Modeling and Prediction of Watershed-Scale Dynamics of Consumptive Water Reuse for Power Plant Cooling

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Final Report: Modeling and Prediction of Watershed-Scale Dynamics of Consumptive Water Reuse for Power Plant Cooling

SUMMARY OF PROBLEM AND RESEARCH OBJECTIVES

The energy-water nexus – the relationship between energy and water resources – is an area of emerging concern among resource managers, policy makers, and academics [1-6]. Of particular interest in Illinois is the overlap between thermoelectric power plants, which require cooling to condense process steam, and water resources. In Illinois, thermoelectric power plants (using primarily coal and nuclear fuels) account for over 85% of freshwater withdrawals [7]. Since many of those facilities use open-loop (or once-through) cooling with lower consumptive demands, they only consume an estimated 2% of the water withdrawn [8]; however, nationwide water consumption data have not been reported since 1995.

As water resources endure strain from additional demands and changing climate, researchers and resource managers have considered use of alternative water supplies, such as reclaimed water from municipal wastewater treatment plants (WWTPs) [9-11]. Reclaimed water can be a drought-resistant, non-potable water source for power plants, decreasing water demand conflicts with other users and reducing thermal loading on major rivers, such as the Illinois River with several power plants in series. However, since reclaimed water use typically requires cooling towers instead of open-loop cooling, water reuse for power plants could increase water consumption via evaporation along with additional capital cost for infrastructure.

Our work modeled water reuse at select thermoelectric power plants in Illinois, and estimated the watershed-scale dynamics of additional water consumption. While water reuse for power plants can be a beneficial water management approach locally, the additional water consumption might have significant negative impacts downstream for other water users, including navigation. To model and quantify these conditions, we completed the following research objectives in the study area shown in Figure 1 and described in Table 1:

1. Evaluate the degree of de facto water reuse at power plants in the study area, based on the incidental presence of wastewater effluent in the natural water source.
2. Determine the geographic and technologic feasibility of using reclaimed water to cool existing power plants in the study area.
3. Create a hydrologic model of the study area watersheds to simulate the dynamic downstream impacts of retrofitting reclaimed water to cool power plants.

Table 1. The study area power plants have varying characteristics and costs to retrofit. Results have been rounded.

				Water Withdrawals		Retrofit to Cooling Towers		
Name	Capacity (MW)	Fuel	Existing cooling system	Open loop (MGD)	Closed loop (MGD)	Capital Cost (10^6 US$)	Annual Treatment Cost[b] (10^6 US$)	Total Annual Cost (10^6 US$)
Will County	898	Coal	Open-loop	607	7.5	US$81	US$4.29	US$9.57
Joliet 9	360	Coal	Open-loop	263	2.1	US$33	US$0.76	US$2.91
Joliet 29	1,320	Coal	Open-loop[a]	956	12.0	--	US$2.71	US$2.71
Braidwood	2,450	Nuclear	Open-loop	1,850	87.6	US$1,770	US$24.8	US$140
Dresden	2,020	Nuclear	Open-loop[a]	1,440	68.9	--	US$31.5	US$31.5
Kendall County	1,260	Natural Gas	Closed-loop	--	0.2	--	US$0.09	US$0.09

4. [a] Has facilities to operate as closed-loop but primarily utilizes open-loop cooling.
5. [b] Estimated as $984 per million gallons [12].

