawn in Illinois, which represents 6% of all withdrawals in the watershed for 2007. Based on USGS information (Kenny 2009), we estimate that approximately 95 MGD (4.17 m^3/s) of self-supply withdrawals (less than 3% of all extractions) occurs within the entire Wabash River watershed. The sub-basins where most of the water was withdrawn are those that have power generation plants (HUC08 05120108, 05120111, 05120113) and those within the most populous region - the Indianapolis-Carmel Metropolitan Statistical Area (U. S. Census Bureau 2013) (HUC08 05120201, 05120202).

2.4.2 Water Use - Discharges

The reported NPDES discharges were compiled, organized by HUC08, and aggregated by Standard Industrial Classification (SIC) code categories **(Table SI-6).** There were 1,331 permitted discharge points that released an average of 3,765 MGD (164.98 m^3/s) of treated wastewater within the watershed in 2007. Facilities with SIC Code #49 - Electric, Gas and Sanitary Services - accounted for the largest volume of treated wastewater discharge. Of these facilities, 21 were classified as “Electric Services” (SIC Code #4911) and accounted for 75% of the total discharges. These power generation plants discharged an average 2,805 MGD (122.89 m^3/s) of water from their cooling systems (Averyt et al. 2013b, U.S. Department of Energy 2006). There were 402 facilities classified as “Sewerage” (SIC Code #4952) consisting of wastewater treatment facilities that accounted for 18% of the total discharge (**Figure SI-6**). Discharges from mining and manufacturing activities accounted for 5%. Consistent with water withdrawals, the largest discharges (over 100 MGD (4.38 m^3/s)) occurred in HUC08 sub-basins 05120108, 05120111, 05120201 and 05120202 (**Table 2.1**).

Table 2.1. Detailed Water Withdrawals[a] and Agregated Wastewater Discharges for the HUC08 Wabash River Sub-Basin for 2007 (m^3/s)

HUC	Energy Production		Industry		Irrigation		Miscellaneous		Public Supply		Rural		Estimated Withdrawals[b]	Estimated Self-supply [c]	Total Withdrawals	Total Discharges[d]	Discharges/ Withdrawals Ratio
	SW	GW	SW	GW	SW	GW	SW	GW	SW	GW	SW	GW	SW	GW			
5120101	0.42	0.00	1.12	0.18	0.02	0.02		0.00	0.06	0.66		0.00		0.18	**2.57**	**2.12**	0.80
5120102		0.00	0.04	0.00	0.00	0.00		0.00		0.06				0.02	**0.13**	**0.24**	1.74
5120103		0.00	0.25	0.02	0.00	0.01				0.36		0.00		0.08	**0.69**	**0.65**	0.88
5120104	0.73		0.00	0.01	0.02	0.04		0.00	0.14	0.04		0.00		0.07	**1.01**	**1.06**	1.02
5120105			0.13	0.05	0.00	0.01				0.19				0.03	**0.40**	**0.53**	1.27
5120106		0.02	0.64	0.09	0.08	0.64		0.00		0.24		0.01		0.12	**1.78**	**0.75**	0.41
5120107			0.28	0.17	0.00	0.03			0.26	0.44		0.00		0.12	**1.23**	**0.89**	0.68
5120108	30.18	0.00	0.02	1.04	0.03	0.15		0.04		1.03		0.00	0.03	0.19	**32.62**	**32.99**	1.01
5120109				0.00		0.01			0.36	0.41			1.91	0.20	**2.73**	**1.91**	0.66
5120110	0.00	0.00	0.03	0.00	0.02	0.00		0.00		0.22		0.00		0.05	**0.31**	**0.32**	0.96
5120111	42.44	0.14	0.02	0.16	0.01	0.42		0.00	0.07	0.76			5.23	0.37	**49.31**	**49.76**	1.00
5120112										0.16			0.78	0.14	**0.96**	**0.78**	0.73
5120113	2.15	0.18	0.03	0.00	0.01	0.31	0.01	0.01		0.29			0.11	0.15	**3.13**	**0.17**	0.05
5120114									0.35	0.07			0.76	0.10	**1.20**	**0.46**	0.36
5120115									0.03				0.01	0.02	**0.05**	**0.01**	0.20
5120201	14.04	0.24	2.13	0.34	0.10	0.17	0.00	0.15	5.98	4.74	0.06	0.08		1.47	**28.78**	**37.07**	1.26
5120202	25.60	0.14	0.01	0.13	0.00	0.07				0.47		0.00		0.12	**26.48**	**29.73**	1.12
5120203	0.15		0.11	0.05	0.00	0.00				0.25				0.07	**0.60**	**0.51**	0.79
5120204		0.01	0.10	0.02	0.02	0.11		0.00		0.66				0.23	**1.04**	**1.22**	1.05
5120205		0.03	0.09	0.00	0.03	0.16	0.00	0.01	0.07	0.29		0.00		0.06	**0.71**	**0.49**	0.65
5120206			0.11	0.00	0.02	0.14			0.08	0.51				0.07	**0.89**	**0.40**	0.43
5120207			0.07	0.00	0.01	0.00		0.00	0.17	0.01	0.00			0.07	**0.31**	**0.42**	1.24
5120208	0.00	0.00	0.14	0.00	0.01	0.03	0.01		0.99	0.11	0.11	0.00		0.17	**1.48**	**1.06**	0.67
5120209	0.22	0.11			0.01	0.00			0.43	0.06				0.05	**0.85**	**1.45**	1.65
SW	**115.94**		**5.32**		**0.42**		**0.03**		**8.99**		**0.17**		**8.82**		**139.68**		
GW		**0.87**		**2.28**		**2.33**		**0.20**		**12.03**		**0.11**		**4.17**	**21.97**		
Total		**116.80**		**7.60**		**2.74**		**0.23**		**21.02**		**0.28**			**161.66**	**164.98**	**1.02**

Table 2.1 Continued

a The data compiled in this table includes: reported Indiana Significant Water Withdrawal Facility data, aggregated by water use category (Energy Production, Industry, Irrigation, Miscellaneous, Public Supply, Rural); reported Ohio significant withdrawals data, estimated significant withdrawals for IL area; and estimated self-supply volumes assumed to be withdrawn from groundwater sources, aggregated by HUC08.

b Commercial and Industrial withdrawals in Illinois are by law confidential; thus, withdrawals were estimated from each facility's discharge data

c Estimated withdrawals for self-supply are detailed in Table SI-5.

d Discharges are characterized in Table SI-6

2.4.3 Water Balance

For the whole watershed, the ratio of discharges to withdrawals was 1.02 (**Table 2.1**) However, within each sub-basin, the ratio of average annual discharges to withdrawals varied from 0.05 to 1.74. There were several reasons for these variations. First, water withdrawals for irrigation (primarily in HUC08 basins 05120106, 05120113, 05120201, and 05120108) result in water being infiltrated or returned to the river as a non-point source with no NDPES permit. Second, some power generation plants exert high water consumption rates (Averyt et al. 2013a, Shaffer 2008); and third, in some cases the location of water removal for a specific use is within a different HUC08 sub-basin than where this water is eventually discharged. Because the SWWF water use classification categories do not map directly to the NPDES SIC Codes, it is often impossible to directly compare withdrawal and discharge volumes among related facilities. This, and data resolution, prevents accurate determination of consumption rates, although the USGS does provide estimates (Shaffer 2008, 2009, Shaffer and Runkle 2007). Several circumstances may lead to some sub-basins having a ratio of annual average wastewater discharges to annual withdrawals greater than 1. This will occur in sub-basins that have numerous small self-supply withdrawals that are ultimately discharged to a permitted POTW. It also will occur in sub-basins with significant combined sewer systems (Marsalek et al. 1993). Additionally, the accuracy and completeness of the discharge data reported to the NPDES database varies from state to state. Thus, it is likely that the aggregated levels of water reuse we report are underestimates to some degree.

2.4.4 Seasonal Variations

The monthly water withdrawals reported in the Indiana SWWF database show a trend of increased water use during the summer (May-October) (Figure SI-4), consistent with previous USGS reports for Indiana (Shaffer 2009, Shaffer and Runkle 2007). This trend is consistent with increased demand for cooling water for energy production (Shaffer 2009), and increased demand by other use categories. Conversely, NPDES treated wastewater discharges do not display a clear seasonal pattern (Figure SI-8). In the case of both water withdrawals and wastewater discharges, the variation between months did not exceed 20% from the annual mean value.

2.4.5 Streamflow

The Wabash River streamflow varies significantly with season. Streamflow data for 2007 at USGS GS 03377500 (Wabash R. at Mt. Carmel, IL) followed the regular seasonal pattern when compared to 85 years of historical monthly means, with slightly larger flows in winter months and reduced flows in May to November (Figure SI-3). Thus, 2007 is an appropriately representative year to use for this case study. The largest monthly average flow occurred in January (72,657 MGD (3183.28 m3/s)) and was 20 times greater than the lowest monthly mean flow (3,357 MGD (147.07 m3/s)) in October. In 2007, the total reported groundwater extraction for Public Supplies was 274.5 MGD (12.03 m3/s), and the estimated self-supply from ground sources was 95.11 MGD (4.17 m3/s) (Table 2.1). Assuming that all groundwater extractions for public supply ultimately were discharged to the Wabash River watershed, human pumped and discharged groundwater contributed up to 11% of the total river flow at its confluence with the Ohio River.

2.4.6 Water Reuse

The indirect water reuse calculation (eq 1) was performed at the 7 GSs selected as reference points within the watershed and at the confluence with the Ohio River (Table 2.2). The fraction of water reuse in the Wabash River at Lafayette (GS 03335500) was minor during the year (1-10%). However, as larger areas contribute to the downstream flow, more facility effluents contribute to the river's flow, and the fraction of water reuse displays a greater seasonal variation. A similar calculation at Petersburg (GS 3374000) defines water reuse on the White River (Upper- and Lower- White HUC08 sub-watersheds, 05010201 and 05010202), a major tributary of the Wabash. During 2007, the fraction of water reuse at Petersburg was 5 to 136%. From August to November, water reuse exceeded 100%, indicating that the water at that point in the river on average had passed through an NPDES permitted facility at least once over the entire four month period. The fraction of water reuse at Mt. Carmel, IL (GS 03377500), which is the closest GS on the Wabash River to its confluence, was 56 to 100% during the low flow months of July-October 2007. For the other months in 2007, the proportion of flow at this GS that had passed through an upstream facility ranged from 5 to 55% (Figure 2.3). By estimating the flow of the Wabash River at its confluence with the Ohio River, the fraction of water reuse for the entire Wabash River Watershed (HUC 0501) was calculated. During low-flow months (July-October, 2007), the fraction of reuse for the entire basin was 82% to 121%; and 5% to 65% during the remainder of the year. Thus, during the low flow months, humans used and pumped on average the equivalent of the entire flow of the river through NPDES facilities. Additionally, an indirect reuse fraction greater than 100% means that some of the water is being used and reused more than once along the watershed.

Table 2.2. Water reuse calculation at selected gauging stations, in a monthly basis.

Fig.2 #	**USGS #**		**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1	3328500	Eel at Logansport	2%	7%	2%	3%	7%	14%	19%	7%	14%	14%	3%	1%
2	3335500	Wabash at Lafayette	1%	3%	1%	2%	3%	8%	10%	6%	6%	7%	3%	1%
3	3342000	Wabash at Riverton	6%	20%	8%	10%	24%	64%	92%	84%	86%	92%	39%	11%
4	3374000	White at Petersburg	5%	13%	9%	9%	18%	55%	65%	108%	136%	96%	102%	20%
5	3376500	Patoka at Princetown	2%	1%	1%	2%	6%	10%	10%	15%	10%	14%	16%	3%
6	3377500	Wabash at Mt.Carmel, IL	5%	13%	8%	8%	19%	56%	71%	93%	100%	92%	55%	14%
7	3381500	Little Wabash at Carmi, IL	0%	0%	0%	1%	2%	3%	2%	18%	21%	4%	22%	1%
	Estimated	**Wabash Watershed Outlet**	**5%**	**13%**	**9%**	**9%**	**21%**	**65%**	**82%**	**114%**	**121%**	**107%**	**65%**	**16%**

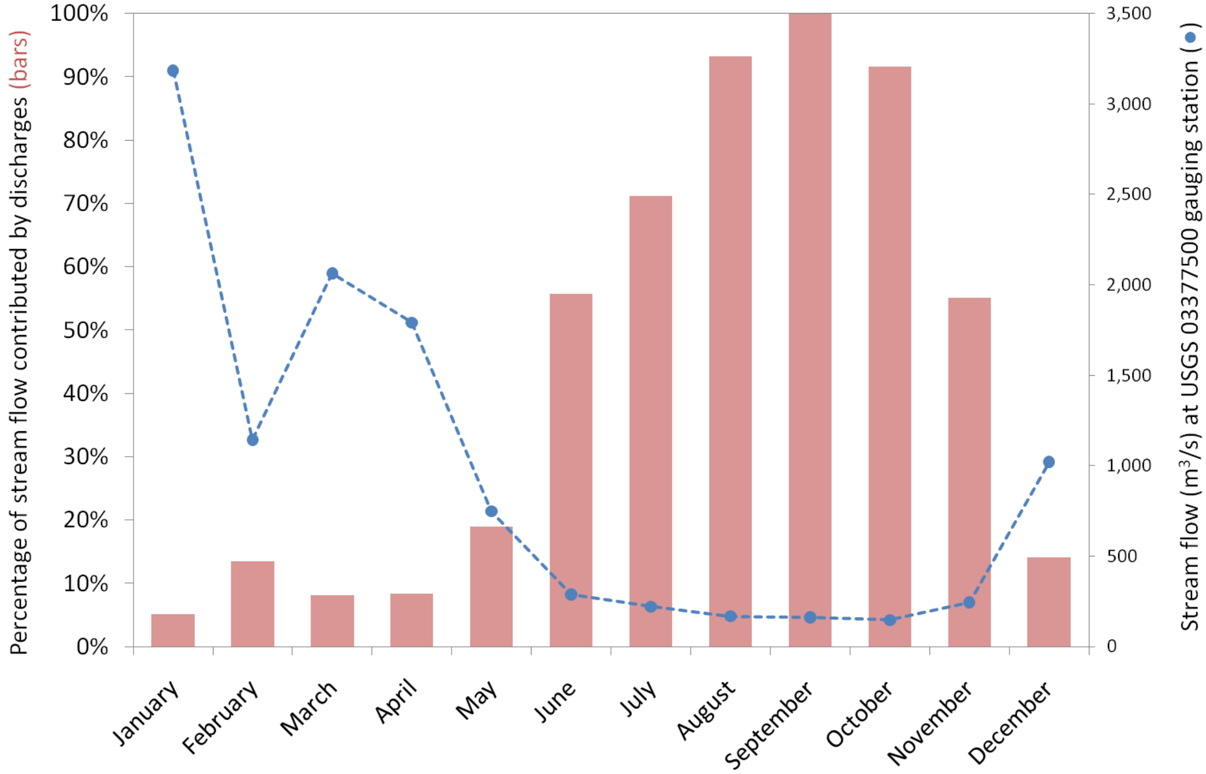

Figure 2.3. Percentage of the Wabash River Flow at Gauging Station #6, USGS 03377500 (Mt. Carmel, IL), that is contributed by NPDES discharges upstream, on a monthly basis, for the year 2007

2.5 Discussion

2.5.1 Implications

The results of this water reuse study demonstrate that current levels of water use in the Wabash River basin are significant. Both quantity and water quality is a major concern for environmental and public health, particularly for the communities that use rivers as a major source for water supply (Kingsbury et al. 2008, Lathrop and Moran 2010, National Research Council 2012). In addition, it is essential that rivers and adjacent wetlands receive sufficient quantity and quality of water necessary to maintain critical ecological functions and provide ecosystem services (Postel 2000, Dudgeon et al 2006). The health of streams depends on maintaining natural flow variability that does not decline below a minimum flow level (Arthington et al. 2006). Hydraulic engineering projects and agricultural drainage are the dominant causes of flow alteration in surface waters (Dudgeon et al 2006). Clearly, human water use must be considered a major type of hydrologic alteration. Results from this study show that ground water extractions may contribute up to 11% of the Wabash River stream flow during low-flow months. During low-flow months the upstream volumetric flow of treated wastewater discharge is approximately equivalent to or greater than the entire volumetric flow of the Wabash River. There is an obvious potential for radical hydrologic alteration in the event of changes in the current water use portfolio, such as diversion of wastewater for reuse in consumptive landscape or crop irrigation. Prospective well-meaning water recycling projects to reuse wastewater should carefully consider the effects this could have on the current watershed hydrology and the watershed's ecosystem needs.

Future energy projects should also take into account the water profile of the Wabash River Watershed. This study is consistent with others that document that thermoelectric power generation facilities use the largest portion of water resources (Kenny 2009, Shaffer 2009, U.S. Department of Energy 2006). The power sector uses water mainly for cooling purposes with relatively low water consumption rates (Averyt et al. 2013a, Wu and Peng 2011), e.g. 0-25 % for Indiana as reported by USGS (Shaffer 2009), and with the remainder returned to the source. Because of higher electricity demand and also higher air temperatures that lead to less efficient heat rejection in the cooling system, power generation plants withdraw larger amounts of cooling water in the summer months (Shaffer 2009), which corresponds with the river's low flow period. There is the potential for watershed scale water stress created by increasing demands for cooling water during times of lower river flow volumes (Shaffer 2008). Increasing limitations on water availability and stricter regulations on using surface water (e.g. Section 316(b) of the Clean Water Act) may motivate power generating companies to move towards closed loop systems (Paton et al. 2006). Closed systems withdraw less water and use cooling towers, ponds and lakes, to release heat via evaporation to the atmosphere, in contrast to open loop systems which release heat to the receiving streams. Closed loop systems reduce the heat input to receiving waters but increase overall water consumption (Stillwell et al. 2011) and internal electricity demand by pumping water (a second time) through cooling towers. At a watershed scale, regulatory efforts to minimize impingement mortality of aquatic organisms at electric power water intakes will also increase water and electricity consumption.

2.5.2 Limitations

The Wabash River Watershed was selected as a preliminary case study that would allow for the development of a methodology and serve to illustrate the significance of integrated research. Results illustrate that there are rich and massive data assemblages on water use that could be employed for sophisticated and beneficial understanding and management of these water resources. However, these data are archived in discrete databases with incompatible units; inconsistent classifications; varied structural, temporal, and spatial organization; and are maintained by different state and federal agencies. Integrating and organizing the data for simple analysis, such as the water reuse calculations provided in this study, reveals challenges that make the process time consuming and not amenable to automation. These challenges will exist in any region of the world where water supply data and wastewater discharge data are archived in discrete databases that are not intentionally designed and coordinated with the structure of the watershed. The US databases were not designed to be integrated for use in a holistic manner. Obstacles other than those mentioned above include: (i) access to the databases, (ii) data completeness and accuracy, and (iii) the appropriateness of the data. The access to the databases varies depending on the agency, from direct and free online downloads, to requirements of formal request with payment of processing fees. Furthermore, most of the databases were designed for individual query and lacked the capacity of retrieval for more research-oriented or larger-scale watershed queries. For example, water withdrawals (IN SWWF), water use (USGS) and population data (US Census Bureau) are compiled and reported by county, preventing direct watershed level analysis. This limitation was overcome in this study by using GIS tools to redefine boundaries; however, this requires time and resources to transform the large datasets. Moreover, state level differences between data management policies on withdrawals make it challenging, at best, to estimate water use within watersheds shared by two states (e.g., HUCs 05120108 through 05120115). In particular, Indiana and Illinois have different policies regarding how water withdrawal data are reported and whether this information is open to the public, despite these withdrawals being taken from a public resource. This situation highlights not only the importance of public policy and law in managing these resources, but also how current policy and law are not aligned with the geospatial boundaries for proper analysis and management. Indeed in most cases, human boundaries do not conform to watershed boundaries, despite the fact that hydrological units are the logical spatial unit for collection and management of water related data. Clearly, there is a need to promote improved coordination among federal and non-federal entities (National Research Council 2012) to overcome obstacles that limit analysis of water resources among states, as the capacity for analysis at the watershed scale is no longer limited by technology (Shaffer 2009). Improvements in the data collection and storage system have occurred as EPA has transitioned from PCS to ICIS-NPDES to DMR. Consistent adherence to guidelines on how data should be formatted and entered is needed. Holistic analysis requires that specific information is compiled in a uniform, complete and coherent structure. Finally, there is a need to develop organizational/relational data structures for the data that would link harmoniously with existing visualization and environmental management tools. This would allow for continuous, near-real-time water use and reuse monitoring. Indeed, major needs in water resources management include improving water supply and demand characterization, monitoring, and integration of regional energy and water resource planning and decision support tools (Pate et al 2007).

