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Time series analysis of water use and indirect reuse within a HUC-4 basin (Wabash) over a nine year period

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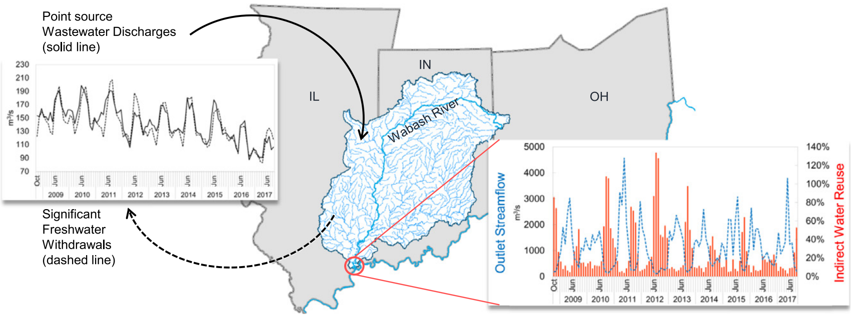
HIGHLIGHTS

- Anthropogenic water use and indirect reuse are key components of the water cycle.
- We combined existing databases of reported data to estimate water use and reuse.
- The Wabash basin indirect water reuse ranged from 3% to 134% with a seasonal pattern.
- Reported treated wastewater data could be used to estimate water use.
- Reported water use data reflects major natural and anthropogenic events.

GRAPHICAL ABSTRACT



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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.

1. 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

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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 >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 >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).

1.1. 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 >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.

2. Material and methods

2.1. Area of study and timeframe

The Wabash River watershed (Fig. 1) is a 4-digit Hydrological Unit Code (HUC) basin, #0512, comprising 85,237 km^2, 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/km^2 (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.

2.2. 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.

2.3. Data & analysis

2.3.1. Outlet streamflow

The U.S. Geological Survey (USGS) National Water Information System provides monthly statistics for surface water sites across the nation