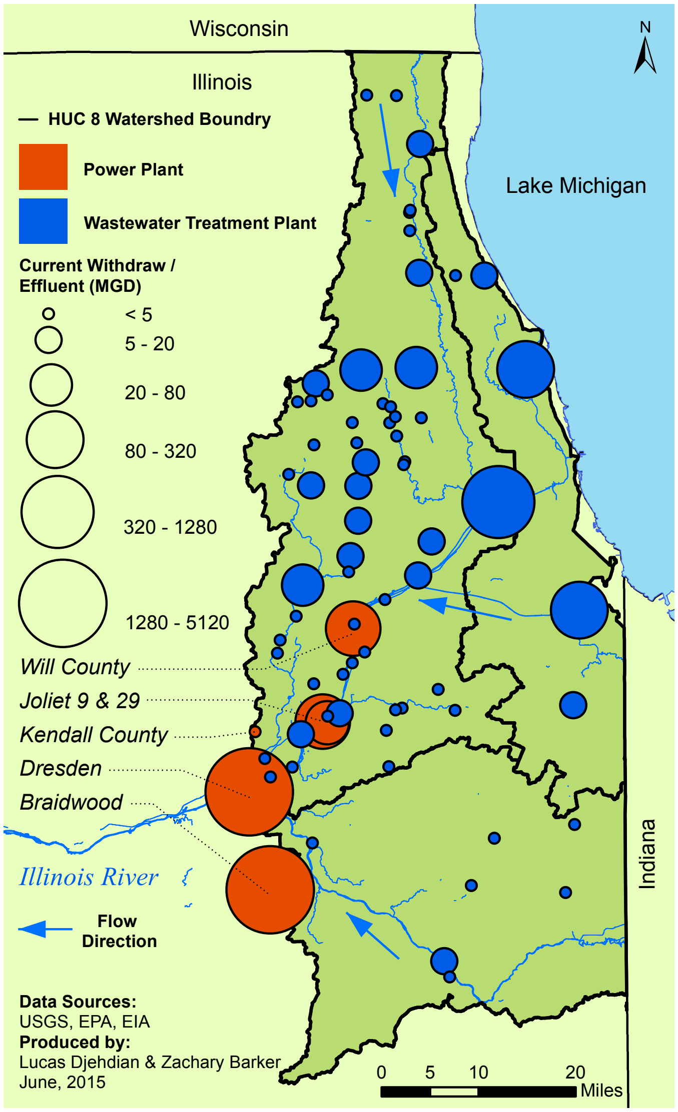


Figure 1. The Greater Chicago Area includes 72 wastewater treatment plants and 6 power plants. Of the power plants, 5 operate primarily by open-loop cooling which cumulatively withdraw more water than the wastewater produced and are located on the downstream side of the study.

SUMMARY OF METHODOLOGY

We used the following high-level methodology to address the project's research objectives:

1. Evaluation of de facto water reuse at power plants.

Using historic streamflow levels for the Des Plaines and Kankakee Rivers, serving as the current sources of cooling water for power plants in the study area, we quantified the current level of de facto water reuse at existing thermoelectric power plants. De facto water reuse is typically evaluated as a ratio of cumulative upstream discharge from WWTPs to instream flow, as demonstrated by Rice et al. for different percentiles of streamflow, which vary throughout the year [13]. We used the quantified de facto water reuse as the baseline current conditions representing power plant cooling operations.

2. Determination of feasibility of reclaimed water use at power plants.
Considering the de facto water reuse baseline, we then determined the geographic and technologic feasibility of retrofitting power plants in the study area to use reclaimed water in closed-loop cooling towers. This feasibility analysis used a GIS-based hydroeconomic model [11] combining land use [14] and elevation raster data [15] with power plant [16,17] and WWTP [18] data to determine the least cost path of a pipeline to deliver reclaimed water to a power plant from surrounding WWTP(s). The least cost path represents the best pipeline route that minimizes capital costs, and was selected with a genetic algorithm to simulate possible pipeline routes between facilities. Output from the GIS-based hydroeconomic model indicates the least cost feasible sources of reclaimed water for a given power plant.

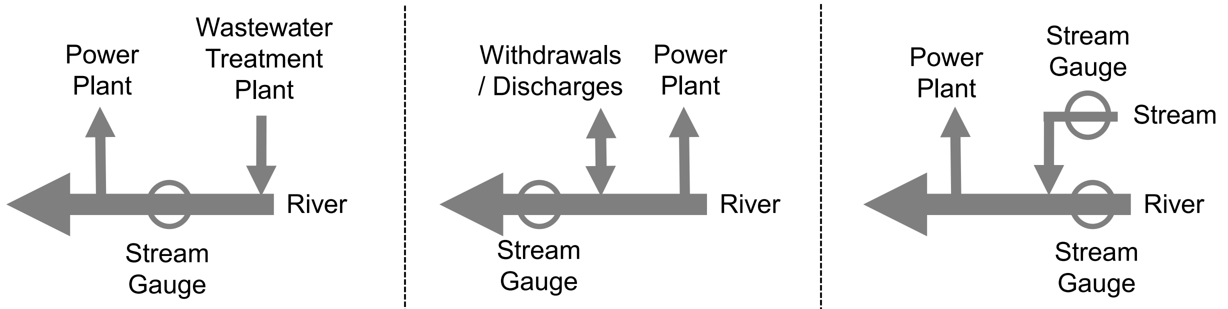
3. Development of a hydrologic model to simulate downstream impacts of water reuse.
Using reclaimed water to cool power plants can help mitigate the impacts of water disruptions (such as droughts and heat waves); however, consumptive use of water that was previously returned to a waterway can have negative downstream impacts on streamflow, especially when supporting navigation. To understand the dynamic impacts of consumptive water reuse, we developed a hydrologic model of streamflow in the study area and in the Illinois River downstream. This statistics-based mass conservation model synthesized historical streamflow records with estimated changes in WWTP discharge and power plant withdrawal and consumption to predict streamflow at various gauge points downstream. Downstream flow was estimated based on historical data from the U.S. Geological Survey (USGS) with different water reuse consumption scenarios. We performed statistical hypothesis testing of output from the downstream impacts model to reveal any statistically significant changes in streamflow as a result of upstream consumptive water reuse.