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2.7 Supplementary Information (SI)

2.7.1 Area of study details

The Wabash River Watershed is mostly agricultural land (Figure SI-1), with corn and soybeans as the predominant crops (Pyron and Neumann 2008). Urban centers within the watershed include the cities of Champaign-Urbana and Danville, Illinois; and Indianapolis, Bloomington, Columbus, Lafayette, Muncie, Terre Haute, and Vincennes, Indiana. Industrial activity in the basin includes production of machinery, chemicals, fabricated metal products, and automotive and electrical equipment and supplies. There are several electric power plants located along the rivers in the basin, and the minerals mined within the watershed include petroleum, coal, natural gas, sand and gravel, clay, limestone, and gypsum (U.S. Geological Survey 1975).

Table SI- 1 Hydrologic Units structure, codes and names of the Wabash River Basin (adapted from Seaber, Kapinos, and Knapp, 1987)

Region (HUC02)	Subregion (HUC04)	Accounting Units (HUC06)	Cataloging Units (HUC08)	Name
05 Ohio	0512 Wabash River Watershed	051201 Wabash	05120101	Upper Wabash
			05120102	Salamonie
			05120103	Mississinewa
			05120104	Eel
			05120105	Middle Wabash-Deer
			05120106	Tippecanoe
			05120107	Wildcat
			05120108	Middle Wabash-Little Vermilion
			05120109	Vermilion
			05120110	Sugar
			05120111	Middle Wabash-Busseron
			05120112	Embarras
			05120113	Lower Wabash
			05120114	Little Wabash
			05120115	Skillet
		051202 Patoka-White	05120201	Upper White
			05120202	Lower White
			05120203	Eel
			05120204	Driftwood
			05120205	Flatrock-Haw
			05120206	Upper East Fork White
			05120207	Muscatatuck
			05120208	Lower East Fork White
			05120209	Patoka

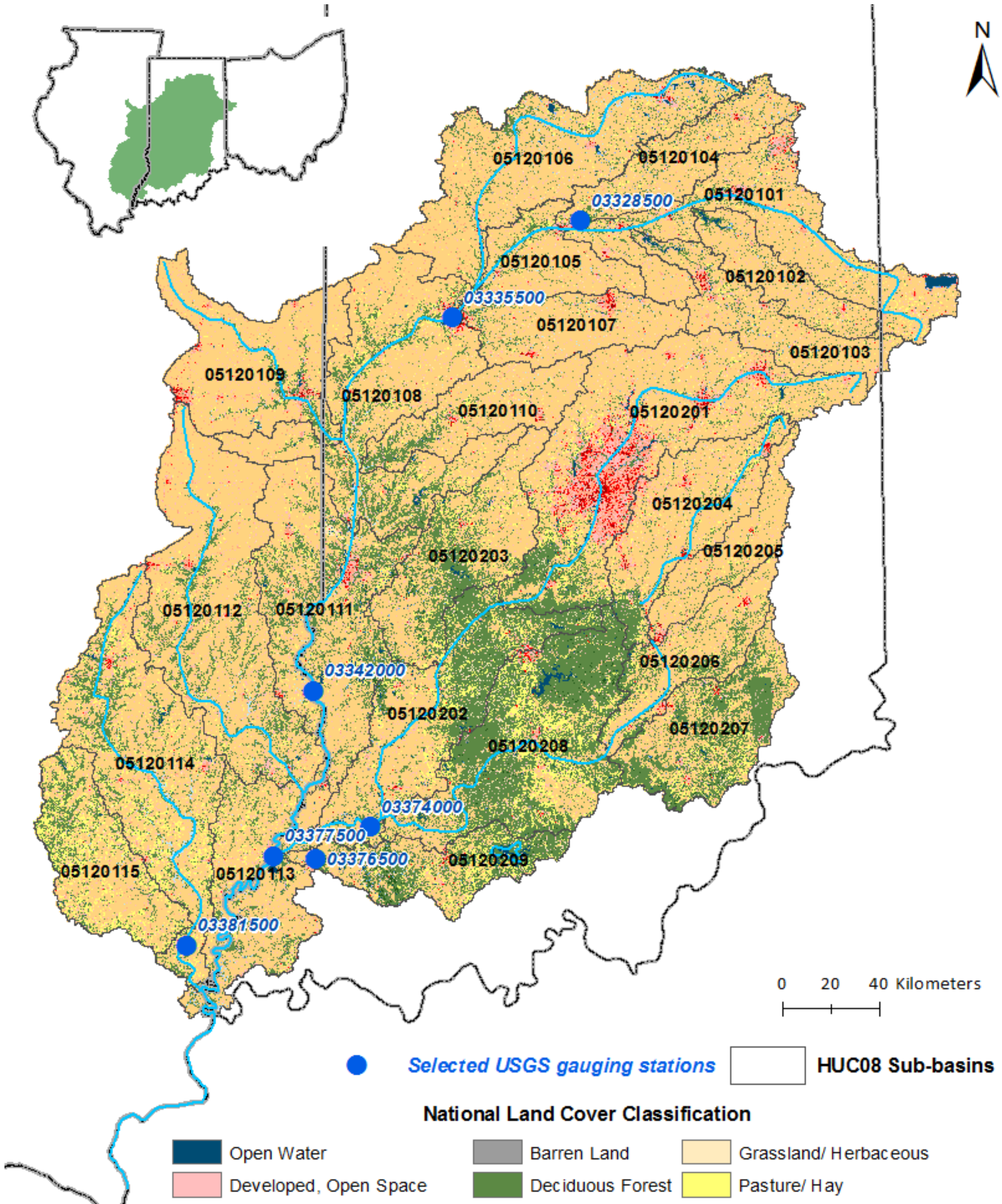

Figure SI- 1 Wabash River Watershed location and delineation, Land Cover, and HUC08 sub-basins subdivision with corresponding identification number

Table SI- 2 Wabash River Watershed HUC08 sub basins characteristics. Area, estimated population and population density

HUC08	Name	Area (km^2)	Estimated Population (inhabitants)	Population density (hab/km^2)
5120101	Upper Wabash	4,066	208,783	51
5120102	Salamonie	1,401	25,744	18
5120103	Mississinewa	2,100	98,114	47
5120104	Eel	2,100	79,167	38
5120105	Middle Wabash-Deer	1,694	38,089	22
5120106	Tippecanoe	4,999	135,581	27
5120107	Wildcat	2,064	142,253	69
5120108	Middle Wabash-Little Vermilion	5,776	224,683	39
5120109	Vermilion	3,652	194,444	53
5120110	Sugar	2,119	61,590	29
5120111	Middle Wabash-Busseron	5,180	194,875	38
5120112	Embarras	6,294	132,352	21
5120113	Lower Wabash	3,367	80,532	24
5120114	Little Wabash	5,491	97,642	18
5120115	Skillet	2,745	21,023	8
5120201	Upper White	6,993	1,695,789	242
5120202	Lower White	4,273	132,892	31
5120203	Eel	3,108	80,839	26
5120204	Driftwood	2,978	262,618	88
5120205	Flatrock-Haw	1,497	73,994	49
5120206	Upper East Fork White	2,088	82,358	39
5120207	Muscatatuck	2,927	85,757	29
5120208	Lower East Fork White	5,258	197,467	38
5120209	Patoka	2,212	56,397	25
Totals		**84,382**	**4,402,976**	**52**

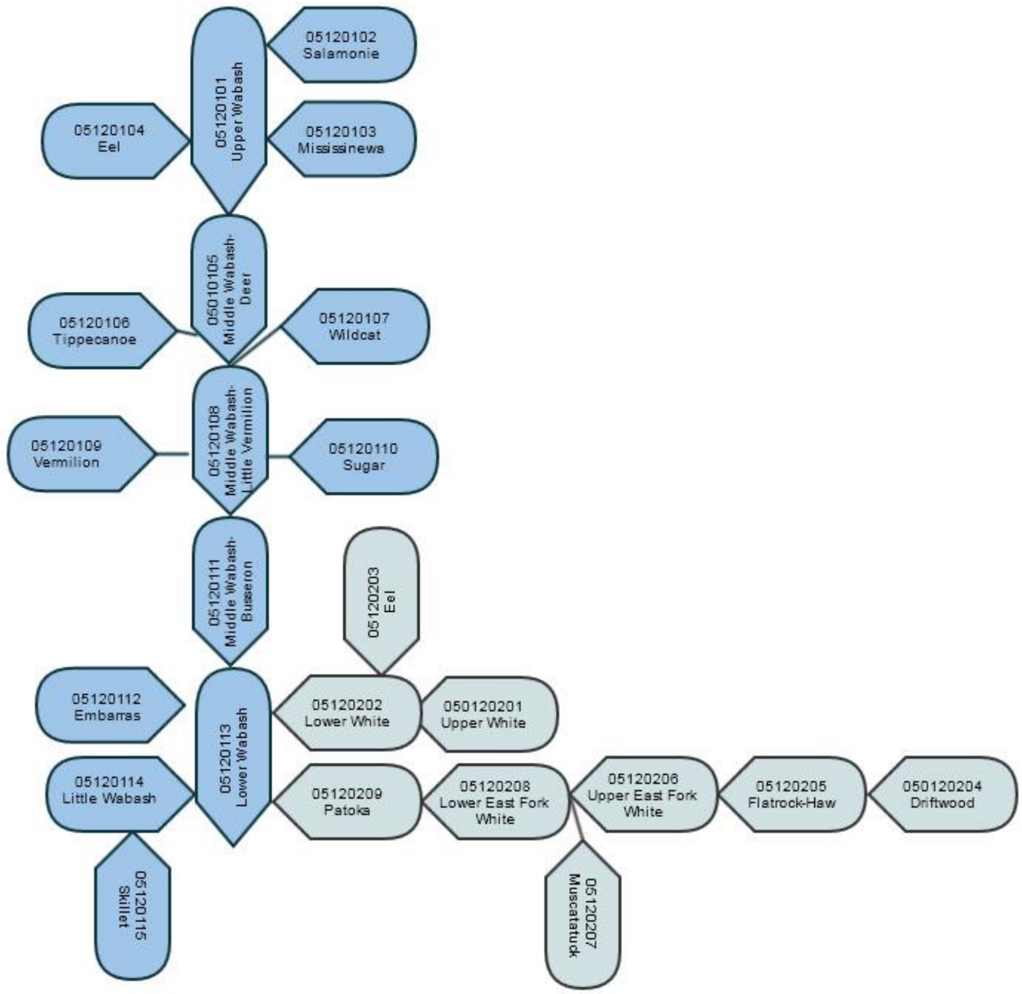

Figure SI- 2 HUC08 connectivity diagram

2.7.2 Databases and Data Management details

Fresh Water Withdrawals. Most large facilities that withdraw water from surface and well sources in the Wabash Watershed during 2007 were identified and monthly and annual extraction rates, intended use of the water, and location for each was determined (**Figure 2.1**). Water withdrawal data were collected at the state level (Shaffer 2009). In the state of Indiana, the Department of Natural Resources (DNR) Division of Water's Water Rights and Use Section, maintains the Significant Water Withdrawal Facility (SWWF) Database which is available online, free of charge to all users. It provides access to SWWF information and water use data submitted by the state's registered active facilities. A "significant water withdrawal facility" is defined to mean *"the water withdrawal facilities of a person that, in the aggregate from all sources and by all methods, has the capability of withdrawing more than 100,000 gallons of ground water, surface water, or ground and surface water combined in one (1) day."* (Indiana Department of Natural Resources 2012). Completeness of Indiana’s SWWF data for 2007 is estimated to be over 99.5% (A. Mann, personal communication, April 1, 2013).

Data from the state of Ohio were obtained from the Ohio Department of Natural Resources, Division of Soil and Water Resources, Water Withdrawal Facilities Registration Program. *“Section 1521.16 of the Ohio Revised code requires any owner of a facility, or combination of facilities, with the capacity to withdraw water at a quantity greater than 100,000 gallons per day (GPD) to register such facilities with the Ohio Department of Natural Resources (ODNR), Division of Water”* (Ohio Department of Natural Resources Division of Soil and Water Resources 2012). Data from the State of Illinois were not completely available. The IL Water Inventory Program (IWIP) compiles mandatory annual submission of data on water withdrawals, use, and returns. Data from public wells and intakes is considered to be public information but the data from commercial and industrial facilities is kept confidential and is not available for public release (Illinois State Water Survey 2012). Therefore, the only data available is annual withdrawal for public supply from surface and groundwater sources.

Across the states of Indiana and Ohio, the water withdrawal programs are different and therefore the data are collected and organized in different ways. In both cases, they are provided in Excel files and organized by county. In order to allow for using the data in a watershed area analysis, they were filtered and reorganized by HUC08 applying ArcGIS tools, and combined in a single Excel database. SWWF data are classified into 6 water use categories based on information the facilities submit in the Registration Report (Indiana Department of Natural Resources 2012). Missing water withdrawals in Illinois were estimated from the NPDES discharges data available for each facility. It was assumed that all the water discharged as wastewater must have been previously extracted from some source. Because of the manner in which DMR data are reported and the use of estimated withdrawals for some Illinois facilities, the resolution between withdrawal and discharge data is unsuitable to reasonably account for consumption rates.

Since the reported and available data only accounts for significant water withdrawals, minor extractions were assumed to be mostly private well withdrawals (**Table SI- 5**). These extractions were estimated by considering population numbers in the area of interest and the USGS Estimated Use of Water in the United States in 2005 self-supply per capita use rates (Kenny, J.F. 2009)

Treated Wastewater. All facilities that discharged wastewater in the Wabash Watershed were identified, and for each of them the monthly and annual flows, location, and whether it was a major or minor facility were determined (**Figure 2.1**). Discharge monitoring and permit data were obtained from the Discharge Monitoring Report (DMR) Pollutant Loading Tool database which uses data from EPA's Permit Compliance System (PCS) and Integrated Compliance Information System for the National Pollutant Discharge Elimination System (ICIS-NPDES). The NPDES permit program regulates municipal and industrial point sources that discharge treated wastewater into receiving waters of the United States (U.S. Environmental Protection Agency 2012). The available data corresponded to permits from facilitates within the entire US territory. The EPA is transparent about the scope and limitations of the DMR database. Because of the characteristics of the reporting system where states collect the information and share with the EPA, data completeness for 2007 reports reached 92% for Indiana, 83% for Ohio and 80.3% for Illinois (U.S. Environmental Protection Agency (2012). The DMR Loading Tool documentation states that the database does not include data on industrial facilities that discharge directly to a publicly-owned treatment works (POTW), biosolids monitoring data, storm water from municipal separate storm sewer systems (MS4s), storm water from industrial facilities, discharges from construction activities, combined sewer overflows, sanitary sewer overflows or discharges from concentrated animal feeding operations (CAFOs) (U.S. Environmental Protection Agency 2012). However, some data of this type were found. Despite the DMR Tool having modules that evaluate the data and correct potential errors, we found some incoherent values, probably due to manual data entry errors. For some facilities, the DMR database show null values in the flow fields, and because of missing spatial data some facilities lack a match with a corresponding discharge. Therefore, the following procedures were followed to address the described data gaps: i) We excluded from the analysis facilities identified to have a pretreatment program based on the PCS denomination system (external permit number with format INPXXX); ii) Missing watershed HUC# identification was assigned to facilities located in OH based on information from the EPA ECHO database, geospatial data and watershed boundaries (U.S. Department of Interior 2013). It is assumed that the facilities retrieved by ECHO database when querying for the Ohio part of the Wabash watershed existed in 2007; iii) we did not assign a flow value to the facilities that did not have flow data available in the DMR database. DMR flow data were reported in multiple units, including monthly values, annual values and averaged daily values, that were converted to standard MGD units as needed. Values of wastewater discharges were obtained from the FQ1 (Flow Quantity - Average) and FQ2 (Flow Quantity - Maximum) reported values in the DMR tool. The classification of discharges was done considering and compiling the reported Standard Industrial Classification (SIC) Codes, as suggested by USGS Guidelines (Kenny 2004).

Population. The population at the HUC08 watershed level was estimated (Table SI- 2**)** using ArcGIS tools. U.S. Bureau Census 2010 population data (U.S. Census Bureau 2010) at the census block scale was aggregated by HUC08. In order to match census blocks with a corresponding HUC08 watershed two different map selection approaches were applied. Census blocks located within the HUC08 watershed boundary were counted without counting the census blocks located on the boundary between two HUC08 watershed areas. Census blocks that intersected the HUC08 watershed boundary were then included however, these census blocks will be double counted when shared by two different watersheds. Therefore, an average between results from both approaches was considered to be a good estimation.

2.7.3 Complementary analysis of available data and estimations

Table SI- 3 Estimation of Wabash Outlet streamflow

Gauging Station #	3378000	3378550	3377500	3381500	HUC 05120113 Lower Wabash *	Wabash Outlet
Name	Bompass creek at Browns, IL	Big creek near Wadesville , IN	Wabash at Mt.Carmel, IL	Little Wabash at Carmi, IL		
Drainage Area (km2)	591	269	74164	8034	2507	
	Mean measured flow 2007 (m3/s)				Estimated flow (m3/s)	Total flow (m3/s)
January	31.49	10.84	3182.81	314.32	110.88	128910
February	17.93	5.33	1142.87	146.68	57.15	48380
March	3.90	1.86	2063.73	132.52	25.07	78649
April	5.31	3.36	1791.32	76.17	25.88	67170
May	0.59	1.84	747.85	18.55	8.48	27450
June	0.45	0.44	287.13	9.63	3.00	10617
July	0.22	0.49	221.21	15.18	3.40	8493
August	0.14	0.03	167.66	1.50	0.44	5995
September	0.02	0.07	162.03	1.30	0.40	5785
October	0.89	0.61	147.08	8.21	4.03	5680
November	0.02	0.11	244.32	1.33	0.51	8697
December	11.58	2.86	1021.11	68.53	32.40	40135

* Estimated remaining contributing area

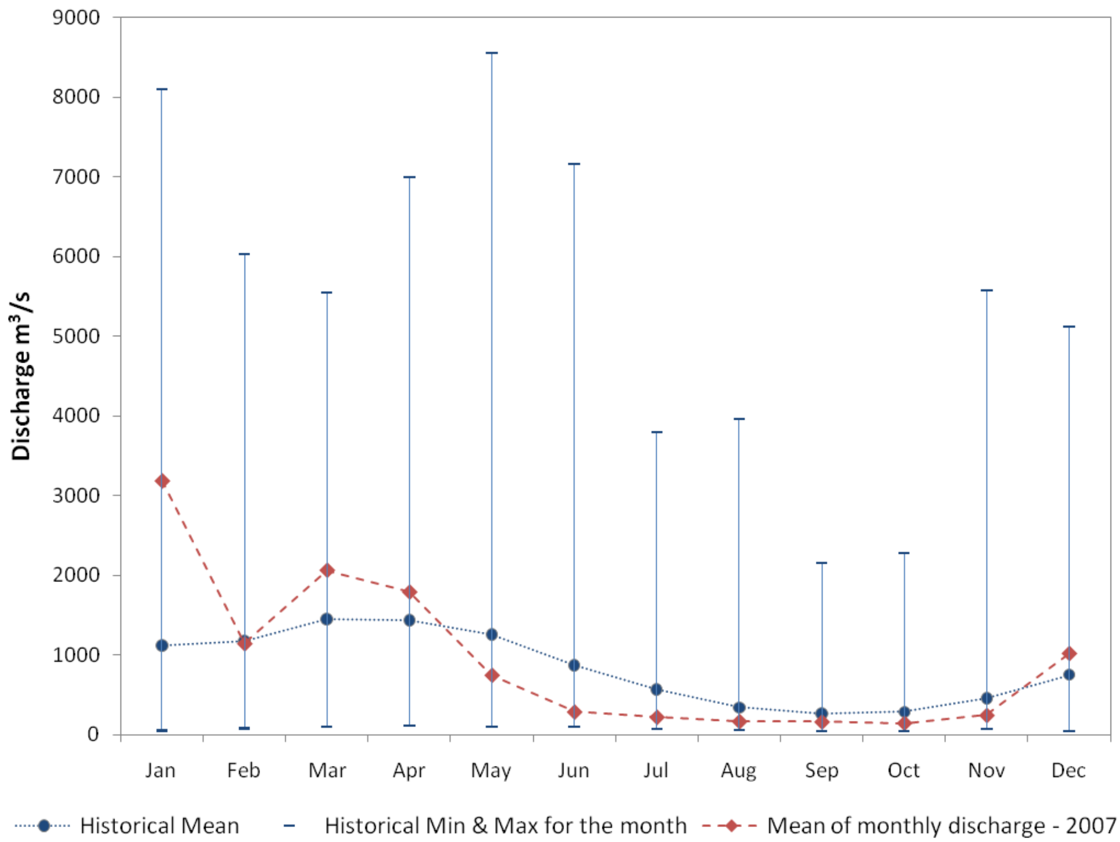

Figure SI- 3 Wabash River at Mt. Carmel, IL. Historical stream flow and mean of monthly discharge for the year 2007