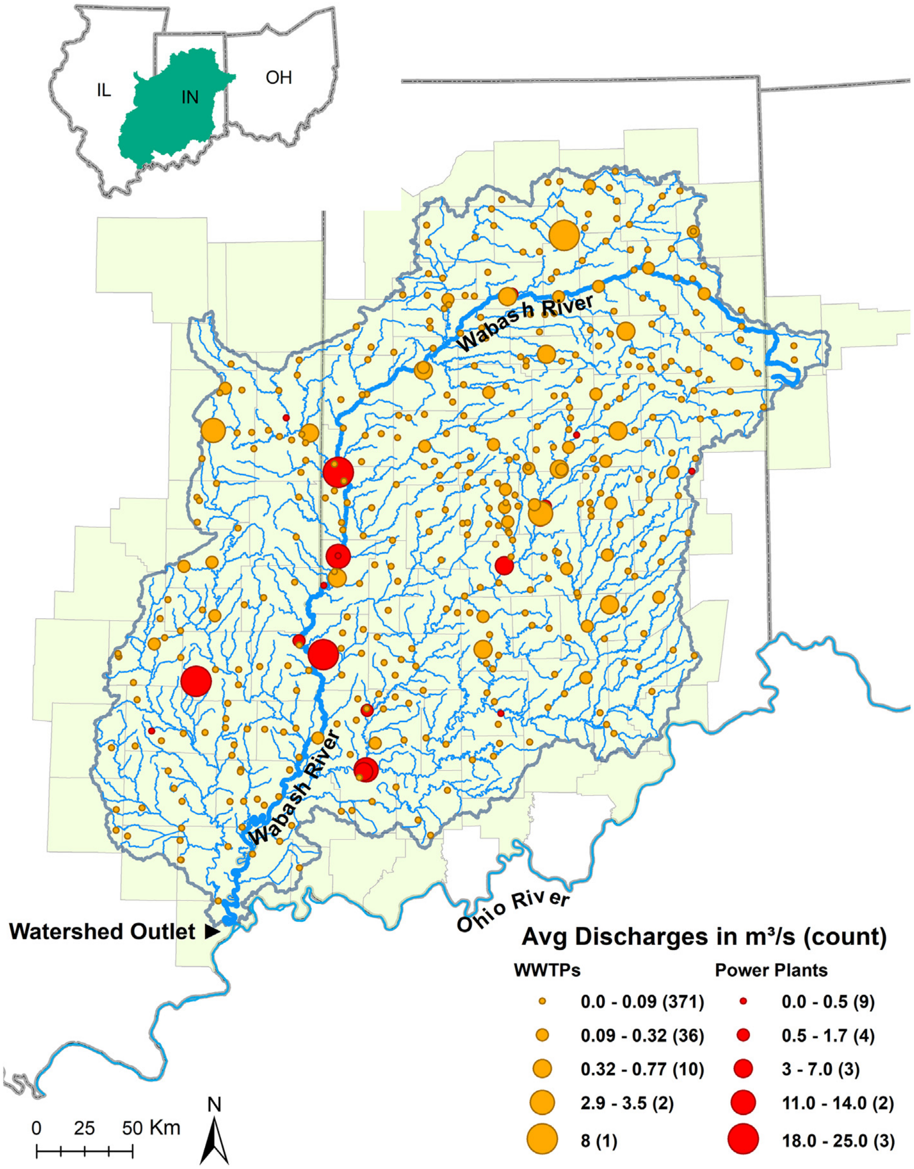

Fig. 1. Map of the HUC 0512 - Wabash River Watershed showing the locations of watershed outlet, SIC code 4911-Power Plants, and SIC code 4952-WWTPs. The size of the points corresponds to average discharge in m^3/s. The legend includes the number of facilities at each size category. For a map showing locations of most significant water withdrawals and major and minor NPDES permitted discharges in 2007 see Wiener et al., 2016.

(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).

2.3.2. 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 include 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 m^3/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 in the data. Negative values and values on the order of thousands of MGDs (equivalent to 43.81 m^3/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 m^3/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, for any given 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, N_d points from the underlying distribution (where N_d 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 N_d times, generating an N_d estimation. Finally, we sorted them and picked the $0.05^*N_d^{th}$ and $0.95N_d^{th}$ points, generating the 90% CI.

2.3.3. 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 >100,000 gal per day (equivalent to 0.0044 m^3/s) (ODNR, 2018).

The Illinois Water Use Act of 1983 (525 ILCS 45) requires reporting withdrawal rates of 70 gal per minute (equivalent to 0.0044 m^3/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 2072 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 Commission, 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 m^3/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. Results & discussion

3.1. Outlet streamflow

For the period of analysis, the estimated outlet streamflow time series is plotted in Fig. 2a. The river presents a wide fluctuation through the period with average estimated streamflow of 1150 m^3/s, with a minimum of 114 m^3/s (July 2012) and a maximum of 4566 m^3/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 (Fig. A-1). The lowest streamflows recorded during the period of analysis, 114 m^3/s and 121 m^3/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.

3.2. 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 Fig. 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: $\beta_1 = -0.554$, $R^2 = 0.85$, p-value $= 2.64E{-}40$) which confirmed a declining trend for average reported flows. The average Q1 was 143 m^3/s of total wastewater discharges for the watershed, ranging from a minimum of 87 m^3/s (October 2016) to a maximum of 199 m^3/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 1110 facilities with Q1 data, decreasing from 1155 in FY2009 to 1105 in FY2017 (Table A-2).

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 Fig. 3, we plot the mean Q1 per 3-month seasons, for every year in the time series. We observe mean Q1 ranged from 112 m^3/s to 192 m^3/s during the warmer months and from 91 m^3/s to 154 m^3/s during the cold months, which confirms the two distinguishable periods.

3.3. 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 (Fig. 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 (Fig. 2a).

3.4. 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 1211 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 (Fig. 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 (Fig. 4a), there is a clear trend of 46% reduction of reported discharges ($\beta_1 = -5.69E{-}01$, $R^2 = 0.88$, 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

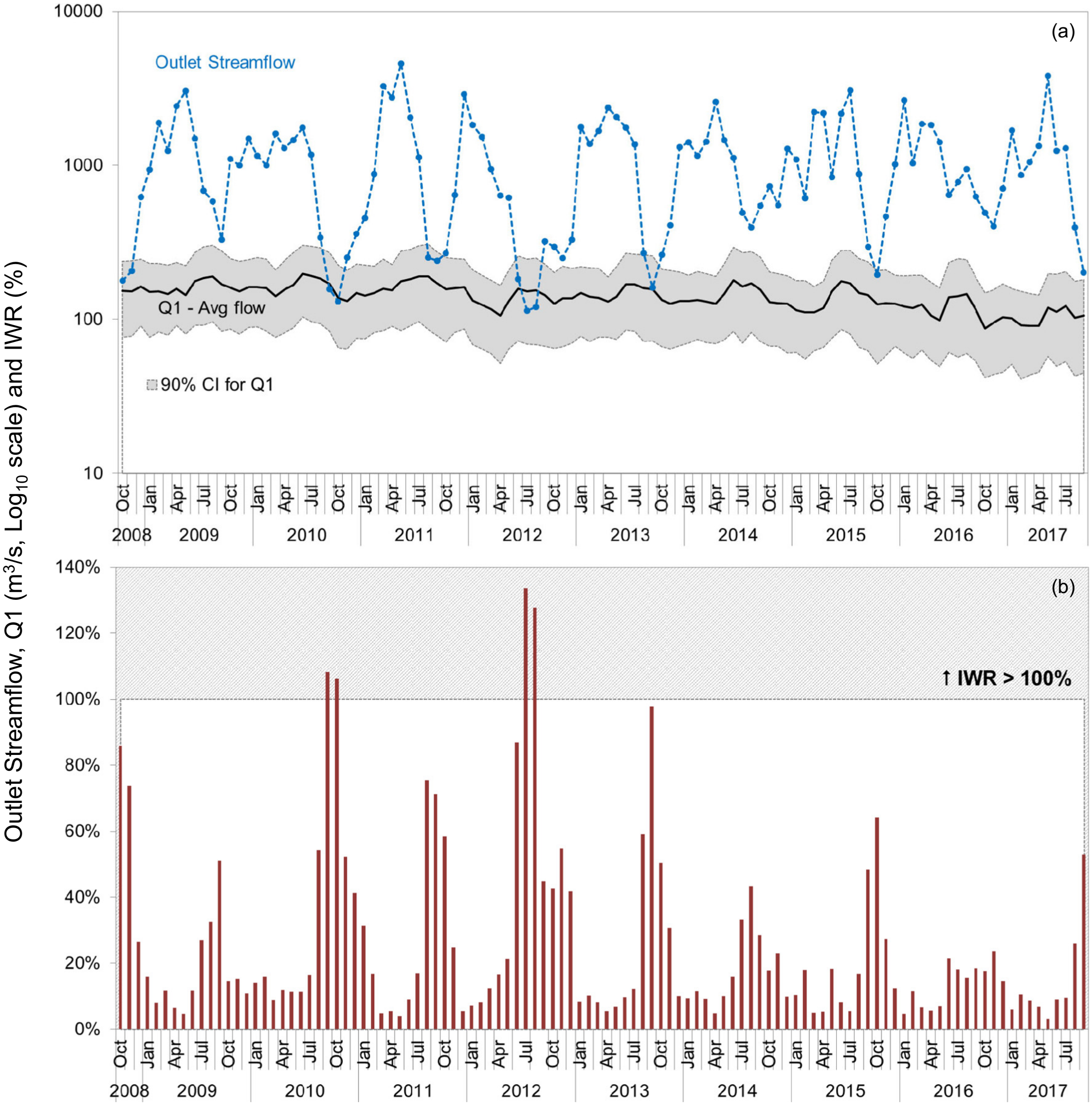

Fig. 2. (a) Estimated monthly mean streamflow at the outlet of the Wabash River basin, sum of Q1-average discharges, and estimated 90% CI (shaded area), on a monthly basis, for the period FY2009–FY2017, in m^3/s. Note the vertical axis is in Log_{10} scale to allow visualization of both outlet streamflow 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.

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 (Fig. 4b) with an average discharge of 24 m^3/s, a minimum of 15 m^3/s, and a maximum of 39 m^3/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 1565 in FY2009 to 7017 in FY2017 (Table A-6, Fig. 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 1323 in FY2009 to 1238 in FY2017. Also, because NPDES DMR is focused on contaminant loads,

Fig. 3. Average Q1 per seasons, considering cold months February to April and warm months June to August, by year, for the period FY2009–FY2017.

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. 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 2032 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 2686 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 (Fig. 4a) and estimated the 90% CI (Table A-8, Fig. 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 Fig. 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 m^3/s, ranging from 83 m^3/s in April 2017 to 207 m^3/s in August 2011 (Fig. 4a). Overall, we observe a decreasing trend of total fresh water withdrawals over time ($\beta_1 = -4.88E{-}01$, $R^2 = 0.85$, 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 ($\beta_1 = -4.84E{-}01$, $R^2 = 0.83$, p-value $=$ 7.46E−38) and a slight decrease of water withdrawals for public supply ($\beta_1 = -1.50E{-}02$, $R^2 = 0.67$, p-value $= 3.87E{-}24$) (Fig. 4b). However, there is an increase in water withdrawals for industry ($\beta_1 = 1.30E{-}02$, $R^2 = 0.24$, p-value $= 5.49E{-}07$) in the latest years (Fig. 4b) and also a slight increase in seasonal water withdrawals for irrigation (IR) (Fig. 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 (Fig. 4b, c).