Table SI- 4 Summary of Wabash River Watershed's reported Indiana Significant Water Withdrawals Facilities data

Year	Source	Water Use Categories[a]	Count of SOURCEID	Sum of PUMPDANNUA (m3/s)	Subtotal	% over Grand total
2007	**INTAKE**	EP	88	115.93		
		IN	189	5.35		
		IR	297	0.44		
		MI	8	0.04		
		PS	37	8.11		
		RU	8	0.18	130.04	88%
	WELL	EP	134	0.88		
		IN	427	2.19		
		IR	1191	2.37		
		MI	78	0.22		
		PS	1346	11.17		
		RU	69	0.09	16.91	12%
Grand Total			**3872**	**146.95**		

[a]Water Use Categories defined by SWWF Database: Energy Production (EP), Industry (IN), Irrigation (IR), Miscellaneous (MI), Public Supply (PS) and Rural (RU) (Indiana Department of Natural Resources 2012)

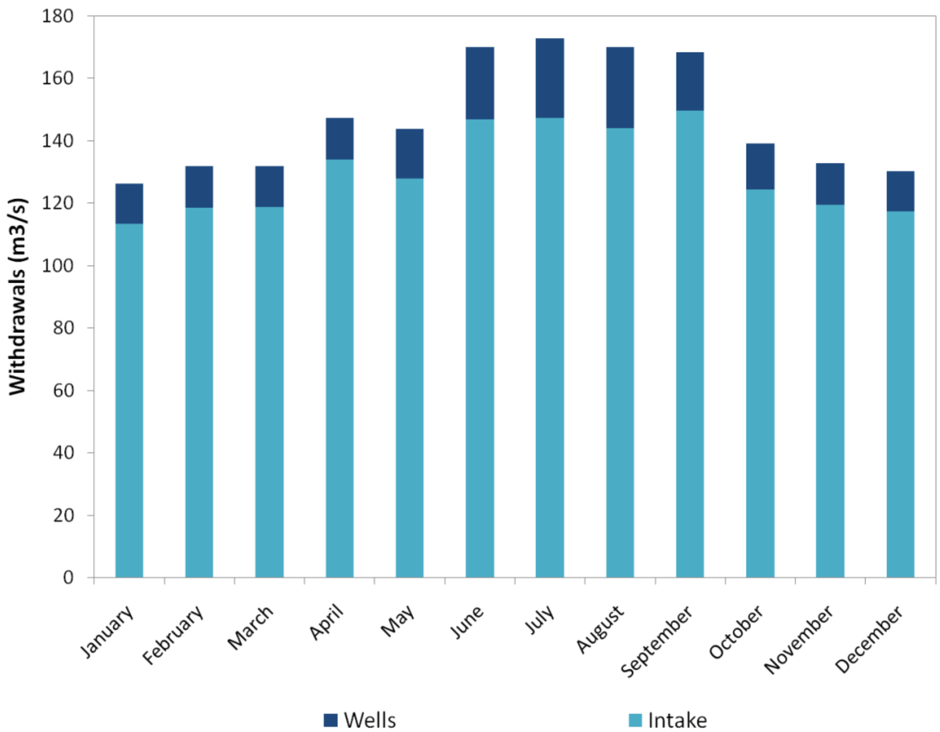

Figure SI- 4 Monthly volumes of water withdrawn in the Wabash Watershed, reported at Indiana SWWF, 2007

Table SI- 5 Private Wells Withdrawal Data Estimation

HUC08	Primary State	Name	Estimated Population [inhabitants][a]	Estimated population with self supply[b]	Estimated Self supply volumes [c] (m^3/s)
05120101	IN	Upper Wabash	208,783	54,284	0.18
05120102	IN	Salamonie	25,744	6,693	0.02
05120103	IN	Mississinewa	98,114	25,510	0.08
05120104	IN	Eel	79,167	20,583	0.07
05120105	IN	Middle Wabash-Deer	38,089	9,903	0.03
05120106	IN	Tippecanoe	135,581	35,251	0.12
05120107	IN	Wildcat	142,253	36,986	0.12
05120108	IN	Middle Wabash-Little Vermilion	224,683	58,418	0.19
05120109	IL	Vermilion	194,444	50,555	0.20
05120110	IN	Sugar	61,590	16,013	0.05
05120111	IN	Middle Wabash-Busseron (IN)[d]	194,875	50,668	0.17
05120111	IL	Middle Wabash-Busseron (IL)[d]	-	50,668	0.20
05120112	IL	Embarras	132,352	34,412	0.14
05120113	IN	Lower Wabash (IN)[d]	80,532	20,938	0.07
05120113	IL	Lower Wabash (IL)[d]	-	20,938	0.08
05120114	IL	Little Wabash	97,642	25,387	0.10
05120115	IL	Skillet	21,023	5,466	0.02
05120201	IN	Upper White	1,695,789	440,905	1.47
05120202	IN	Lower White	132,892	34,552	0.12
05120203	IN	Eel	80,839	21,018	0.07
05120204	IN	Driftwood	262,618	68,281	0.23
05120205	IN	Flatrock-Haw	73,994	19,238	0.06
05120206	IN	Upper East Fork White	82,358	21,413	0.07
05120207	IN	Muscatatuck	85,757	22,297	0.07
05120208	IN	Lower East Fork White	197,467	51,341	0.17
05120209	IN	Patoka	56,397	14,663	0.05
		Total		**1,216,381**	**4.17**

[a] From Census 2010
[b] % of population with self-supply: IN: 26%; IL: 9% (Kenny 2009)
[c] Self supply per capita use (gal/day): IN:76 ; IL: 90 (Kenny 2009)
[d] Watersheds shared by both IN and IL states.

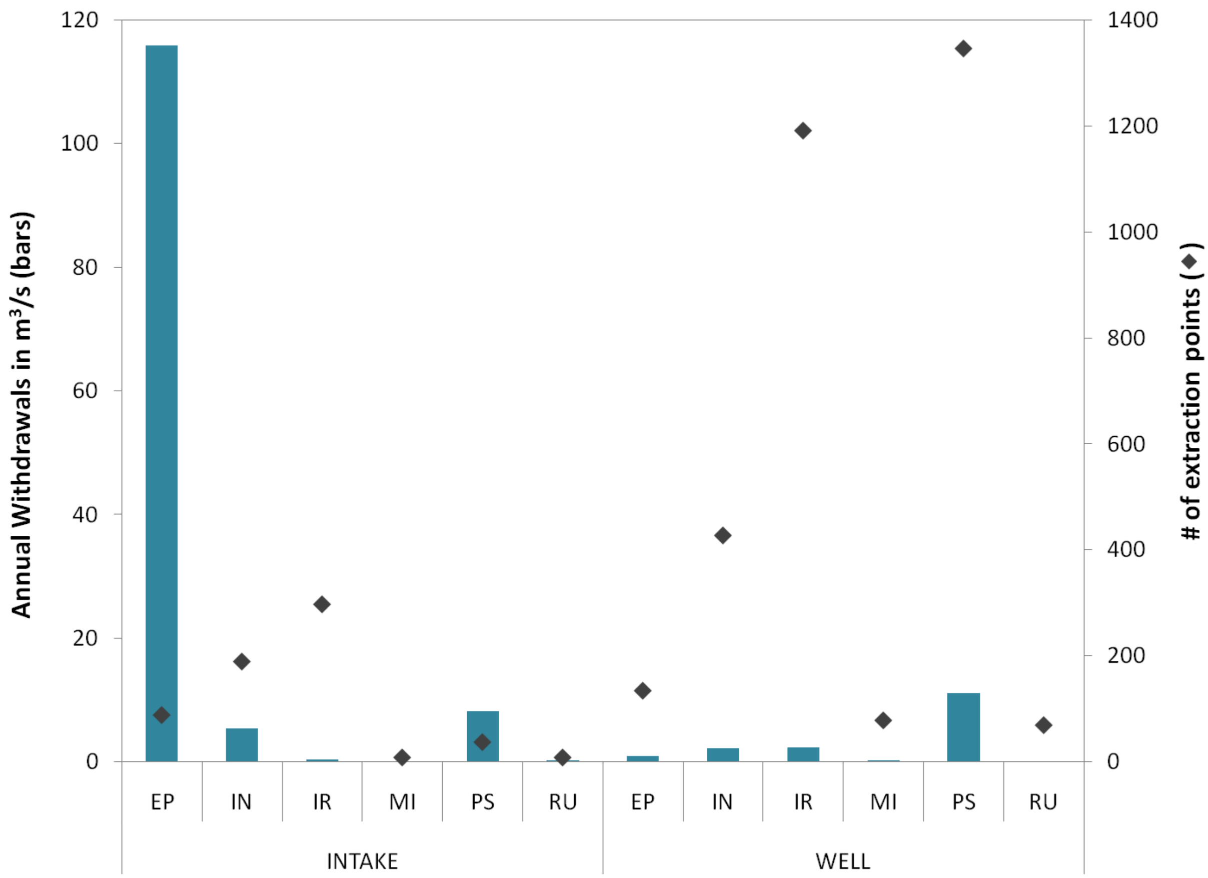

Figure SI- 5 Total annual volume of water withdrawn by Indiana Significant Water Withdrawal Facilities in the Wabash Watershed (bars) and the corresponding number of points of extraction (◆), by Water Use Category, 2007

Table SI- 6 Wabash River sub-basins discharge[a] characterization (in m^3/s) for 2007

Categories Name & SIC# HUC08	Agriculture 2	Mining 12, 14	Manufacturing 20, 24, 26, 27, 28, 29, 30, 32, 33, 34, 35, 36, 37, 38	Transportation 40, 42, 45, 46, 47	Electric, Gas and Sanitary Services 49	Wholesale trade 51	Retail Trade 55, 58, 59	Finance, Insurance, Real state 65	Services 70, 75, 79, 80, 82, 83, 86, 87, 88	Public Administration 91, 92, 95, 96, 97, 99	Others non classified	Total Discharges
05120101		0.04	0.19	0.00	1.75	0.00	0.00	0.13	0.00	0.00		**2.1**
05120102		0.00	0.09	0.00	0.14		0.00	0.00	0.00	0.00	0.00	**0.2**
05120103	0.00	0.00	0.03	0.00	0.61		0.00	0.00	0.00	0.00		**0.6**
05120104		0.00	0.01	0.00	1.05		0.00	0.00	0.00	0.00		**1.1**
05120105		0.04	0.00	0.00	0.48		0.00	0.00	0.00	0.00		**0.5**
05120106		0.12	0.11	0.00	0.51		0.00	0.01	0.00	0.00	0.00	**0.8**
05120107		0.00	0.10	0.00	0.77	0.00	0.00	0.01	0.01	0.00		**0.9**
05120108		0.00	0.91	0.00	32.00		0.00	0.06	0.02	0.01		**33.0**
05120109		0.07	0.08	0.00	1.76		0.00	0.00	0.00	0.00		**1.9**
05120110		0.00	0.04	0.00	0.28		0.00	0.00	0.00	0.00		**0.3**
05120111		1.74	1.06	0.00	46.46		0.00	0.00	0.00	0.50		**49.8**
05120112		0.14	0.10	0.00	0.53		0.00	0.00	0.00	0.00		**0.8**
05120113		0.00	0.01	0.00	0.13	0.03	0.00	0.00	0.00	0.00		**0.2**
05120114		0.00	0.00	0.00	0.46	0.00	0.00		0.00	0.00		**0.5**
05120115		0.00	0.00	0.00	0.01		0.00		0.00	0.00		**0.0**
05120201		0.00	0.76	0.98	35.04	0.07	0.00	0.11	0.01	0.00	0.11	**37.1**
05120202		1.46	0.15	0.00	28.05		0.00	0.00	0.00	0.05	0.00	**29.7**
05120203		0.08	0.11	0.00	0.30		0.00		0.00	0.01	0.00	**0.5**
05120204		0.00	0.07	0.00	1.10	0.00	0.00	0.04	0.02	0.00	0.00	**1.2**
05120205		0.00	0.03	0.00	0.44		0.00	0.00	0.00	0.00	0.01	**0.5**
05120206		0.00	0.00	0.00	0.36	0.02	0.00	0.01	0.00	0.00		**0.4**
05120207		0.05	0.06	0.00	0.28	0.00	0.00	0.02	0.01	0.00		**0.4**
05120208		0.17	0.03	0.00	0.85		0.00	0.00	0.00	0.00		**1.1**
05120209		1.13	0.02	0.00	0.28	0.01	0.00		0.00	0.00		**1.4**
Subtotal	**0.00**	**5.05**	**3.96**	**0.99**	**153.65**	**0.14**	**0.02**	**0.39**	**0.09**	**0.59**	**0.12**	**164.98**

[a]*Data compiled: Reported NPDES data, aggregated by SIC Codes categories, and total average discharges, aggregated by HUC08.*

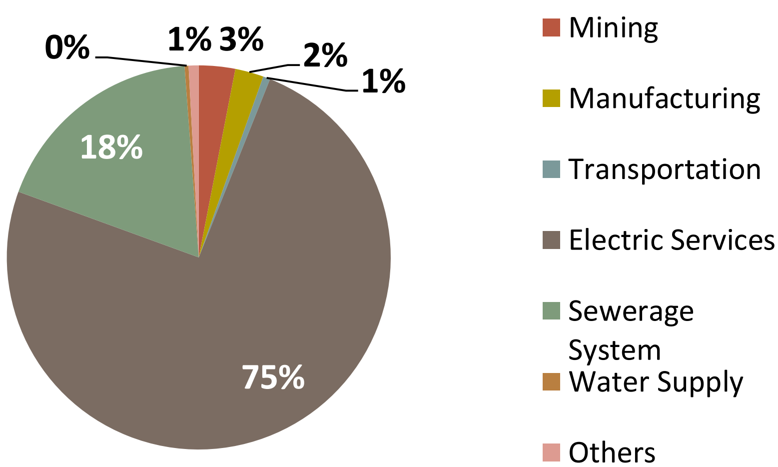

Figure SI- 6 Distribution of treated wastewater discharges by major categories (based on SIC Codes)

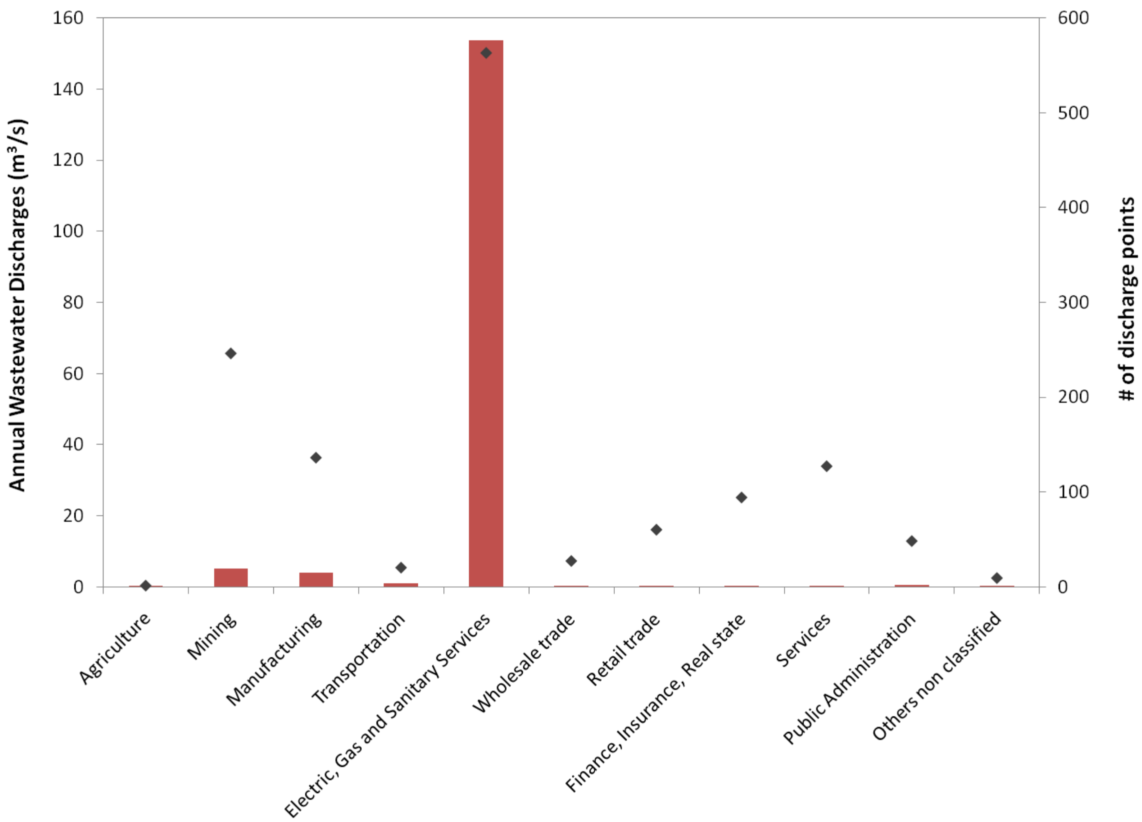

Figure SI- 7 Total annual average volume of wastewater discharged by NPDES Facilities in the Wabash Watershed (bars) and the corresponding count of points of discharge (◆), by SIC Code, 2007

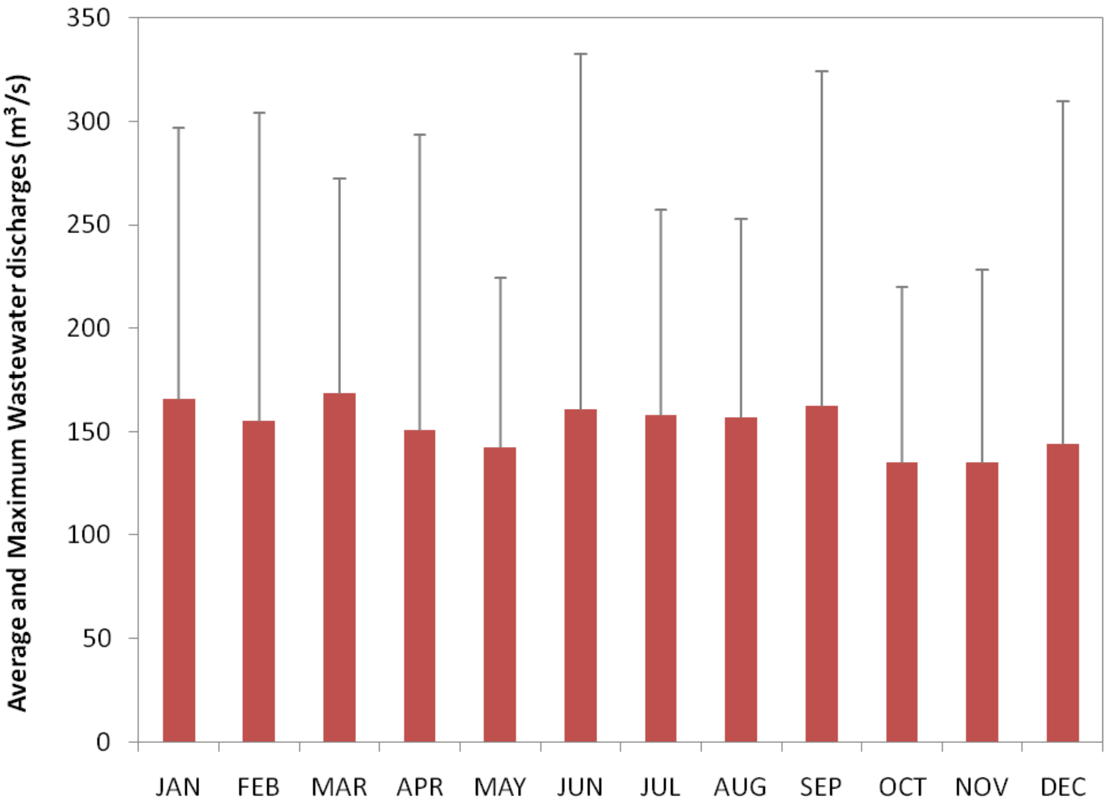

Figure SI- 8 Monthly average and maximum volumes of wastewater discharged by NPDES facilities in the Wabash Watershed, 2007.