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 (Fig. 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 m^3/s, and no clear trend or seasonal patterns for either series (data shown in Fig. A-5). In Fig. 4a, both total Q1 discharges and total withdrawals follow the same seasonal pattern. The correlation between the curves is high, obtaining a value of $\rho = 0.89$ (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,

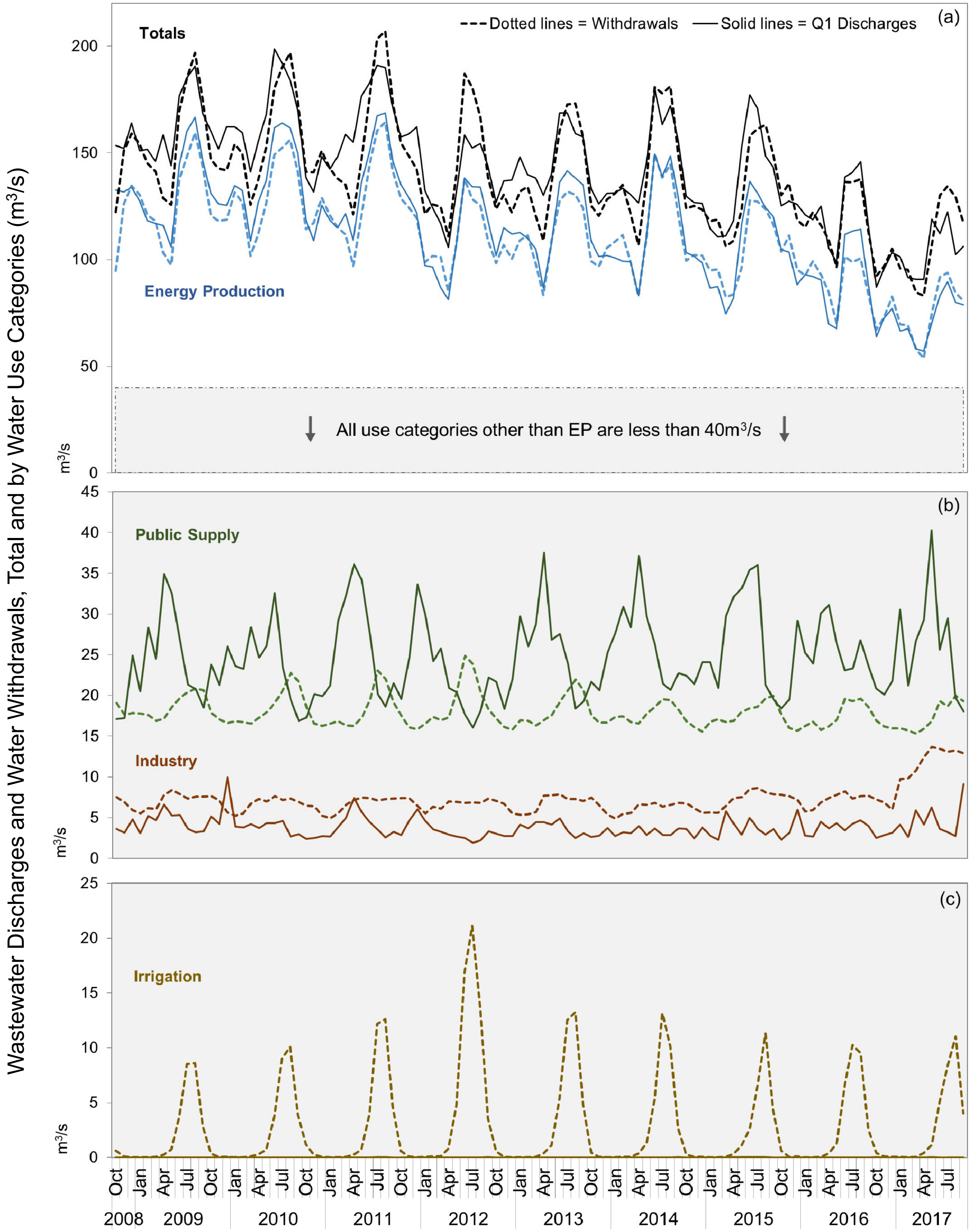

Fig. 4. Sum of Q1 average wastewater discharges (solid lines) and total water withdrawals (dotted lines) for the period FY2009–FY2017. (a) Total and by water use category EP-energy production; (b) PS-public supply and IN-industry discharges and total water withdrawals; (c) IR-irrigation total water withdrawals. Not shown: rural and miscellaneous uses are <0.5% total.

Table 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 (m^3/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		
Energy Production	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%
Public Supply	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%
Industry	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%
Irrigation	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%
Rural Use	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%
Miscellaneous	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%

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 (Fig. 4a). Water withdrawals for EP ranged from 53.8 m^3/s (April 2017) to 164.5 m^3/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.

Withdrawals in the Public Supply sector (Fig. 4b) ranged from 15.3 m^3/s (April 2017) to 24.9 m^3/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 m^3/s (January 2011) to 13.7 m^3/s (May 2017) (Fig. 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 m^3/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 (Fig. 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 m^3/s and the maximum of the series was 21.1 m^3/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.

4. 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 >30% during August to October and <20% from January to May. Indirect water reuse >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.

CRediT authorship contribution statement

M. Julia Wiener: Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing - original draft. **Sebastián Moreno:** Methodology, Formal analysis, Software, Writing - review & editing. **Chad T. Jafvert:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Loring F. Nies:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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