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3. TIME SERIES ANALYSIS OF WATER USE AND INDIRECT REUSE WITHIN A HUC-4 BASIN (WABASH) OVER A NINE YEAR PERIOD

Reproduced from Wiener, M.J., Moreno, S., Jafvert, C.T., Nies, L.F., 2020. Time series analysis of water use and indirect reuse within a HUC-4 basin (Wabash) over a nine year period. Sci. Total Environ. 140221. https://doi.org/10.1016/j.scitotenv.2020.140221

3.1 Abstract

Anthropogenic water use and reuse represent major components of the water cycle. In the context of climate change, water reuse and recycling are considered necessary components for an integrated water management approach. Unplanned, or de facto, indirect water reuse occurs in most of the U.S. river systems, however, there is little real-time documentation of it. Despite the fact that there are national and state agencies that systematically collect data on water withdrawals and wastewater discharges, their databases are organized and managed in a way that makes it challenging to use them for water resource management analysis. The ability to combine reported water data to perform large scale analysis about water use and reuse is severely limited. In this paper, we apply a simple but effective methodology to complete a time series watershed-scale analysis of water use and unplanned indirect reuse for the Wabash River Watershed. Results document the occurrence of indirect water reuse, ranging from 3% to 134%, in a water-rich area of the U.S. The time series analysis shows that reported data effectively describe the water use trends through nine years, from 2009 to 2017, clearly reflecting both anthropogenic and natural events in the watershed, such as the retirement of thermoelectric power plants, and the occurrence of an extreme drought in 2012. We demonstrate the feasibility and significance of using available water datasets to perform large scale water use analysis, describe limitations encountered in the process, and highlight areas for improvement in water data management.

Key Words: Indirect water reuse, water use, wastewater discharges, water withdrawals, Wabash River, water data

3.2 Introduction

In the context of climate change, the uncertainty about future fresh water availability creates challenges for current water resources managers, particularly about ensuring the distribution of safe water while mitigating the effects of potential severe droughts. Accordingly, the U.S. Environmental Protection Agency (EPA) recently announced the development of a Water Reuse Action Plan to improve the effective use of the Nation's water resources. In the first draft of the plan, water reuse and recycling are considered to be an important element in an integrated water management approach. Solutions are required to address a wide range of water needs, including agriculture and irrigation, supplying potable water, groundwater replenishment, industrial processes, and environmental restoration (U.S. EPA, 2019a). However, the EPA plan does not include understanding and measuring unplanned indirect water reuse as part of the critical analysis, before possibly considering implementing direct water reuse initiatives.

Unplanned, incidental, or de facto, indirect water reuse occurs when treated wastewater is discharged into surface waters upstream of water intakes (National Research Council, 2012, Rodriguez et al., 2009). It occurs in most river systems and has direct implications in terms of water quality and public health. With increased urbanization, de facto water reuse also can be expected to increase, potentially with deleterious effects (i.e., increases in concentrations of hormones, pathogens and trace organic chemicals) such that providing safe drinking water becomes more challenging (Weisman et al., 2019, Karakurt et al., 2019). Furthermore, return flows are an important source of downstream water supply. If intentional and planned direct water reuse initiatives are put in place, they require an understanding of how changes in water allocation might impact the downstream aquatic ecosystems and water users. Changes in the distribution of stream flows affect water quality and the density and diversity of in-stream habitats (Cherkauer and Sinha, 2010). In many regions where water is relatively abundant, anthropogenic systems may dominate the water cycle, and during low flow months, diversion of treated wastewater for intentional water reuse could create ecosystem water scarcity (Mubako et al., 2013). Furthermore, in watersheds where return flows are a significant fraction of the total main stream flow, diversion for crop or landscape irrigation could adversely impact downstream water rights holders (Ruddell, 2018).

In 2012, the U.S. National Research Council stated that understanding the extent of unplanned water reuse was a critical need for managing water resources (National Research Council, 2012). Rice et al. developed a geospatial model to predict the percentage of publicly owned treatment works (POTWs) treated wastewater at downstream raw surface water intakes used for public drinking water supply (Rice et al., 2013). They studied the extent and possible impacts of unplanned wastewater reuse in the rivers of the U.S. (Rice et al., 2015). They found that wastewater discharges contribute more than 50% of in-stream flow for over 900 receiving streams in the contiguous U.S., making these streams predominately effluent dominated (Rice and Westerhoff, 2017). However, their approach is limited to considering only point source discharges from large POTWS, serving greater than 10,000 people. Their analysis did not include other point source discharges, like small POTWS, industries, or other discharging facilities such as thermoelectric power plants. Based on our analysis here, major POTWs in the Wabash River basin contribute approximately 15% of the return flow. Therefore, it is likely that Rice et al. significantly underestimate the magnitude of total de facto water reuse.

We previously developed a simple and effective methodology to provide an estimate of indirect water reuse at the watershed scale by compiling existing reported wastewater data (Wiener et al., 2016). This work was limited to an analysis of a single year's data on a monthly basis. The one-year timeframe was sufficient to test the methodology and document seasonal variations. However, one year did not provide enough temporal information to understand trends in indirect water reuse or study any extreme events. For example, how a severe drought in the Wabash River basin in 2012 would affect de facto water reuse was a remaining question.

Previous results highlighted many limitations of current water databases (Wiener et al., 2016). In recent years, there has been an active discussion about the need to have an improved, extended, national water database, a water census (Michelsen et al., 2016), a web portal (Josset et al., 2019), or even an "internet of water" (Patterson et al., 2017). Criticism of existing water databases calls attention to their limitations (Perrone et al., 2015, Sprague et al., 2017), including the methods of data collection, data resolution (Ruddell, 2018), the lack of coordination among state and federal agencies, the time it takes to make water data available (Jerome, 2016), and the contradictions that exist in how the same data are reported to and by different agencies (Diehl and Harris, 2014). Due to these limitations, few analyses have been performed with available datasets. Water-related research questions are often answered with mathematical models, however, if the models are not evaluated with real data, conclusions drawn from them are suspect. It is known that available datasets are not perfect, but it must be acknowledged that the U.S. has an extensive compilation of reported water data, and its use in managing water resources with modern computational and visualization technology should be enabled. There are many important public resources and scientific questions that could be answered with existing data if it were to be organized with an aim to facilitate analysis (Ruddell, 2018). For example, consumptive water use and withdrawal and consumption of water by thermoelectric power plants are poorly quantified (Diehl and Harris, 2014, Ruddell, 2018).

3.2.1 Scope and Purpose

The Wabash River watershed was selected as a case study due to its size and relevance for multiple water use purposes, including public supply, industry, and irrigation. Potential changes in the climate, as well as increasing demands for fresh water in the watershed, suggest the need to understand not only the current status of water use and reuse in the region but also temporal trends that could help forecast future water resource scenarios. Furthermore, preliminary results from the year 2007 suggest that during low-flow months the water resources are used extensively (Wiener et al., 2016), placing at risk the river ecosystems' needs. The Wabash River watershed provides habitat to more than 350 terrestrial fauna species, 151 fish species, and 75 mussel species. Several threatened or endangered species are found within the basin waters or adjacent terrestrial habitats (U.S. American Corp of Engineers Louisville District, 2011). The river flow variability and consequent habitat stability appear to influence the fish assemblage structure (Pyron and Lauer, 2004). The Wabash River watershed provides an optimum test case for the present study: the size is large enough to show issues that arise when combining water data from 3 different states; however, it is not so large as to preclude controlled management and curation of the data. The basin is predominantly located in Indiana (IN), which has consistently reported good quality water data over time, which is crucial to complete the analysis. The Wabash watershed is located in a water rich area of the U.S. that is not regularly affected by extreme drought and has not been extensively studied from the water reuse perspective.

Our main research objectives were to: (i) Understand the occurrence of unplanned indirect water reuse in the Wabash Watershed, (ii) understand the water use dynamics in the basin over time, and (iii) explore the feasibility of integrating existing databases for large watershed scale analysis. By performing a nine-year time series analysis of water withdrawals, treated wastewater discharges, and calculated indirect water reuse, we aimed to understand the drivers of water use and reuse in the watershed that would reflect the general trends through the seasons, and illustrate particular variations in time with changes dependent on biophysical variables (e.g. weather conditions), and anthropogenic influence (e.g. modifications in projects that use water). This analysis serves as an example of what could be performed in larger watersheds (i.e., the Mississippi Basin), shared by various states, incorporating reported data from different sources. Previous analyses that considered only design flows of POTWs (Rice et al., 2013), not measured data, miss real month to month variation evident in currently available data. Reported water data might not be 100% accurate or complete, but it is of sufficiently high quality to reflect trends and represent reality and is suitable as a valuable starting point for applied basin-scale analysis. In the process, we have identified data limitations to give insight into what is needed to improve such analyses.

3.3 Material and methods

3.3.1 Area of study and timeframe

The Wabash River watershed (Figure 1) is a 4-digit Hydrological Unit Code (HUC) basin, #0512, comprising 85,237 km2, located in the U.S. states of Indiana (73%), Illinois (26%), and Ohio (1%). The population of the watershed as per the 2010 Census was estimated to be 4,402,976 inhabitants. The average density is 52 people/km2 (Wiener et al., 2016). For a detailed description of the basin, see Gammon, 1998. The Wabash River flows almost freely over a length of 764 km. There is only one impoundment on the main branch in Huntington, IN, on its upper section (Gammon, 1998) making the undammed reach the longest in the U.S. east of the Mississippi River. Point source discharge data are organized by fiscal years (October to September) and became available for direct online download starting in FY 2009 (U.S. EPA, 2019b). This study commenced upon the data completion of the ninth fiscal year in September 2017.

3.3.2 Indirect water reuse calculation

To calculate the percent indirect or de facto reuse, we followed the methodology described previously by Wiener et al., 2016. Estimates of indirect water reuse were determined at the estimated outlet of the basin, on a monthly basis for the period FY2009-FY2017, considering the parameter Q1-Average discharge for the month, where Q1-Average discharge is described below.

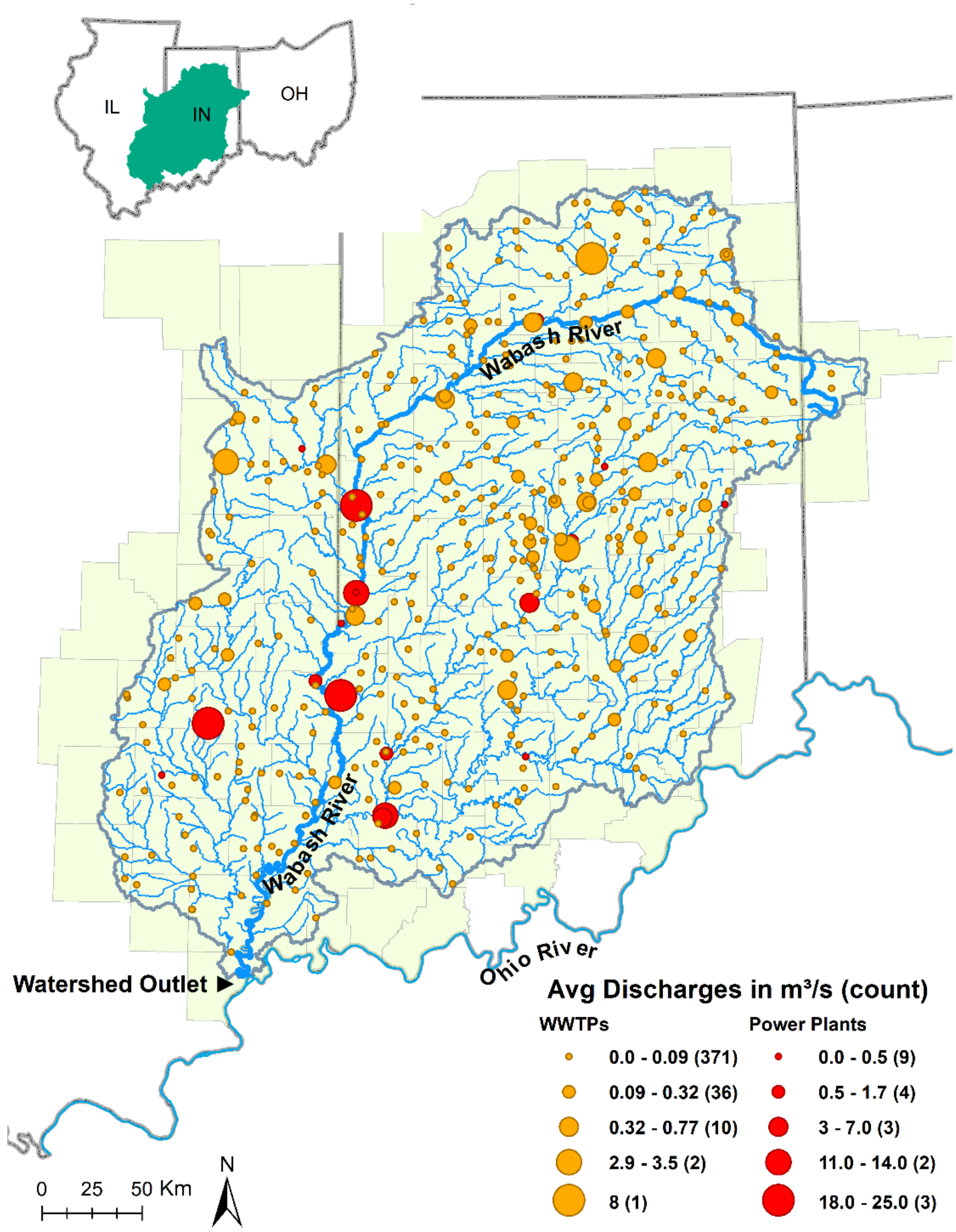

Figure 3.1. Map of the HUC 0512 - Wabash River Watershed showing the locations of watershed outlet, SIC code 4911-Power Plants, and SIC code 4952-WWTPs. The size of the points corresponds to average discharge in m3/s. The legend includes the number of facilities at each size category. For a map showing locations of most significant water withdrawals and major and minor NPDES permitted cdischarges in 2007 see Wiener et al. 2016.

3.4 Data &Analysis

3.4.1 Outlet Streamflow

The U.S. Geological Survey (USGS) National Water Information System provides monthly statistics for surface water sites across the nation (U.S. Geological Survey, 2019). Because there is no gaging station located at the Wabash River watershed outlet at its confluence with the Ohio River, we followed the methodology of Wiener et al., 2016, to estimate the basin´s outlet streamflow. A detailed calculation for the monthly mean streamflow estimation is included in the Appendix (Table A-1).

3.4.2 Point source wastewater discharges

EPA Office of Compliance maintains the Integrated Compliance Information System (ICIS) to track permit compliance and enforcement status of facilities regulated by the National Pollutant Discharge Elimination System (NPDES) under the Clean Water Act (U.S. EPA, 2017). Although all point source discharges to the waters in the U.S. are required to obtain an NPDES permit and monitor their wastewater, not all discharge monitoring data are uploaded into ICIS-NPDES. A detailed description of the limitations of this database is described on their website (U.S. EPA, 2020). The types of discharges that are not included in the online database include: a) Wastewater releases from industrial facilities that are connected to a publicly-owned treatment works (POTW) sewerage system (e.g., indirect discharges, these are reported under POTWs data); b) biosolids monitoring data; c) discharges related to wet-weather events, such as stormwater from municipal separate storm sewer systems (MS4s), stormwater from industrial facilities, discharges from construction activities, combined sewer overflows, sanitary sewer overflows, and concentrated animal feeding operations (CAFOs).

Discharge Monitoring Reports (DMR) data includes flow parameter 50050-Flow in conduit or through treatment plant, which was used to estimate the monthly volume of wastewater discharged along the watershed. It is important to highlight that we are secondary data users of a database that was not designed for this research purpose. There are 5 flow parameters listed in the database. The EPA Support Team indicated that 50050 was the parameter most commonly used in the monitoring reports (Personal Communication, December 14, 2018). We filtered the database by Discharge Monitoring Location Code = 1 (Effluent), and Value Type Code = Q1 (Average flow), to obtain the average sum of all discharges in the watershed. Most of the wastewater discharges are reported monthly. Original data from ICIS NPDES units are Million Gallons Day (MGD), transformed to SI units of m3/s by the conversion factor 0.0438.

To allow for comparison between DMR data and withdrawals data by water use categories, we assigned each facility in the NPDES DMR database a water use category. We used the IN Significant Water Withdrawals Facility (SWWF) water use categories as reference (Indiana DNR, 2019), and the USGS methodology (Kenny, 2004) to relate Standard Industrial Classification (SIC) codes with water use categories.

We applied different data preprocessing techniques to remove inconsistent points of the data. Negative values and values on the order of thousands of MGDs (equivalent to 43.81 m3/s) not plausible for wastewater discharges, were flagged and evaluated. Outliers were identified for every facility, identifying average monthly discharge values that exceeded 5 standard deviations from the median, and were larger than 10 MGD (0.4381 m3/s). From 184,861 data values, we identified 253 with quality issues including negative numbers (2), manual data entry errors (30), decimal point (181), and missing unit conversion (40). Most of these values were manually recovered.

To understand the variability of the dataset, a 90% confidence interval (CI) of the average facility discharges (Q1) in the same month over nine years was generated. Given a month, Q1 values are not independent and identically distributed, and even assuming independency, they are not identically distributed. Then, given a month d, and N facilities (random variables), the sum of them follow an unknown distribution with mean equal to the sum of these N values. To estimate the 90% CI for total Q1, a bootstrap sampling method was applied (Efron, 1979). Specifically, we randomly sampled, with replacement, Nd points from the underlying distribution (where Nd is the number of facilities with data for that month d, and took the sum of them, generating a single point estimate for the total mean. To obtain the 90% CI, this process was repeated Nd times, generating an Nd estimation. Finally, we sorted them and picked the 0.05*Ndth and 0.95Ndth points, generating the 90% CI.

3.4.3 Significant Water Withdrawals

To complete a water balance study, we analyzed a time series of the fresh water withdrawals in the Wabash watershed for the defined period of analysis (FY 2009 to 2017). The collection of water withdrawals data in the U.S. is performed by state water institutions. Complete data were obtained for the states of Indiana and Ohio, and partial data for the state of Illinois.

The Indiana Water Resource Management Act (IC 14-25-7) states that "…owners of significant water withdrawal facilities are required to register with the Department of Natural Resources (DNR) and report water use on an annual basis" (Indiana DNR, 2019). SWWF data are available for download in a file for the entire state which compiles monthly data for 3 years previous to the year of download. This required a long-term plan of downloading data to complete the dataset for nine years. SQL programming was used to combine the datasets, which were not identical in structure nor maintained in a standardized format over time. The SWWF database assigns each facility a water use category code, based on their own definitions: IR-Irrigation; IN-Industry; PS-Public Supply; EP-Energy Production; RU-Rural Use; MI-Miscellaneous. For a detailed description of the activities included in each category see Indiana DNR, 2020. SWWF categories are similar but not the same as the USGS water use categories defined for state water use estimates (Dieter et al., 2018). Since there is not sufficient information available to recode them to comply with USGS standards, and the SWWF data corresponds with most of the water withdrawn in the Wabash Watershed, the SWWF water use categories were used to analyze and present results.

Ohio water withdrawals data were provided upon request by the Water Inventory and Planning Program Manager from the Ohio Department of Natural Resources (ODNR) Division of Water. This office registers facilities, or a combination of facilities, with the capacity to withdraw water at a quantity greater than 100,000 gallons per day (equivalent to 0.0044 m3/s) (ODNR, 2018). The Illinois Water Use Act of 1983 (525 ILCS 45) requires reporting withdrawal rates of 70 gallons per minute (equivalent to 0.0044 m3/s) or greater (Illinois DNR, 2020) annually through the Illinois Water Inventory Program (IWIP), which maintains a database of high-capacity water wells and intakes from public water supplies, self-supplied industries, irrigation, fish and wildlife, and conservation (Illinois State Water Survey, 2019). Upon request, IWIP provided two datasets: annual withdrawals for Public Water Supply (PWS) facilities; and annual withdrawals for non-PWS facilities. Both datasets include well and intake withdrawals from facilities located in the counties that corresponded with the Wabash Watershed only. Illinois law considers private facilities' data to be confidential, so it can only be provided in a way that is not identifiable. The non-PWS datasets are an aggregation, by county, of the annual water withdrawals done by private entities. We also obtained the non-PWS dataset aggregated by SIC code. We followed USGS guidelines (Kenny, 2004) and IN SWWF data description to categorize these withdrawals by type of use. To complete the water use analysis on a monthly basis, and because IWIP data consists of annual values, we estimated monthly contributions. For each water use category we aggregated IN and OH monthly data to annual totals, calculated the proportion that corresponded to each month for the nine fiscal years of analysis, and, assuming the watershed would have a similar overall water use behavior, we applied the calculated proportions to the IWIP annual totals to estimate the average monthly contribution per water use categories.

IN SWWF, OH division of water, and IWIP databases are verified by the officials and subject to quality control. However, we curated the data quality as follows. Of 2,072 facilities, there were 42 facilities listed in the IN SFFW database with no associated water withdrawal data. We found four (4) negative values, which are not possible. Some specific cases presented a wide range of values for water withdrawals throughout a year, however, there was consistency between years, which we confirmed was possible due to the type of operations (e.g. it is typical for a quarry to cease operations, including dewatering, during the winter months depending on their aggregate orders). In the case of IWIP data, for both the PWS and non-PWS datasets, we observed that the data presents a trend of reduced data compiled for the most recent years, in the form of reduced values over time for the same county, or counties with null data. We confirmed that facilities do not necessarily report on time, and IWIP needs to request the submission of older reports every year, or sometimes facilities do not report at all, therefore there remain permanent data gaps which in some cases are not reconcilable due to non-reporting, missing knowledge on the end of the operator, or just no proper method to estimate/report water use (Conor Healy, personal communication, September 6, 2019). Still, the resulting data from the IL IWIP is consistent and in the order of magnitude of other IL water use estimates (Dieter et al., 2018, The Ohio River Valley Water Sanitation Comission, 2013).

The three withdrawals databases are organized by county and do not include HUC references. ArcGIS tools were used to remove data points not located within the Wabash watershed. Datasets were converted to SI units of m3/s and combined to form a unified withdrawals database. The same methodology described above was used to generate a 90% confidence interval for total Withdrawals.

3.5 Results & Discussion

3.5.1 Outlet Streamflow

For the period of analysis, the estimated outlet streamflow time series is plotted in Figure 2a. The river presents a wide fluctuation through the period with average estimated streamflow of 1150 m3/s, with a minimum of 114 m3/s (July 2012) and a maximum of 4,566 m3/s (May 2011). The outlet streamflow shows a steady trend, with a clear pattern of peak flows during winter and spring months (January-June) and lower flows during the end of summer and fall months (August-November), with December and July as transition months (Figure A-1). The lowest streamflows recorded during the period of analysis, 114 m3/s and 121 m3/s, occurred in July and August 2012, which was a year of significant drought in the U.S. and the Wabash River basin (Schnoor, 2012). The year 2012 ranks as the warmest on record to date, with July 2012 being the 2nd warmest month since 1936 (NOAA National Centers for Environmental Information, 2020). This anomalous heat increased evaporation and intensified drought conditions. In combination with reduced precipitation, the streamflow observed at the Mississippi River and its tributaries was below the 10th percentile of historical records.

3.5.2 Total average wastewater discharges time series

The sum of Q1-Average wastewater discharges along the Wabash watershed is plotted as the solid black line in Figure 2a (data in appendix Table A-2). The shaded area shows the estimated 90% CI for Q1. The average discharges present a seasonal pattern and a decreasing trend over time. A linear regression model was applied to the trend part of the additive decomposition of the time series (Hyndman and Athanasopoulos, 2018) (Q1: □1= -0.554, R2=0.85, p-value=2.64E-40) which confirmed a declining trend for average reported flows. The average Q1 was 143 m3/s of total wastewater discharges for the watershed, ranging from a minimum of 87 m3/s (October 2016) to a maximum of 199 m3/s (June 2010). The sum of Q1 reported annual average values decreased 37% from FY2009 to FY2017. The decreasing trend can partially be explained by the number of reports considered. Over the entire period of analysis, there were on average 1,110 facilities with Q1 data, decreasing from 1,155 in FY2009 to 1,105 in FY2017 (Table A-2).

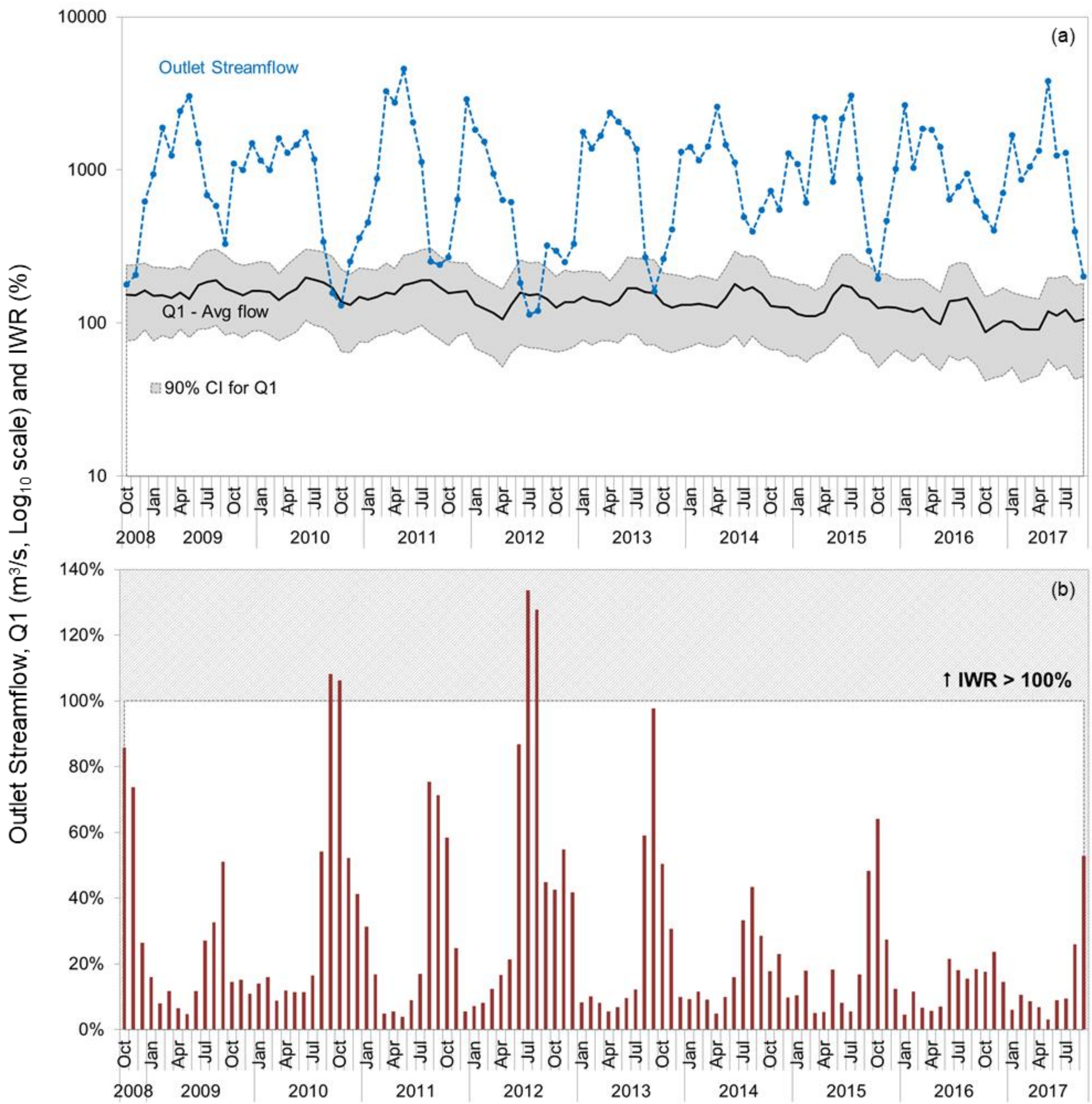

Figure 3.2. (a)Estimated monthly mean streamflow at the outlet of the Wabash River basin, sum of Q1-average discharges, and estimated 90% CI (shaded area), on a monthly basis, for the period FY2009-FY2017, in m3/s. Note the vertical axis is in Log10 scale to allow visualization of both outlet streamflow and wastewater discharges time series. (b) Average indirect water reuse (IWR=sum of wastewater discharges/outlet streamflow) in %, for the period FY2009-FY2017, on a monthly basis.

The sum of reported Q1 wastewater discharges shows a seasonal pattern of greater discharges during the warmer months of June to August and lower recorded discharges during colder months of February to April, with May as a transition month. In Figure 3, we plot the mean Q1 per 3-month seasons, for every year in the time series. We observe mean Q1 ranged from 112 m3/s to 192 m3/s during the warmer months and from 91 m3/s to 154 m3/s during the cold months, what confirms the two distinguishable periods.

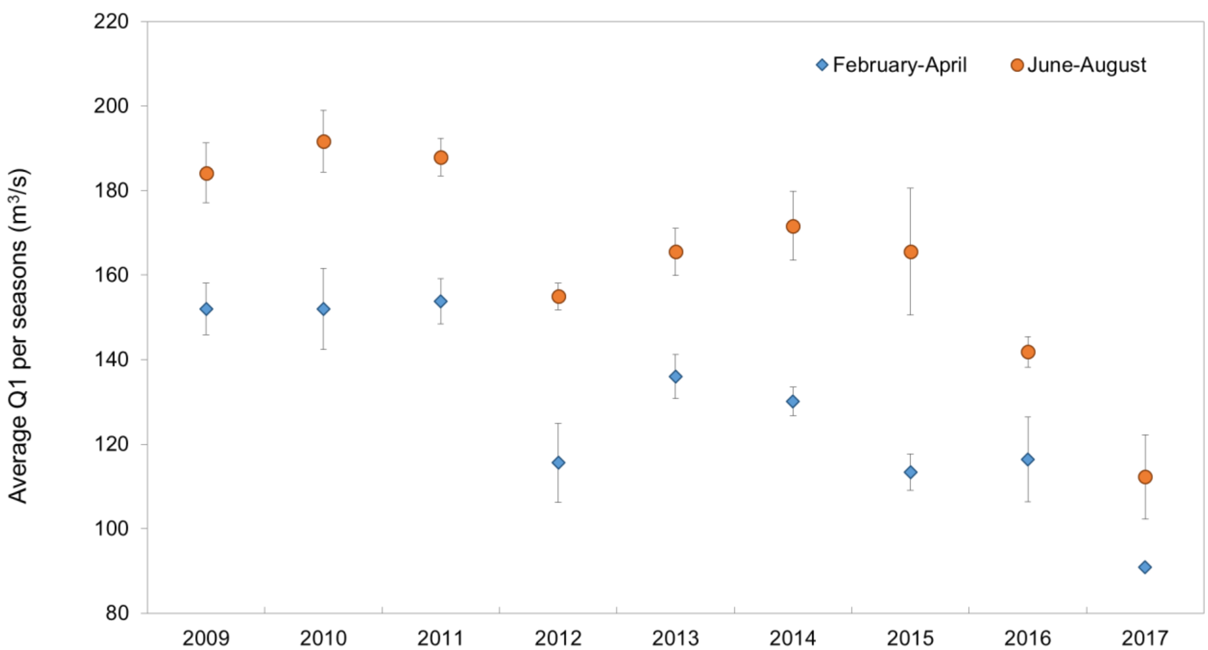

Figure 3.3. Average Q1 per seasons, considering cold months February to April and warm months June to August, by year, for the period FY2009-FY2017.

3.5.3 Indirect Water Reuse estimation

The indirect water reuse (IWR) index for the Wabash River Watershed at the outlet of the basin was calculated on a monthly basis (Figure 2b, data in appendix Table A-3). The ratio of discharges to streamflow is displayed as bars, representing the average percentage of indirect reuse that occurred in the entire watershed that month. The IWR ranged from 3% to 134%. It shows an expected inverse relationship with streamflow: the lower the streamflow, the higher the %IWR. The occurrence of high IWR coincides with a time of the year when the surface streams have reduced flow and the demand for fresh water is increased. There is a wide range of higher values of indirect reuse rates during the months of June to November and reduced IWR rates, mostly under 20%, from December to May. As expected, the drought of 2012 is visible as the maximum percentage of indirect water reuse rates observed over the entire time series of the analysis. The peak estimations of IWR > 100% are displayed in the shaded area. They signify that, during low flow months, the entire surface water resources of the watershed are being used, and then reused, in a downstream cycle. Over the time series, peaks in IWR occur when streamflow is less than the sum of reported discharges (Q1). This happened four times during the period of analysis in Sept-October 2010 and July-August 2012 (Figure 2a).

3.5.4 Wastewater Discharges Analysis

The Q1 average discharges data are valuable and unexplored indicators of water use in the watershed. Major facilities account for 81% of the total volume discharged, and minor facilities contribute the remaining 19%. Only a few major facilities are responsible for most of the discharges. From 1,211 facilities with Q1 data over the entire period of analysis, 34 facilities accounted for 80% of the cumulative average discharges, including 12 electric power generating facilities and 16 wastewater treatment plants (Figure A-2). This shows that the drivers of wastewater discharges are the major users of fresh water in the watershed, in the following order: 1) power plants -SICCODE=4911 Electric Services, and 2) public supply and industries that have pretreatment programs and discharge through a POTW- SICCODE=4952 Sewerage Systems.

The major water user in the Wabash Watershed is the thermoelectric power sector. Thermoelectric power discharges average 79% +/-6% of all the reported water discharged into the Wabash River basin, although the exact fraction varies from month to month, with a minimum of 59% and a maximum of 89% over the period of analysis. In the time series plot of power plant water use data (Figure 4a), there is a clear trend of 46% reduction of reported discharges (□1= -5.69E-01, R2=0.88, p-value=3.17E-45) from FY2009 to FY2017. There are 22 power plants in the database under SICCODE=4911; 14 of them reported some decreased discharges, and 5 facilities reported that discharges had dropped to zero at some point in the timeframe. The U.S. Energy Information Administration (EIA) reports (U.S. EIA, 2019) confirm that generators were removed from 10 power plants located in the Wabash Watershed (Table A-4). The decrease in water discharges for each of these facilities matches the dates of generator removals, which in some cases means that the plants changed technologies (coal to natural gas) or the power plants closed (Table A-5). The reasons for coal power plant closure in the last decade include age, stricter EPA regulations and regulatory compliance costs, and low natural gas prices (Pratson et al., 2013, U.S. EIA, 2012). Because natural gas power plants use and consume less water than coal power plants, the change in technology reduces considerably the need for water for electricity production (Grubert et al., 2012, Meldrum et al., 2013, DeNooyer et al., 2016). Diehl and Harris found that EIA reported water withdrawals from thermoelectric power plants in the U.S. declined 18% from 2005 to 2010 (Diehl and Harris, 2014). Despite known shifts to natural gas generation with conversion from once-through to recirculating-tower cooling, Diehl and Harris suggest that reporting changes and data limitations are a significant source of uncertainty in estimating thermoelectric water use.

The sum of all SIC CODE=4952 Sewerage Systems contributes, on average, 17% +/- 5% of all discharges in the Wabash watershed, with a monthly minimum for the time series of 9% and a maximum of 33%. Major POTWs discharge 90% of total volume reported, and minor sewerage treatment plants (STPs) are responsible for the other 10%. The WWTPs Q1 data time series shows an overall trend of stable discharges over time (Figure 4b) with an average discharge of 24 m3/s, a minimum of 15 m3/s, and a maximum of 39 m3/s. This stable trend aligns with the population estimates from the U.S. Census Bureau that indicate that much of the Midwest experienced slow population growth (Kinghorn, 2016). Indeed, over the entire basin the change in population estimates from July 1, 2010 to July 1, 2018 are -0.78% for IL, +3.1% for IN, and +1.3% for OH (STATS Indiana, 2019). Furthermore, some of the major POTW facilities in the area have decreased their discharges over time. These might reflect a more rational use of water by the communities, the implementation of active programs to significantly reduce stormwater flows into their combined sewer collection systems, and or the closure of high water use industries.

The phenomenon of total Q1 discharges decreasing consistently is partially explained by the reduction or changes in operations in the thermoelectric sector. Data curation and analysis also reveals anomalies with reporting and data completeness. The count of NPDES-regulated entities in the Wabash watershed increased from 1,565 in FY2009 to 7,017 in FY2017 (Table A-6, Figure A-3). This is the result of EPA and states implementing the NPDES Electronic Reporting Rule (40 CFR part 127) starting in December 2015 (U.S. EPA, 2015). However, this increase corresponds mostly to facilities required to report only their facility information. From the DMR data available, the number of records that provide discharge data decreased 6% from 1,323 in FY2009 to 1,238 in FY2017. Also, because NPDES DMR is focused on contaminant loads, not all the reported data includes Q1 values. Indeed, the number of facilities reporting Q1 decreased 4% in the period of analysis (Table A-2).

3.5.5 Fresh water withdrawals, water use analysis and water balance

To complete a water use analysis in the Wabash watershed, we compiled the data available on significant freshwater withdrawals. We aggregated data from 2,032 facilities from the IN SWWF database, 15 facilities from the OH DNR database, and 101 public water supply facilities plus 173 non-PWS intakes or wells from IL. Due to data confidentiality, it is not possible to know the exact number of facilities that withdraw water in the IL section of the watershed; however, the aggregated data provided corresponds to 2,686 points of extraction (Table A-7). We summed the volumes of water withdrawn in the entire watershed, monthly, for the period of analysis to obtain the total withdrawals time series (Figure 4a) and estimated the 90% CI (Table A-8, Figure A-4). Considering annual averages, 88% of total water withdrawals volume are surface water intakes, and the remaining 12% are groundwater well extractions.

Annual average volumes and % share of both withdrawals and wastewater discharges were calculated (Table 1). Energy production is the largest user of water in the watershed (around 79.5%) followed by public supply (13% to 17%) and industry (5% to 3%). Differences in withdrawals or discharges % share are due to the source of water, consumption factors, and the influence of other categories, like irrigation which accounts for 2.1% of withdrawals but has no share in point source wastewater discharges.

The FY2009-FY2017 monthly time series for withdrawals and discharges, as a cumulative total, and by water use category are shown in Figure 4. Withdrawals are represented with dotted lines and the sum of Q1 discharges is represented with solid lines. The monthly sum of reported significant withdrawals in the Wabash watershed averaged 139 m3/s, ranging from 83 m3/s in April 2017 to 207 m3/s in August 2011 (Figure 4a). Overall, we observe a decreasing trend of total fresh water withdrawals over time (□1= -4.88E-01, R2=0.85, p-value=3.80E-41), with a seasonal pattern of peak withdrawals during summer months, June to August, and less withdrawals during January to April. There is a 31% drop in total average withdrawals from FY2009 to FY2017. The decreasing trend is mainly explained by a major decrease in the water withdrawals for energy production (□1= -4.84E-01, R2=0.83, p-value=7.46E-38) and a slight decrease of water withdrawals for public supply (□1= -1.50E-02, R2=0.67, p-value=3.87E-24) (Figure 4b).

However, there is an increase in water withdrawals for industry (□1= 1.30E-02, R2=0.24, p-value=5.49E-07) in the latest years (Figure 4b) and also a slight increase in seasonal water withdrawals for irrigation (IR) (Figure 4c). We observe an increase in total withdrawals during the year 2012, which was particularly dry. There was an overall 5% to 10% increase in total withdrawals during May to July 2012, compared to the average water withdrawn for the same months between 2007 and 2017. This is principally reflected by the increase of volumes of water withdrawn for PS and IR purposes (Figure 4b, 4c).

Table 3.1. Summary of reported treated discharges (D) and significant Withdrawals (W) in the Wabash Watershed, by IN SWWF Water Use Categories: EP-Energy Production, PS-Public Supply, IN-Industry, IR-Irrigation, RU-Rural Use, MI-Miscellaneous; aggregated by Fiscal Year, Annual Averages (m3/s), and % share.

Water Use Category		**Fiscal Year (October-September) Annual Average (m^3/s)**									**Inter-annual Avg (m^3/s)**	**Share**
		2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**		
EP	D	133.39	138.29	132.11	115.00	116.81	114.33	105.24	94.78	72.04	113.55	79.6%
	W	126.20	129.58	127.95	113.97	110.80	113.95	104.33	94.56	74.92	110.69	79.5%
PS	D	23.95	24.13	24.85	22.78	25.00	26.05	26.69	25.06	25.31	24.87	17.4%
	W	18.68	18.43	18.20	18.79	18.02	17.72	17.55	17.38	17.18	17.99	12.9%
IN	D	4.32	4.49	3.84	3.38	3.59	3.18	3.57	3.80	4.19	3.82	2.7%
	W	7.05	6.77	6.58	6.75	6.72	6.26	7.01	7.29	10.77	7.25	5.2%
IR	D	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.0%
	W	2.12	2.37	2.98	5.13	3.19	2.80	2.22	2.63	2.57	2.89	2.1%
RU	D	0.01	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.02	0.0%
	W	0.19	0.25	0.30	0.33	0.35	0.31	0.35	0.32	0.30	0.30	0.2%
MI	D	0.12	0.15	0.27	0.34	0.49	0.45	0.27	0.40	0.27	0.31	0.2%
	W	0.26	0.28	0.25	0.20	0.15	0.18	0.17	0.12	0.13	0.19	0.1%

The resulting water withdrawals time series for the Wabash watershed are consistent with the latest USGS report on historical trends in water use in the U.S. (Dieter et al., 2018). They state that total national withdrawals in 2015 were estimated to be 9% less than in 2010, continuing a downward trend since 2005. This was mostly caused by a historical decrease in withdrawals for thermoelectric power plants, which in 2015 were 18% less than in 2010, and in 2010 were about 20% less than in 2005. The USGS reports that IN, IL and OH were among the states with the largest reduction in withdrawals for thermoelectric power. Furthermore, for the same period, the report describes a nationwide decrease of 7% in water withdrawals for public supply, which also continues a decline that was first observed historically in 2010.

The water balance plots (Figure 4) describe the overall performance as well as the relationship between discharges and withdrawals for the water use categories Energy Production, Public Supply, Industry, and Irrigation. The categories Rural and Miscellaneous use were not included because they have a minimal contribution to total water withdrawals and discharges, with volume rates between 0.01 and 2.4 m3/s, and no clear trend or seasonal patterns for either series (data shown in Figure A-5). In Figure 4a, both total Q1 discharges and total withdrawals follow the same seasonal pattern. The correlation between the curves is high, obtaining a value of □ = 0.89 (p-value=2.20E-16). This indicates the seasonal water use trends in the watershed consist of increased water use during warmer, dry months. It also indicates a direct relationship between ICIS-NPDES DMR data collected by the EPA and the significant withdrawal data collected by state agencies. Clearly, the reported treated wastewater discharge data does provide valuable information on water use, even though this was never the intended purpose of these data. Withdrawals were larger than discharges during the drought (2011-2012) and during the last years of analysis (2016-2017) when the data might still be incomplete due to reporting and compiling delays. It is important to note that whereas DMR data correspond with both major and minor facilities, withdrawals data consist of extractions by larger users only. Thus, it is reasonable to conclude that water withdrawals are underestimated by possibly as much as 20%. Furthermore, underestimates are evident for EP where it can be observed that discharges are larger than withdrawals most of the time. Several of the largest power plant facilities are located in Illinois, from where the water withdrawal data were provided as aggregated data, and not available at the facility level. The dominance of energy production on the anthropogenic water cycle is apparent as it tracks very closely with the total water withdrawals and discharge data (Figure 4a). Water withdrawals for EP ranged from 53.8 m3/s (April 2017) to 164.5 m3/s (August 2011) and follows the discharges curve. Both show a clear seasonal pattern of increased water use during summer months (June to September) and a declining trend, explained previously.

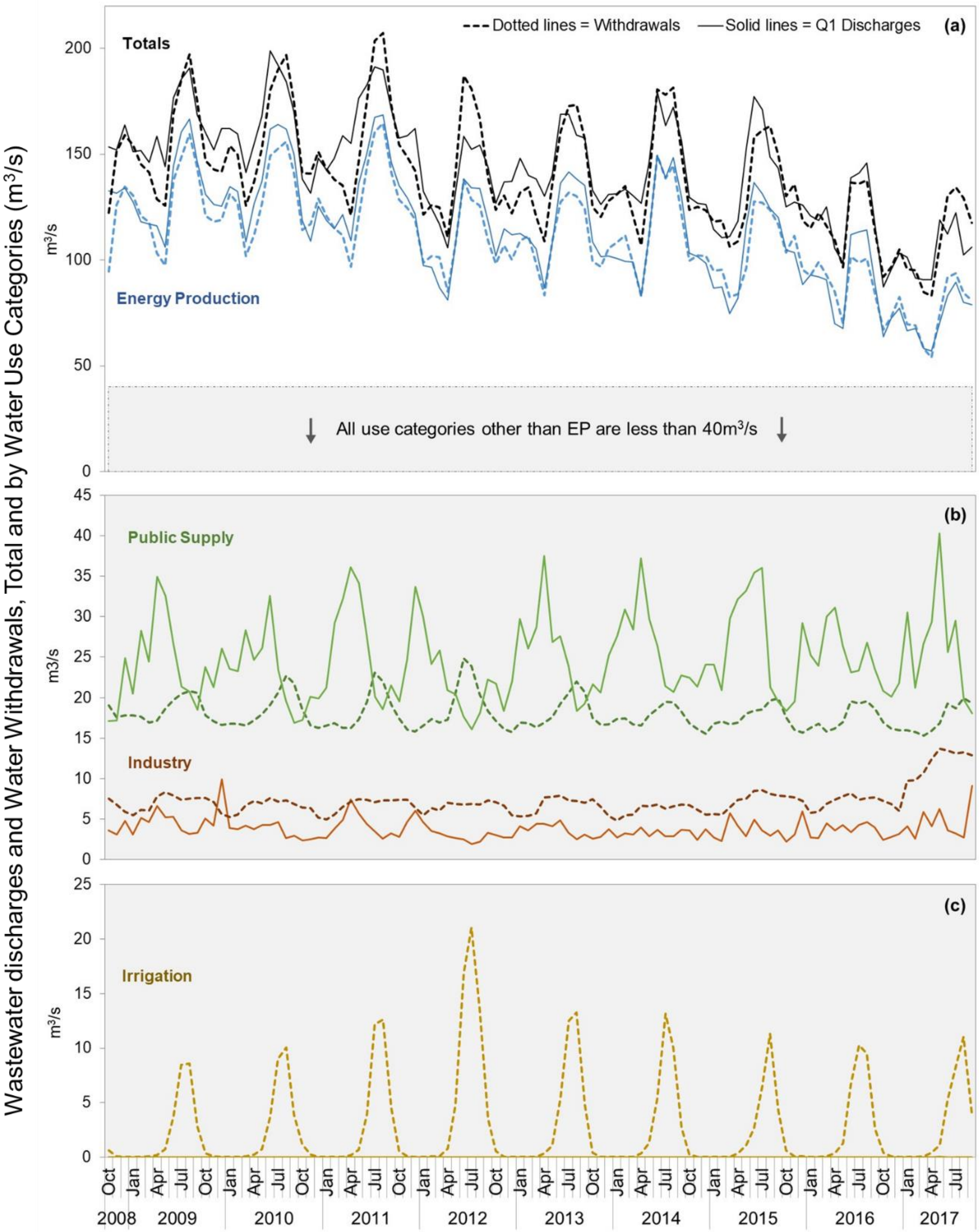

Figure 3.4. Sum of Q1 average wastewater discharges (solid lines) and total water withdrawals (dotted lines) for the period FY2009-FY2017. (a)Total and by water use category EP-Energy Production; (b) PS-Public Supply and IN-Industry discharges and total water withdrawals; (c) IR-Irrigation total water withdrawals. Not shown: rural and miscellaneous uses are less than 0.5% total.

Withdrawals in the Public Supply sector (Figure 4b) ranged from 15.3 m3/s (April 2017) to 24.9 m3/s (June 2012) with a steady trend and seasonal increase during May to October. It can be observed that discharges surpass withdrawals at most times. This is expected as withdrawals are the extraction by utilities to supply fresh water to public supply, which consumes some 10% to 15% (Shaffer and Runkle, 2007), and discharges some as runoff and some to the wastewater collection systems. Whereas wastewater discharges represent the effluents from all WWTP and STPs in the watershed. These facilities combine treated water from sewer systems with water from industrial pretreatment programs, and sewer inputs from urban runoff. Moreover, the sewer systems might include wastewater from self-supply domestic withdrawals, which are not accounted for in the Total Withdrawals estimation and which, in the case of IN, IL, and OH, represent 9% to 25% of total domestic water use (Dieter et al., 2018).

The industry sector withdrawals ranged from 4.9 m3/s (January 2011) to 13.7 m3/s (May 2017) (Figure 4b). This time series presents a stable, seasonal pattern, with reduced extractions from December to February, which could be related to the holiday season. This sector shows an increase in water withdrawals towards the end of the period of analysis, during the year 2017. Discharges present peaks in April and December with a possible influence of stormwater. Here, withdrawals surpass discharges by 2.3 m3/s on average. This can be explained by the consumption of water by the industrial sector, with an estimated median of 6% to 12% (Shaffer and Runkle, 2007), and the fact that industries with pretreatment programs return their treated wastewater through POTW sewerage systems.

The irrigation water sector is accurately described by the discharges and withdrawals plot (Figure 4c). Withdrawals present a seasonal pattern of increased extractions during summer months and dry seasons (July and August), which turns to minimal extractions during wet months (November to March). Peak withdrawals averaged 11 m3/s and the maximum of the series was 21.1 m3/s in July 2012, clearly showing an increase due to the severe drought of that year. Irrigation is a water use activity with major consumption rates due to large evaporation and small returns to surface and groundwater via infiltration and runoff (Ruddell, 2018), and because rural runoff is not part of the DMR database, we observe a null discharge line for this sector.

3.6 Conclusions

Analysis of the compiled data shows that in the period FY2009 to FY2017 monthly indirect water reuse ranged from 3% to 134% in a water rich region of the Midwestern U.S. The data show a clear seasonal pattern of indirect water reuse greater than 30% during August to October and less than 20% from January to May. Indirect water reuse greater than 100% occurred four times during the time series analysis, meaning that in those months the surface water resources of the watershed were used and reused extensively, in a downstream cycle through the basin. Essentially, a flow of water equal to or greater than that leaving the watershed at its confluence with the Ohio River was being pumped through facilities within the watershed during these months.

Reported treated wastewater discharges in the watershed showed a declining trend throughout FY2009 to FY2017, with an estimated reduction of 37% caused mainly by a significant drop in wastewater discharges from power generation facilities (down 46%). Water withdrawals, an indicator of water use, also showed a declining trend over time, down an estimated 31%. State-collected significant water withdrawals data and EPA DMR discharge data show a significant correlation, indicating that reported wastewater discharge volume data can be used for estimations of water use, a relationship that has not been explored previously.

Results from this study demonstrate that the reported volumes of treated wastewater discharges and significant withdrawals comprise an important amount of data currently available for water-related analysis at the watershed scale. The dataset could be improved by collecting incomplete or missing reports, and by including minor facilities not required to report. However, in terms of watershed management, and for planning purposes, the data available seems to be sufficient to quantify water use and indirect reuse by different sectors. Results show the impact that major changes in the thermoelectric power sector (reduction or pause of operations, change of technology, etc.) have in the anthropogenic water cycle. Water use data should be more easily available for resource managers to evaluate the impact of installing new water-using facilities or to consider irrigation permit allocations. Furthermore, analyses of (real) reported data over time, would be valuable information for water managers in planning any new water infrastructure. There are important economic implications, as water infrastructure costs are heavily conditioned on flow rates (Ruddell, 2018).

We also show the relevance of combining datasets to address regional and national water resources management questions, which could not be evaluated otherwise. This is important as the current situation of the surface waters in the U.S. should be carefully studied and considered before implementing direct water reuse initiatives. Despite suggestions that there is significant capacity to expand water reuse in the country (Martin and Via, 2020), not all the potential sources of water for reuse (e.g. municipal wastewater, surface and groundwater withdrawals for agriculture and industry, stormwater, etc.) will be viable. As described in our results, these waters are already part of an anthropogenic water cycle that sustains downstream water uses and the surrounding ecosystems. Considering future climate change scenarios for the Midwest, it is expected that summers will be drier, and there will be increased precipitation in winter and spring months, with increased streamflow during these months (Mishra et al., 2010). Streamflows in the Wabash River basin are expected to become more seasonally variable. Increases in precipitation intensity and frequency in spring months likely will increase nutrient runoff, which combined with potentially warming water will adversely affect water quality, with increased potential for algal blooms and depleted dissolved oxygen. Extended periods with little precipitation in warmer months could harm sensitive species such as Indiana's endangered freshwater mussels (Höök et al., 2018). Therefore, it is relevant to identify areas of the watershed where intensive water use and reuse could negatively impact the natural environment, particularly during low-flow months.

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3.8 APPENDIX A: SUPPLEMENTARY FIGURES AND TABLES

Table A.1. Supplementary data and example calculation for Wabash Watershed's outlet streamflow estimation, for the FY2009.

	Gauging Station #	3378000	3378550	3377500	3381500	HUC 05120113 Lower Wabash	Wabash Outlet
	Name	Bompass creek at Browns, IL	Big creek near Wadesville, IN	Wabash at Mt.Carmel, IL	Little Wabash at Carmi, IL		
	Drainage Area (km2)	591	269	74164	8034	2507*	
		Monthly mean measured flow (m^3/s)				Estimated flow (m^3/s)	Total flow (m^3/s)
2008	October	0.01	0.10	164.69	12.43	1.62	178.85
2008	November	0.20	0.19	189.84	13.45	2.28	205.96
2008	December	4.28	0.73	553.88	49.36	13.45	621.69
2009	January	0.67	0.13	869.89	62.50	7.85	941.04
2009	February	14.81	3.25	1599.90	213.96	53.30	1885.22
2009	March	1.36	1.16	1201.20	34.69	9.14	1247.55
2009	April	21.79	4.55	2027.20	303.84	76.56	2433.93
2009	May	20.73	8.35	2585.04	324.23	88.96	3027.31
2009	June	4.19	2.04	1309.09	153.39	28.20	1496.89
2009	July	6.64	3.75	571.43	72.46	28.57	682.86
2009	August	0.84	0.72	560.96	17.11	5.20	584.83
2009	September	7.22	0.43	279.66	27.88	14.46	329.65

* Estimated remaining contributing area

Table A.2. EPA ICIS NPDES wastewater discharges. Sum of Q1-Average reported values from facilities along the 0512 Wabash River Watershed, on a monthly basis for the period FY2009-FY2017, in m3/s.

Sum of Q1 - AVG wastewater discharges (m^3/s)

# Facilities	**Fiscal Year**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Annual Average**
1155	**2009**	153	152	164	151	152	146	158	144	177	185	191	168	**162**
1146	**2010**	160	152	162	162	160	141	155	168	**199**	192	184	170	**167**
1130	**2011**	138	132	148	142	148	159	155	176	183	191	190	171	**161**
1111	**2012**	158	159	162	132	124	117	106	132	158	152	154	144	**142**
1103	**2013**	127	137	137	148	140	138	130	140	169	169	159	158	**146**
1093	**2014**	133	126	131	131	133	130	127	146	180	163	172	156	**144**
1083	**2015**	130	127	126	115	111	111	118	153	177	171	149	143	**136**
1071	**2016**	125	127	126	121	119	125	105	99	139	141	146	116	**124**
1105	**2017**	**87**	96	103	101	92	91	91	119	112	122	102	106	**102**

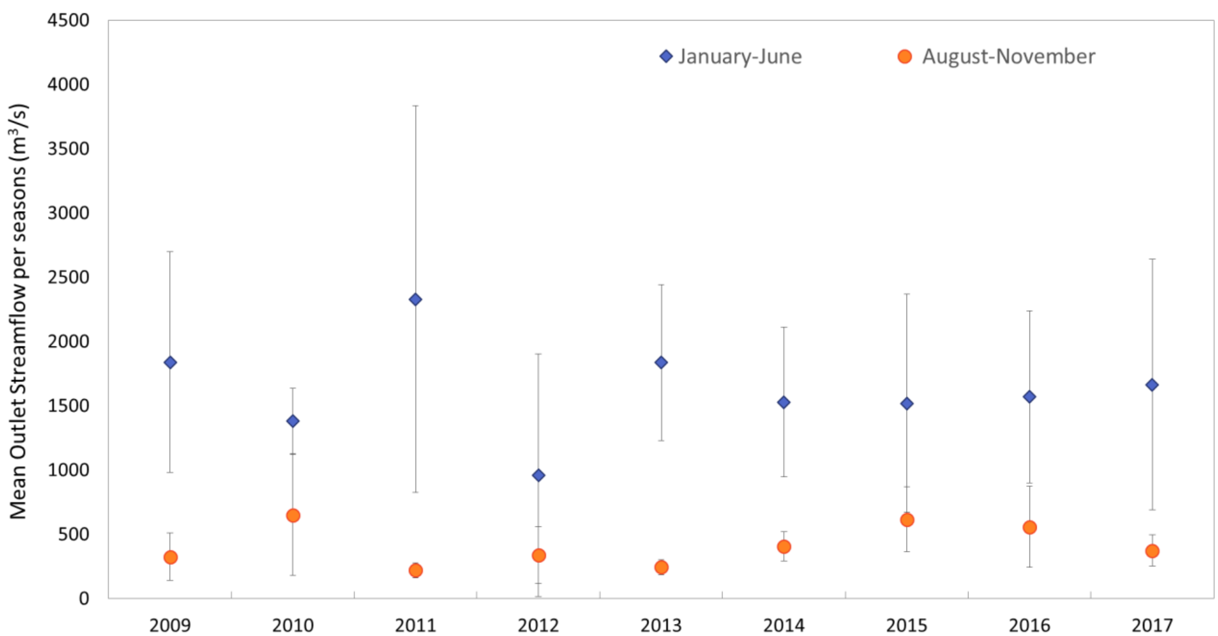

Figure A.1 Mean Streamflow, considering high flows period January- June and low flow period August-November, by year for the period FY2009-FY2017.

Table A.1. Average Indirect Water Reuse rate estimated at the Wabash Watershed outlet, for the period FY2009-FY2017. The months of low flow are from July to November (Shaded columns).

IWR -Average

Fiscal Year (FY)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
2009	86%	74%	26%	16%	8%	12%	7%	5%	12%	27%	33%	51%
2010	15%	15%	11%	14%	16%	9%	12%	11%	11%	16%	54%	108%
2011	106%	52%	41%	31%	17%	5%	6%	4%	9%	17%	75%	71%
2012	58%	25%	6%	7%	8%	12%	17%	21%	87%	134%	128%	45%
2013	43%	55%	42%	8%	10%	8%	6%	7%	10%	12%	59%	98%
2014	50%	31%	10%	9%	12%	9%	5%	10%	16%	33%	43%	29%
2015	18%	23%	10%	10%	18%	5%	5%	18%	8%	6%	17%	48%
2016	64%	27%	12%	5%	12%	7%	6%	7%	22%	18%	15%	19%
2017	18%	24%	15%	6%	11%	9%	7%	3%	9%	9%	26%	53%

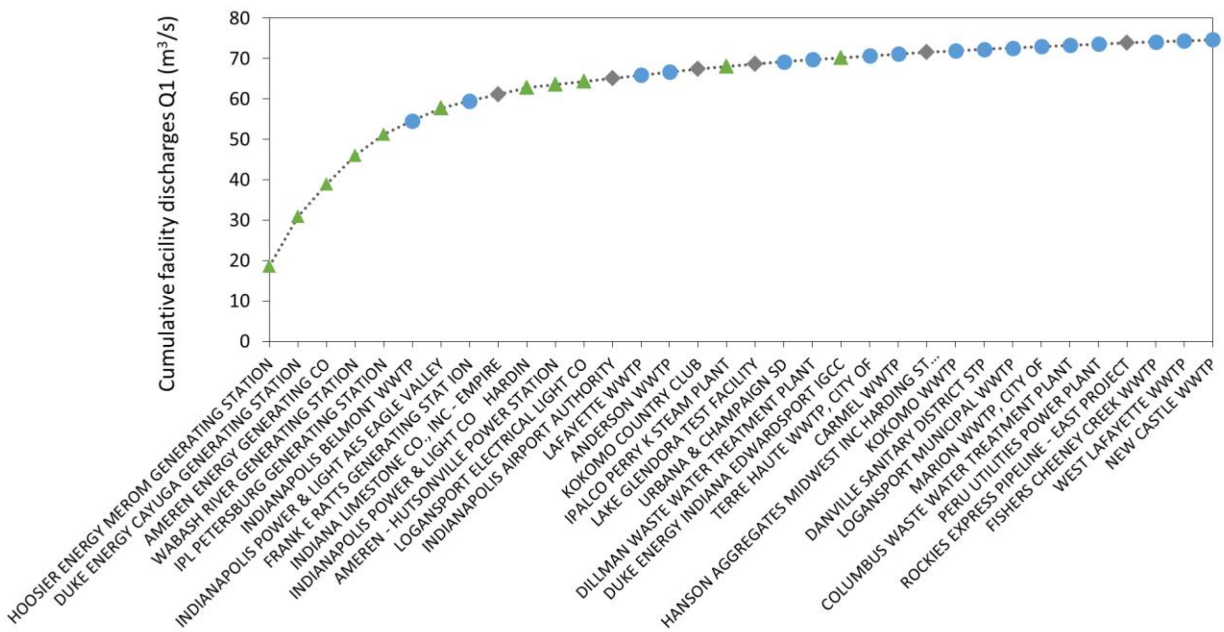

Figure A.1. Cumulative sum of Q1-average DMR reported wastewater discharges per individual facilities over the period FY2009-FY2017. Symbols represent the type of facility as follows: power plants are represented with green triangles (▲), Publicly Owned Treatment Plants are represented with solid blue dots (●), industries are represented with grey diamonds (◆)

Table A.2. Adapted from U.S. Energy Information Administration, 2019. Inventory of Retired Generators as of April 2019.

Entity Name	Plant ID	Plant Name	Plant State	Generator ID	Nameplate Capacity (MW)	Net Summer Capacity (MW)	Net Winter Capacity (MW)	Technology	Retirement Month	Retirement Year
Duke Energy Indiana, LLC	1004	Edwardsport	IN	6	35.0	40.0	40.0	Petroleum Liquids	3	2011
Duke Energy Indiana, LLC	1004	Edwardsport	IN	7	40.2	45.0	45.0	Conventional Steam Coal	3	2011
Duke Energy Indiana, LLC	1004	Edwardsport	IN	8	69.0	75.0	75.0	Conventional Steam Coal	3	2011
Ameren Energy Medina Valley	863	Hutsonville	IL	3	75.0	75.0	76.0	Conventional Steam Coal	12	2011
Ameren Energy Medina Valley	863	Hutsonville	IL	4	75.0	76.0	78.0	Conventional Steam Coal	12	2011
Ameren Energy Medina Valley	863	Hutsonville	IL	D1	3.0	3.0	3.0	Petroleum Liquids	12	2011
City of Peru - (IL)	955	Peru (IL)	IL	IC1	6.3	6.0	6.0	Petroleum Liquids	12	2011
Indianapolis Power & Light Co	990	Harding Street	IN	3	43.8	35.0	35.0	Petroleum Liquids	6	2013
Indianapolis Power & Light Co	990	Harding Street	IN	4	43.8	35.0	35.0	Petroleum Liquids	6	2013
Indianapolis Power & Light Co	990	Harding Street	IN	GT3	26.0	10.0	10.0	Petroleum Liquids	6	2013
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	2	46.0	39.0	39.0	Petroleum Liquids	6	2013
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	ST1	46.0	39.0	39.0	Petroleum Liquids	6	2013
Hoosier Energy R E C, Inc	1043	Frank E Ratts	IN	1	116.6	110.0	115.0	Conventional Steam Coal	3	2015
Hoosier Energy R E C, Inc	1043	Frank E Ratts	IN	2	116.6	100.0	105.0	Conventional Steam Coal	3	2015
City of Logansport - (IN)	1032	Logansport	IN	4	18.0	16.5	16.5	Conventional Steam Coal	1	2016

Table A.4 continued

Entity Name	Plant ID	Plant Name	Plant State	Generator ID	Nameplate Capacity (MW)	Net Summer Capacity (MW)	Net Winter Capacity (MW)	Technology	Retirement Month	Retirement Year
City of Logansport - (IN)	1032	Logansport	IN	5	25.0	22.0	22.0	Conventional Steam Coal	1	2016
City of Logansport - (IN)	1032	Logansport	IN	6	18.0	15.0	17.0	Natural Gas Fired Combustion Turbine	1	2016
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	3	50.0	40.0	40.0	Conventional Steam Coal	4	2016
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	4	69.0	56.0	57.0	Conventional Steam Coal	4	2016
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	5	69.0	62.0	63.0	Conventional Steam Coal	4	2016
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	6	113.6	99.0	100.0	Conventional Steam Coal	4	2016
Indianapolis Power & Light Co	991	Eagle Valley (IN)	IN	IC1	2.7	3.0	3.0	Petroleum Liquids	4	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	2	112.5	85.0	85.0	Conventional Steam Coal	4	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	3	123.2	85.0	85.0	Conventional Steam Coal	4	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	4	112.5	85.0	85.0	Conventional Steam Coal	4	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	5	125.0	95.0	95.0	Conventional Steam Coal	4	2016
Wabash Valley Power Assn, Inc	57842	Wabash Valley Power IGCC	IN	1	112.5	85.0	85.0	Petroleum Coke	5	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	6	387.0	318.0	318.0	Conventional Steam Coal	12	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	71	2.7	3.0	3.0	Petroleum Liquids	12	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	72	2.7	3.0	3.0	Petroleum Liquids	12	2016
Duke Energy Indiana, LLC	1010	Wabash River	IN	73	2.7	2.0	2.0	Petroleum Liquids	12	2016

Table A.3. Major Power generating Facilities situation

NPDES Number	Name	FY 2009 Avg monthly Discharges (m^3/s)	FY2017 Avg monthly Discharges (m^3/s)	% change	Retired Generators Date (Year-Month)*	Verified status as of FY2017
IL0076490	Raccoon creek power plant	0.0	0.0	-100%		OPERATING
IN0004693	Indianapolis power & light aes eagle valley	6.2	0.0	-100%	2013-Jun, 2016-Apr	CHANGED TECHNOLOGY
IN0041246	Logansport electrical light co	0.7	0.0	-100%	2016-Jan	REMOVED
IN0044130	Peru utilities power plant	0.5	0.0	-100%	2011-Dec	REMOVED
IN0004391	Frank e ratts generating stat ion	8.7	0.0	-100%	2015-Apr	OPERATING
IL0004120	Ameren - hutsonville power station	3.2	0.0	-100%	2011-Dec	REMOVED
IN0002810	Wabash river generating station	20.8	0.3	-99%	2016-Apr, May, Dec	REMOVED
IN0002780	Duke energy indiana edwardsport igcc	2.0	0.2	-92%	2011-Mar	OPERATING
IN0063134	Wabash valley resources llc	0.0	0.0	-80%	2016-May	REMOVED
IN0062138	Hoosier energy lawrence co station	0.0	0.0	-75%		OPERATING
IN0002801	Duke energy indiana - noblesville generating station	0.0	0.0	-70%		OPERATING
IN0004677	Ipalco perry k steam plant	1.6	0.5	-68%		OPERATING
IN0004685	Indianapolis power & light co hardin	4.7	1.9	-60%	2013-Jun	CHANGED TECHNOLOGY
IL0049191	Ameren energy generating co	27.1	14.0	-48%		PARTIALLY SHUT DOWN
IN0002887	Ipl petersburg generating station	15.7	11.9	-24%		OPERATING
IN0050296	Hoosier energy merom generating station	19.7	17.0	-14%		OPERATING
IN0061361	Henry county generating station (duke)	0.0	0.0	-7%		OPERATING
IL0004057	Vermilion power station (duke)	0.0	0.0	1%	2011-Nov	OPERATING
IN0060950	Pseg lawrenceburg energy llc	0.1	0.1	3%		OPERATING
IN0002763	Duke energy cayuga generating station	22.6	26.0	15%		OPERATING
IN0060844	Sugar creek generating station	0.0	0.1	37%		OPERATING
IN0038806	Crawfordsville energy llc	0.0	0.0	44%		OPERATING

*Note: Retirement of generators does not necessarily mean cease of operations but upgrades, changes in technology or partial shutdown of power plants

Table A.4. EPA ICIS-NPDES data, Facilities Counts, by Fiscal Year

	Facilities Counts				**Facilities Counts**		
	(Based on Facility Data)				**(Based on Facility and Permit Data)**		
Reporting Fiscal Year	**All Facilities**	**Majors**	**Non-Majors**	**With Facility Info Only**	**With Facility and Permit Data**	**Majors**	**Non-Majors**
2009	1565	124	1441	242	1323	123	1200
2010	1542	124	1418	238	1304	123	1181
2011	1549	123	1426	248	1301	121	1180
2012	1623	122	1501	341	1282	121	1161
2013	2107	122	1985	825	1282	121	1161
2014	3323	123	3200	2043	1280	122	1158
2015	4545	123	4422	3282	1263	122	1141
2016	5861	123	5738	4611	1250	122	1128
2017	7017	122	6895	5779	1238	122	1116

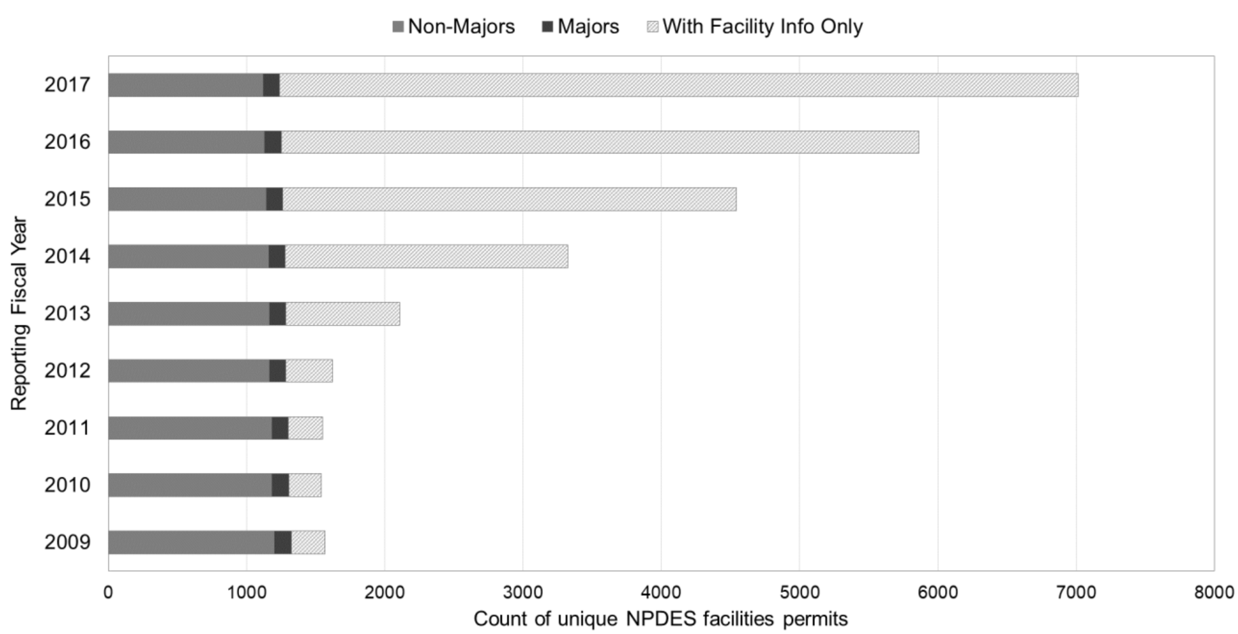

Figure A.2. EPA ICIS- NPDES data, Facilities permits Counts, Minor and Major with discharging data, and with facilities info only, by Fiscal Year

Table A.5. Water Withdrawals Data Compilation and characterization

STATE		#FACILITIES	# EXTRACTIONS	
			wells	Intakes
IN		2032	1763	446
OH		15	11	5
IL	PWS	101	268	19
	Non-PWS	Unknown	158	15
TOTALS			2201	485

Table A.6. Sum of IN SWWF Withdrawals, OH withdrawals, and IL IWIP withdrawals, for the Wabash Watershed, on a monthly basis for the period FY2009-FY2017, in m3/s.

Sum of Significant water withdrawals (m^3/s)

Fiscal Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual Average
2009	122	151	159	154	145	141	129	126	169	185	197	175	**155**
2010	147	143	142	154	150	126	137	153	180	190	197	174	**158**
2011	141	141	151	143	138	135	121	146	176	203	**207**	173	**156**
2012	155	149	142	121	126	125	111	140	187	181	167	139	**145**
2013	124	130	122	132	134	121	109	136	160	173	173	157	**139**
2014	125	120	128	131	135	121	107	137	181	178	181	150	**141**
2015	124	125	124	118	119	106	109	124	158	161	163	149	**132**
2016	130	136	119	115	122	116	109	96	136	136	138	113	**122**
2017	92	97	105	96	95	85	**83**	107	130	134	129	117	**106**

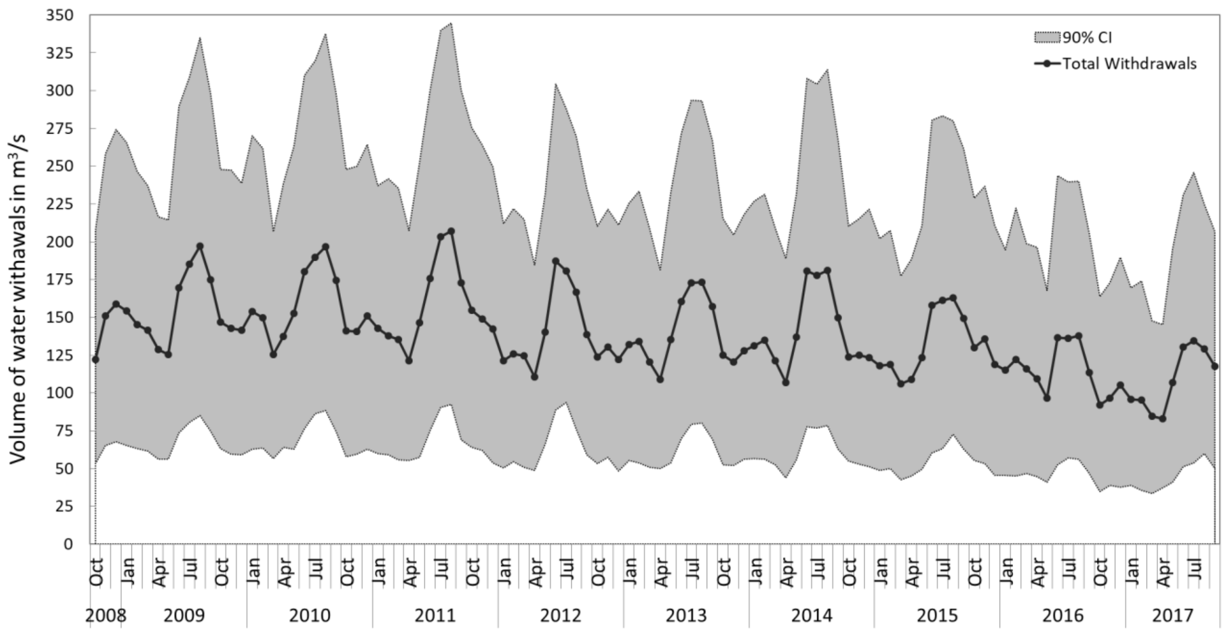

Figure A.3. Sum of significant withdrawals (black solid line) and estimated 90% CI (shaded area) for the Total Withdrawals, on a monthly basis for the period FY2009-FY2017, in m3/s.

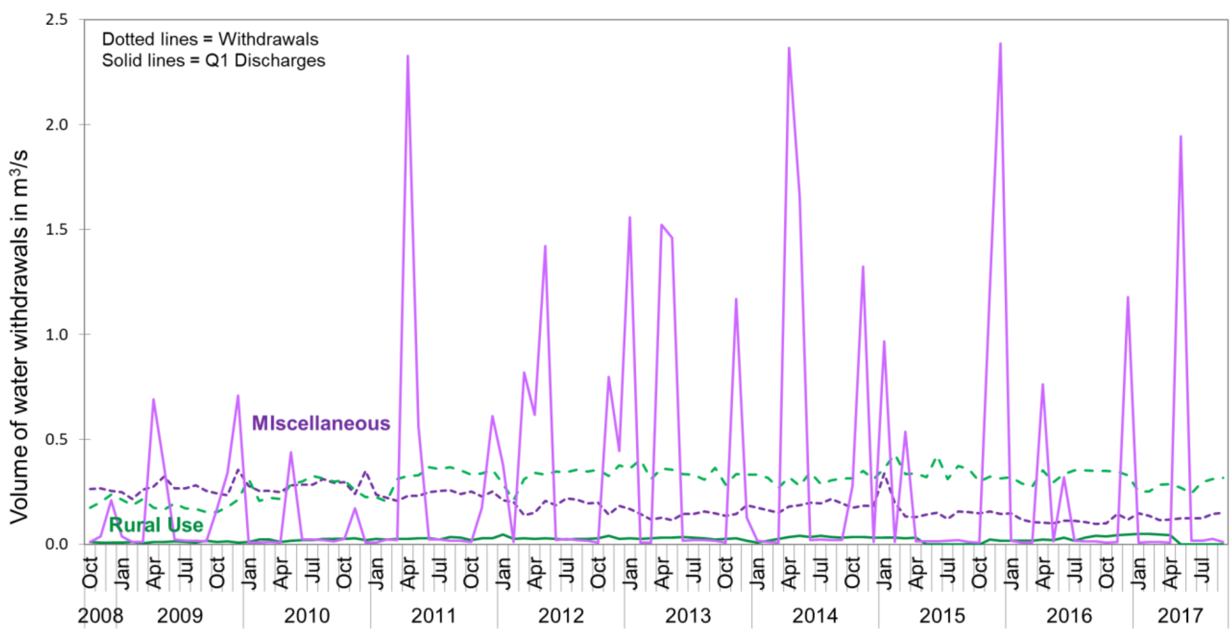

Figure A.4. Time series of significant water withdrawals (dotted lines) and wastewater discharges (solid lines) for water use categories Miscellaneous (purple) and Rural Use (green), in the Wabash Watershed, for the period FY2009-FY2017.

4. THE FUTURE OF MEASURING, REPORTING, AND VISUALIZING LARGE-SCALE WATER DATA: INSIGHTS GLEANED FROM EXISTING METHODS

Submitted for publication in the journal Water Research's Making Waves

4.1 Abstract

Despite U.S. federal and state agencies collecting and publishing water data regularly, it is an uncoordinated effort, making it difficult to answer basic research or management questions. The water data of the nation (especially those involving the anthropogenic water cycle) currently are dispersed among heterogeneous databases making aggregation for large scale watershed analysis tedious and time consuming. As a result, all these data on water extractions and point source discharges only serves regulatory purposes, as its collection and dissemination were not intended for secondary use for research or resources management. Since real data provides better information than models, estimates, or forecasts, and because current technology allows for real time water data acquisition, visualization, and analysis, federal and state water institutions should work together to rapidly move in such direction to help address current and future water demands and issues. Accordingly, we describe attributes of existing reported water datasets and the limitations encountered when integrating these data for large scale water use analysis. We list five major areas that need improvement, that if rapidly developed, would significantly advance our nation's ability to better measure, report, manage, and disseminate the large-scale water data that currently is collected in such a disparate manner. These five improvements are to: i) Develop coordination among agencies managing water, ii) revisit regulations that impede access to water data, iii) deploy existing sensing and communication technology for real-time data collection, iv) enable computational and visualization tools for data analysis, and v) enable access to water data for the public and research community. We expect that making advances in these areas would not only significantly advance U.S. water resources information analysis and dissemination, but should also be considered internationally, especially when designing new water infrastructure and monitoring systems, and particularly when international watersheds are under consideration.

4.2 Introduction

How much water is being used and reused in the United States (or in any country) and for what purposes? This simple question has no simple answer because there is no up-to-date national accounting of how and where water is used in each regional watershed or at the national scale. Every five years the U.S. Geological Survey (USGS) does report on water-use within eight major categories at the county scale, however, this timeframe and resolution impede the use of the data for watershed scale seasonal analysis, or for real-time integration with databases from other disciplines such as for economic forecasting or timely decision making (Ruddell et al., 2020). Furthermore, because of USGS does not distinguish the self-supplied water withdrawals by manufacturing subsector, these water intakes at the national, state, and county-levels must be estimated using international data (Rao et al., 2019). This limits the ability to estimate supply chain or indirect water use for the production of goods and services in the United States (Blackhurst et al., 2010). Nationwide, thermoelectric power plants are responsible for almost half of the annual water withdrawals, however the U.S. Energy Information Administration (EIA) collects and publishes self-reported cooling water usage on an annual basis only, yielding an incomplete database of U.S. thermoelectric power water use (Peer and Kelly, 2016). Lastly, there is no official accounting for treated wastewater volumes discharged into U.S. surface waters. The U.S. Environmental Protection Agency (EPA) National Permit Discharge Elimination System (NPDES) program regulates point sources that discharge pollutants to waters of the country, and collects and reports a set of required measurements taken by the regulated entities on a monthly basis. However, the purpose of the data collected is for tracking permit compliance and enforcement on water quality parameters, with little attention to the volumes discharged other than the "monthly average flow rate." As a result, in some cases researchers have used facility "design flows" as estimates of actual flows (Rice et al., 2013).

This lack of easy access to basic water data seems inexplicable in times of Big Data, sensor networks, and the Internet of Things (IoT), which currently provides immediate feedback and information for decision making. If we have cell phone location data to detect highway congestion, smart homes systems to reduce energy consumption, reporting of hundreds of millions of votes within hours of national polls closing, and a list of other integrated sensor network systems for the 21st century, the collection, integration, and real time assessment of water data should rapidly proceed to such a state, especially given the fact that at most locations where measurements are desired, the primary infrastructure (e.g., Parshall flumes) already exist. Moreover, rapid advancements are occurring in sensor technology development for physical, chemical, and biological constituents within waterbodies. An obvious outcome of high temporal data collection is the ability to observe short time-scale changes in water quality and allow for immediate analysis and visualization, which facilitates real time decision making. Indeed, Pellerin et al. (2016) stated: "Sensors and associated physical and cyberinfrastructure — the telecommunications, collection platforms, data standards, and data management tools required to transform data into information in a timely manner — are becoming increasingly important for water quality monitoring and associated water resources management decisions."

Then, why do we not have a network of water quantity and quality sensors placed in NPDES reporting facilities that actually report in real or near-real time the data that are required of them to report? "Continuous nutrient monitoring has a history of use in the wastewater industry, allowing for real-time control of processes in treatment plants" (Pellerin et al., 2016). If water quantity and quality data are already being monitored in real-time by regulated facilities, enforcement authorities are missing valuable data by requesting only monthly "average" values. "The United States (U.S.) environmental regulatory system relies heavily on self-reports to assess compliance among regulated facilities. However, the regulatory agencies have expressed concerns regarding the potential for fraud in self-reports and suggested that the likelihood of detection in the federal and state enforcement processes is low" (Beiglou et al., 2017). For the public good, when it is possible, water use data should be collected continuously and automatically, and integrated with computational and visualization methods in real-time for analysis and compliance purposes. It is feasible at this point in time to augment the nation's existing infrastructure to provide immediate access to real-time data for more precise water resources management and evaluation. Furthermore, both permitted withdrawal facilities and point source discharging facilities constitute a large network of water users nationwide. If a sensor network system of reported data existed, many regional or nationwide issues of concern, such as the current COVID19 pandemic whose virus is being identified in Publicly Owned Treatment Works (POTWs) sludge (Peccia et al., 2020), could be informed and more soundly managed by access to these data.

4.3 Identified Reported Water Data Limitations

A shift to monitoring and reporting water use and reuse into the U.S. in real time, requires that a comprehensive understanding of the current state of the science be evaluated. In two previous publications, we analyzed water use and indirect water reuse at the HUC8 watershed scale. We completed a study integrating existing reported data of water withdrawals and point source discharges (Wiener et al., 2016). The main reason to incorporate reported data in the analysis was to have more accurate results. Point source discharges and withdrawals are subject to fluctuations due to economic, social and environmental factors, such as the weather, holidays, and productivity. Therefore, analyses that considered only design flows of POTWs rather than measured data, miss real month to month variations and seasonal effects on the returned flows to the surface streams. We experienced the challenges of combining available datasets to address regional and national water resources management questions that could not be approached otherwise. The process of data collection and analysis from disparate databases obtained from multiple state and federal government agencies was time consuming and tedious. As secondary users, we found that there are currently major limitations and obstacles to using the available U.S. water data for water resources research (Figure 1), including:

- **Regulatory Restrictions.** Some data have regulatory restrictions regarding collection, use, and publication. For example, in Illinois, the reporting of significant withdrawals is not mandatory, and private facilities' withdrawal data are considered confidential (Illinois Department of Natural Resources, 2020) which creates significant limitations for data publication or use for any water research.
- **Lack of Coordination.** Water data do not share a general, unified set of parameter definitions nor a standardized use of units for data collection and publication. Among state and federal water agencies, the differences in terminology and methods used to compile the different datasets, make it time consuming to combine the datasets for watershed scale analysis. Hence whole datasets often require translation to make them compatible with one another. This is the case of significant withdrawals data, which are collected by state agencies, and all are organized differently because there is no federal coordination, despite some efforts by the USGS to do so. Moreover, even if coordination occurred successfully among all federal agencies, data collection often depends on state reporting requirements, such as point source discharge data under the EPA NPDES program, where inconsistencies

exist among the state agency databases. For example, our first water-use and indirect-reuse analysis was performed on the Wabash River watershed because it only involved three states, and the data on withdrawals and point source discharges were reasonably complete. However, we were unable to scale up the analysis to the entire Ohio River watershed as it involved 14 states that were not consistent in reporting NPDES data to the U.S. EPA, and each state has a dissimilar system to collect water withdrawals information. In the case of point source discharges, it is possible that in the near future, due to the implementation of the EPA Electronic Reporting Rule (U.S. Environmental Protection Agency, 2015), the NPDES Discharge Monitoring Report (DMR) data for the nation will allow for an extension of the analysis performed in our first study to other watersheds and regions of U.S., including the entire Ohio River watershed. A final point regarding parameter definitions, is that even within a single database, parameter definitions are often vague. For example, the NPDES DMR database contains more than 60 pollutant parameters that contain the word "FLOW" in the label, however there is no clear definition regarding which of these parameters specifically refer to the flow of wastewater discharged to surface receiving streams. In addition, the same database provides a definition of average and maximum quantities (Q1, Q2) that are open to interpretation, which can create a database with ambiguous, lower quality data, as even the data providers may not fully understand under which parameter to place the data.

- **Limited Scope Underlying Data Collection.** The collection of monthly "average" facility discharge data satisfies agency-specific regulatory purposes, however it sharply curtails meaningful application of the data for resource management and scientific discovery (i.e., important and necessary secondary uses). For example, the EPA DMR database was not designed for the purpose of measuring water flows and therefore it has no clear account of the actual quantities of point source wastewater discharged. However, the system does collect data on wastewater flows, under various parameters and timescales. Thus, we highlight the opportunity for improving the discharge monitoring reports to specifically measure data on quantities of wastewater discharged by different types and sizes of facilities. Incorporating a specific, defined, parameter for return flows (i.e., volumes) in the database on a much shorter time scale (i.e., daily) would be a strong addition to the NPDES program. A greater contribution would be to publish near real-time data on flows that return to the surface waters in U.S. (i.e., 15 minute intervals).

- **Spatial Resolution.** Water data are collected and organized according to political boundaries, limiting the ability to directly perform analyses on any given watershed. This is particularly true when a basin covers parts of more than one state. For example, in 2013 the Ohio River Valley Water Sanitation Commission published a report on water use in the Ohio River basin (The Ohio River Valley Water Sanitation Commission, 2013) by compiling USGS water data sets from 2005. They specifically described the limitations and challenges of aggregating data organized by county to approximate "watershed" water use. The difficulty of reorganizing water data reported on a county basis to conform to watershed boundaries begs the question why some water data, currently being reported to state and national agencies within artificial governmental boundaries, do not include the necessary metadata information so that these data can be rapidly associated with natural watershed boundaries. Most anthropogenic influences occur at watershed scales, not point scales (Ruddell, 2018), and so it would be relevant for research and management purposes to be able to rapidly organize data on a watershed basis to allow for immediate applied use and research analysis.
- **Data Completeness and Robustness.** Major facilities (e.g., POTWs) that serve 10,000 people or more, receive more regulatory attention because they would have a larger impact on receiving waters, if not controlled. State agencies collect water withdrawal data mainly from significant facilities. Therefore, water databases contain more and better information on large water users. However, in the case of point source dischargers, minor facilities account for 10 to 20% of the volumes of return flows (Wiener et al., 2020). Thus, it is relevant to collect and analyze data from minor facilities to increase the accuracy of any analysis. However, sometimes reporting is voluntary and/or not enforced, so it is rare to achieve 100% completeness. Sometimes facilities do not report at all, so permanent data gaps remain which are not reconcilable.
- **Temporal Resolution.** Across databases, the data are rarely collected and reported at the same temporal frequency. Indeed, for some databases, different facilities are required to report at different time scales (i.e., monthly, quarterly, yearly) which contributes to difficulty in compiling, integrating, and analyzing the data, and this creates obvious data

gaps. Data collected on an annual basis may provide an indication of order-of-magnitude flow, but lacks any relevance regarding seasonal variability, or even typical daily variability, and clearly loses the resolution necessary to correlate with other economic, social and environmental data.

- **Database Design.** Other data limitations occur with changes in database structure over time, and the form in which the data are compiled. Some databases change their structure with each new version (e.g., change of header names or change the order of columns). These changes might be considered trivial, but when combining data over long periods of time, they require considerable effort to ensure data integrity. This discourages use of multiple-year water databases, which is why we suggest they should be consistent and maintain some formal structure over time.
- **Data Curation.** Despite the extensive effort performed by agencies to curate the data, existing databases contain many errors related to manual entry and paper reporting, parameter interpretation, unit transformations, etc. This is particularly true for older records. Electronic reporting, and implementation of newly developed database management and processing tools should be applied to improve data quality.

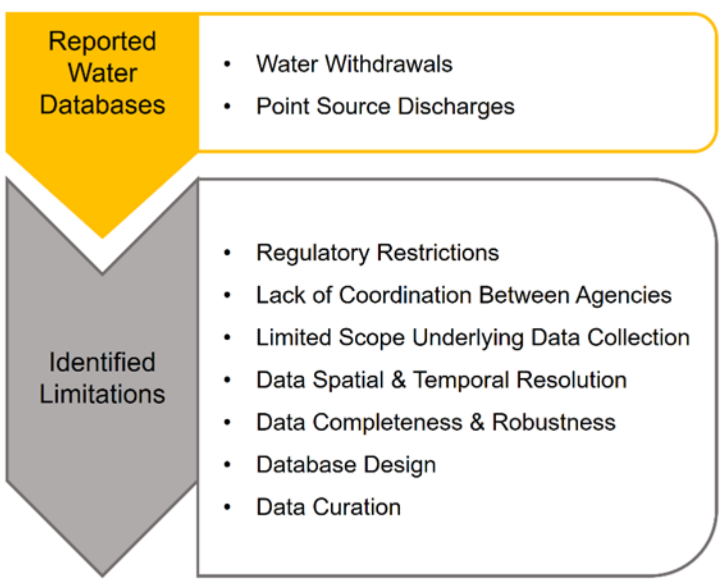

Figure 4.1. Identified limitations in current reported water databases.

4.4 Proposed advancements

Based on lessons learned through integration and analysis of existing water data, below we list some suggestions for improving water data collection, management, and dissemination in the U.S. and elsewhere (Figure 2). Importantly, the list is our attempt to address current limitations with a forward-thinking view of what is possible with technology that exists today.

- Coordination among state and federal agencies needs to be formalized for the purpose of developing a national water database. The Water Quality Portal (https://www.waterqualitydata.us/) is as an example where various agencies do share their data on water quality for the nation. In this time of regional water scarcities, water quantity (i.e., flow) is also important, but not considered in this "water quality" portal. Hence, it is vital that volumes of water withdrawals and wastewater discharges be included, led by the USGS and EPA which currently coordinate the compilation of water withdrawals and point source discharges data by all the states.
- U.S. institutions should revisit water data regulations with respect to reporting requirements, especially taking into consideration the quantity of data that is already measured but not reported. Large POTWs and power plants certainly have sophisticated sensors and measurement systems in place to support operations management, yet they are only required to report a monthly value for many parameters. Thus, a tremendous amount of information is lost that may be valuable and of future interest to water resource managers and planners, and to the public.
- Incorporate technology for real time reporting and publishing of data, both for withdrawals and discharges. Sensor technology currently is available to measure, electronically archive, analyze, and create real time notifications and data visualizations. Reporting facilities should be tasked with instrument and sensor calibration (and reporting) such that high quality data can be reported in real time through internet tools that compile data over both political and watershed boundaries. Because archived data would be easily accessible, it would surely be used for many purposes.
- Consider secondary users' needs in the design of new archival databases and visualization tools. In addition to regulatory and compliance purposes, there exists significant untapped value in the data for water resources management and basic research that would be enabled by making the data available on the world-wide-web.

- Water data portals should include built-in tools to allow for data visualization and instant data analysis. Currently, EPA is working on a dashboard and ECHO tools for water quality data, but there are no plans for publishing flow or other water discharge data. USGS does excellent work on publishing near real-time data from natural stream gauging stations across the country, offering raw data and various graphical forms. It seems logical to integrate into such tools similar access to NPDES facility wastewater discharge data. This would provide for more direct incorporation of anthropogenic water cycle data into hydrological water cycle models, for refined calibration and analysis, by making the data easily available to research communities (e.g., CUAHSI HIS).

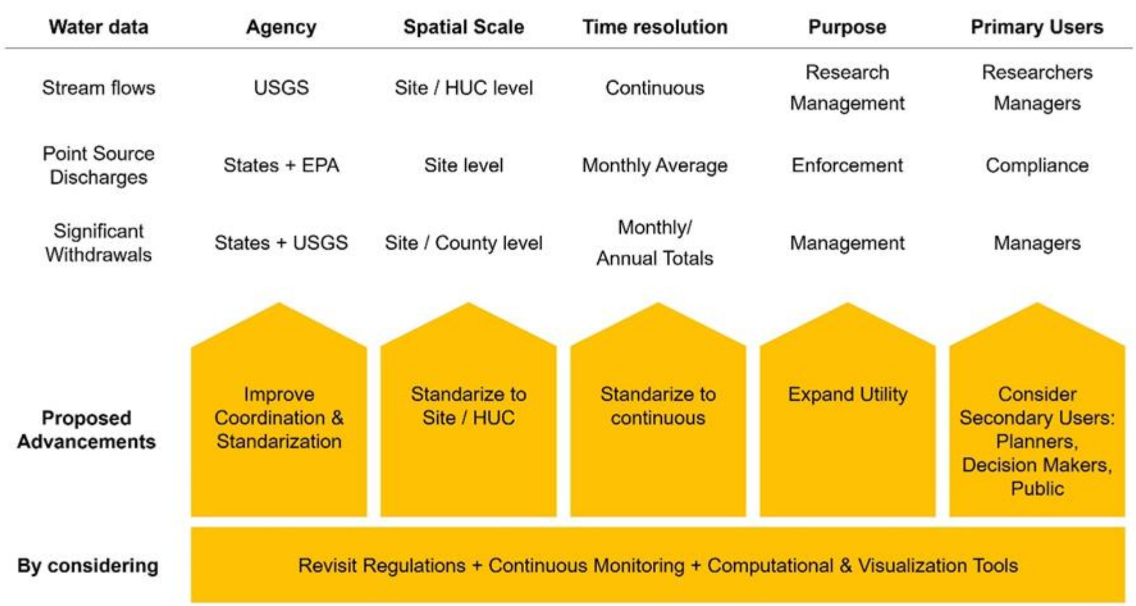

Figure 4.2. Current methods for large scale water data design, collection and management and proposed advancements needed.

4.5 Concluding Remarks

- Water use data collection, management, visualization, and sharing in the U.S. needs to improve at a fast pace to help address current and future water issues.
- There exists a large amount of reported water data, available through federal and state agencies, that is not currently being used effectively for water research and resource management. The existing water data are, in some cases, of sufficient quality to provide

preliminary estimates of water use and indirect reuse until better data collection and reporting methods are developed and implemented. The existing water data are not currently widely used. This is likely because the way in which it is collected was designed for the sole purpose of regulatory use, with little consideration given to secondary uses.

- The active use (i.e., analysis) of data is critical for identifying new ways for improving its collection, organization, and visualization, for more robust future use. As secondary users, scientists and engineers can help to identify issues with databases and queries that agencies would not have identified otherwise.
- These new methods should be adapted and improved upon by other countries, particularly as emerging economies build new water infrastructure or when international watersheds are under consideration. The cost of incorporating measurement and monitoring hardware in new infrastructure comes at a minimal cost, yet will have long term value in helping address water resource limitations and needs.

4.6 References

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5. CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The results of this research study demonstrate that current levels of water use and indirect reuse in the Wabash River basin are significant. As larger areas contribute to the downstream flow, more facility effluents contribute to the river's flow, and the fraction of indirect water reuse (IWR) displays a greater seasonal variation. The occurrence of high IWR coincides with a time of the year when the surface streams have reduced flow and the demand for fresh water is increased. During the low flow months, humans use and pump, on average, the equivalent of the entire flow of the Wabash River through NPDES facilities. Additionally, an IWR fraction greater than 100% means that some of the water is being used and reused more than once along the watershed. Results show the impact that major changes in the thermoelectric power sector (reduction or pause of operations, change of technology, etc.) have in the anthropogenic water cycle. There is also an obvious potential for radical hydrologic alteration in the event of changes in the current water use portfolio, such as diversion of wastewater for reuse in consumptive landscape or crop irrigation. Prospective well-meaning water recycling projects to reuse wastewater should carefully consider the effects this could have on the current watershed hydrology and the watershed's ecosystem needs.

State-collected significant water withdrawals data and EPA DMR discharge data show a significant correlation, indicating that reported wastewater discharge volume data can be used for estimations of water use, a relationship that has not been explored previously. Results from this study demonstrate that the reported volumes of treated wastewater discharges and significant withdrawals comprise an important amount of data currently available for water-related analysis at the watershed scale. Results also show the relevance of combining datasets to address regional and national water resources management questions, which could not be evaluated otherwise. There are rich and massive data assemblages on water use that could be employed for sophisticated and beneficial understanding and management of these water resources. However, these data are archived in discrete databases with incompatible units; inconsistent classifications; varied structural, temporal, and spatial organization; and are maintained by different state and federal agencies. Integrating and organizing the data for simple analysis, such as the water reuse calculations provided in this study, reveals challenges that make the process time consuming and not amenable to automation. Furthermore, analyses of (real) reported data over time, would be valuable information for water managers in planning any new water infrastructure. Water use data collection, management, visualization, and sharing in the U.S. needs to improve at a fast pace to help address current and future water issues. There are five major areas that need improvement: i) Develop coordination among agencies managing water, ii) revisit regulations that impede access to water data, iii) deploy existing sensing and communication technology for real-time data collection, iv) enable computational and visualization tools for data analysis, and v) enable access to water data for the public and research community.

5.2 Future Work and Recommendations

5.2.1 Extend analysis to other watersheds

The methodology and analysis presented in this study could be extended in time and space to cover most U.S. watersheds, at different HUC scales. It would be of particular interest for areas where water scarcity and severe drought are a current issue or future threat, or areas where infrastructure projects could significantly alter the allocation of water resources. Such extension of the analysis is subject to the limitations in point source wastewater discharge data from many states, which is incomplete or contains substantial data quality issues. However, it is possible that in the near future, due to the implementation of the EPA Electronic Reporting Rule (US Environmental Protection Agency, 2015), the DMR data for the nation will allow for an extension of the analysis performed in this research work to other watersheds and regions of US.

5.2.1.1 Limitations for scale up

The present research work was initially motivated by the question of how many times the water of the Mississippi river is used and reuse along the path from Lake Itasca, Minnesota, to the Gulf of Mexico; information that is currently non-existent but could be approached considering the methodology proposed. Since the Wabash River Watershed is a HUC04 sub-basin from the Ohio River, estimating indirect water reuse at the sub-watershed, region and whole watershed level would "scale-up" the magnitude of the analysis of utilization of water resources in the Mid-west.

There was an attempt to perform the indirect reuse calculation for the Ohio River Watershed for the year 2010. This basin comprises the 05-Ohio and 06-Tennessee hydrological regions, which include 18 HUC04 sub-basins and intersect 13 different states. The major limitation encountered in the process was the DMR data completeness. Estimates indicated that for the year of analysis 2010, the Upper Ohio states had missing data for 90% of the facilities listed in the database, what made preliminary results unreliable. There were also major data quality issues, including geocoding coordinates that differ from point source discharging location, inconsistent reporting of parameters, incomplete reports, and more, what made working with such database tedious and time consuming. However, it is expected that the NPDES DMR database improves over time and, thanks to electronic reporting, achieves higher rates of reporting, increasing completeness and data quality. Therefore, it is recommended that a large scale analysis, e.g. the Ohio River Basin, is attempted with the most up to date data possible. It would also be beneficial to partner with EPA officials to guaranty access to complete data and get the necessary support to understand their complex database.

Completing a water use analysis and point source discharges and freshwater withdrawals water balance at a larger scale could also be challenging. Because water withdrawals data is collected and administered at the state level, to assess water extraction in e.g. the Ohio River Watershed requires to collect and aggregate all the withdrawals data from, at least, 6 state agencies. In the case of the entire Mississippi River Basin, it includes parts or all of 31 states and 2 Canadian Provinces. Then, it is recommended to obtain some partnership or support from USGS to assist in the collection and aggregation of the water use data when the watershed of interest intersects with a large number of states.

5.2.2 Integrate results with ArcGIS tools

This study used a discrete model to estimate Indirect Water Reuse at the outlet of the Wabash River watershed, because it is a simple and direct way to use the available wastewater discharge data. By integrating this data with a geospatial tool, a continuous model could be developed to represent the indirect water reuse at every point of the surface streams of the basin.

5.2.3 Including additional elements in the analysis

There are elements of the natural and human water cycle that could be incorporated in the analysis to achieve a more complete water balance study. Possible future lines of research that would complement the present study, improve the IWR calculation, and advance in the understanding of a watershed water resources dynamics include: estimating runoff contributions to surface streamflow, quantifying the surface supplementation from groundwater withdrawals, and measuring the share of interbasin transfers (Dickson et al., 2020) in the watershed water use budget.

5.3 References

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VITA

Maria Julia Wiener was born and raised in Neuquén, Patagonia Argentina. She received her Industrial Engineer degree from Universidad Nacional de La Plata (UNLP). She started her academic and researcher experience at UID Gestión Ambiental at UNLP. She moved to West Lafayette, IN, to pursue her dream of graduate education abroad, and joined the Ecological Sciences and Engineering Program. She was awarded the Purdue Cyber Center Special Incentive Research Grant (SIRG). She received her M.S.E. She was Graduate Assistant at the Purdue Women in Engineering Program. She was selected as the recipient of the Emily M. Wadsworth Graduate Mentoring Award. Her first publication was selected for the Purdue Policy Research Institute's Excellence in Research Award.

Her research interest include reported water data, water use, indirect water reuse, point source waste water discharges, water withdrawals, anthropogenic water cycle, and urban solid waste management.