MAJOR FINDINGS

De facto water reuse at power plants
Using flow data from USGS gauging stations in the study area and wastewater effluent averages, we calculated the median de facto reuse at each power plant. Although a straightforward calculation, the spatial aspects of the data are important. For our small urban watersheds, quantifying de facto reuse requires consideration of any discharges, withdrawals, or engineered operations of the waterways. In a few instances, discharges or withdrawals exist between the stream gauge and power plant. Figure 2 illustrates one of these instances (panel (B)) where a wastewater treatment plant might discharge downstream from a stream gauge. Under this condition, we include the wastewater effluent in the numerator and denominator of the de facto calculation (using Equation 1) since the upstream gauge does not account for its flow.

$$\%\ de\ facto\ reuse = \frac{\sum_{all\ i} q_{w,i}}{q_s} \tag{1}$$

where q_w is the wastewater effluent from an upstream wastewater treatment plant i and q_s is streamflow at the point of withdrawal, both in similar units. We use similar mass balance logic for instances where two streams merge or the nearest gauge is downstream from the power plant.



A. The basic de facto reuse calculation divides all wastewater effluent upstream by the streamflow.

B. Withdrawals or discharges occurring between the power plant and nearest stream gauge must be accounted for.

C. Power plants not sufficiently close to a gauge measuring streamflow might require combining data from multiple gauges.

Figure 2. This hypothetical diagram illustrates the need to account for withdrawals and discharges that occur after the stream gauge and before the power plant in both the numerator and denominator of the de facto reuse calculation.

In the City of Chicago, as well as many older cities, the storm and sanitary sewers are combined, which is an important consideration in calculating de facto reuse. During large storm events, stormwater combined with sanitary wastewater can overwhelm wastewater treatment infrastructure, causing a combined sewer overflow (CSO). Since wastewater bypasses the treatment plant (and, therefore, measurement), we did not have sufficient data to calculate de facto reuse during a CSO event; in response, we removed data associated with CSOs.

We used the medians of the remaining data to calculate the de facto reuse at each power plant. The Will County power plant has the largest median de facto reuse at 65% while the two Joliet and Kendall County power plants are at 55% and 25%, respectively. (The two Joliet power plants are adjacent and therefore have the same de facto calculation.) The two nuclear power plants, Dresden and Braidwood, have de facto reuse less than 0.5%, due to withdrawals from the Kankakee River, a primarily agricultural basin that does not include large quantities of wastewater discharge. We can explain these results as a function of proximity to the large Metropolitan Water Reclamation District of Greater Chicago (MWRD) wastewater treatment plants. Following the waterway downstream, the de facto reuse percentage decreases because the catchment area contributes more streamflow while discharges from smaller wastewater treatment plants have minor effects.

We analyzed daily wastewater effluent and streamflow data from the MWRD and the USGS, respectively, between the years 2007 and 2014. Daily data for the remaining wastewater treatment plants were unavailable; therefore, we approximated daily effluent flow from reported annual averages. In our study area, MWRD effluent comprises 85% of the total wastewater produced such that sufficient daily variation is captured.

Upon first analysis, a large number of days yield a de facto reuse greater than 100%, which is inconsistent with the physical representation in Equation 1. This finding reveals that on some days USGS stream gauges report less flow downstream than is reported being discharged from the wastewater treatment plants upstream. Our study area scale was sufficiently small to avoid time lag challenges; similarly, infiltration, evaporation, or unaccounted withdrawals do not appear to be of concern. We explain this result by the highly engineered and complex system of dams controlling the waterways and employ a one-week moving average to the data before calculating the de facto reuse. We represented the de facto reuse visually by depicting wastewater effluent (numerator in Equation 1) against streamflow (denominator in Equation 1), shown in Figure 3. Although the one-week moving average smoothing did not eliminate all the points greater than 100%, it reduced their number and magnitude. The remaining percentages greater than 100, left of the dotted line in Figure 3, were within our margin of error.

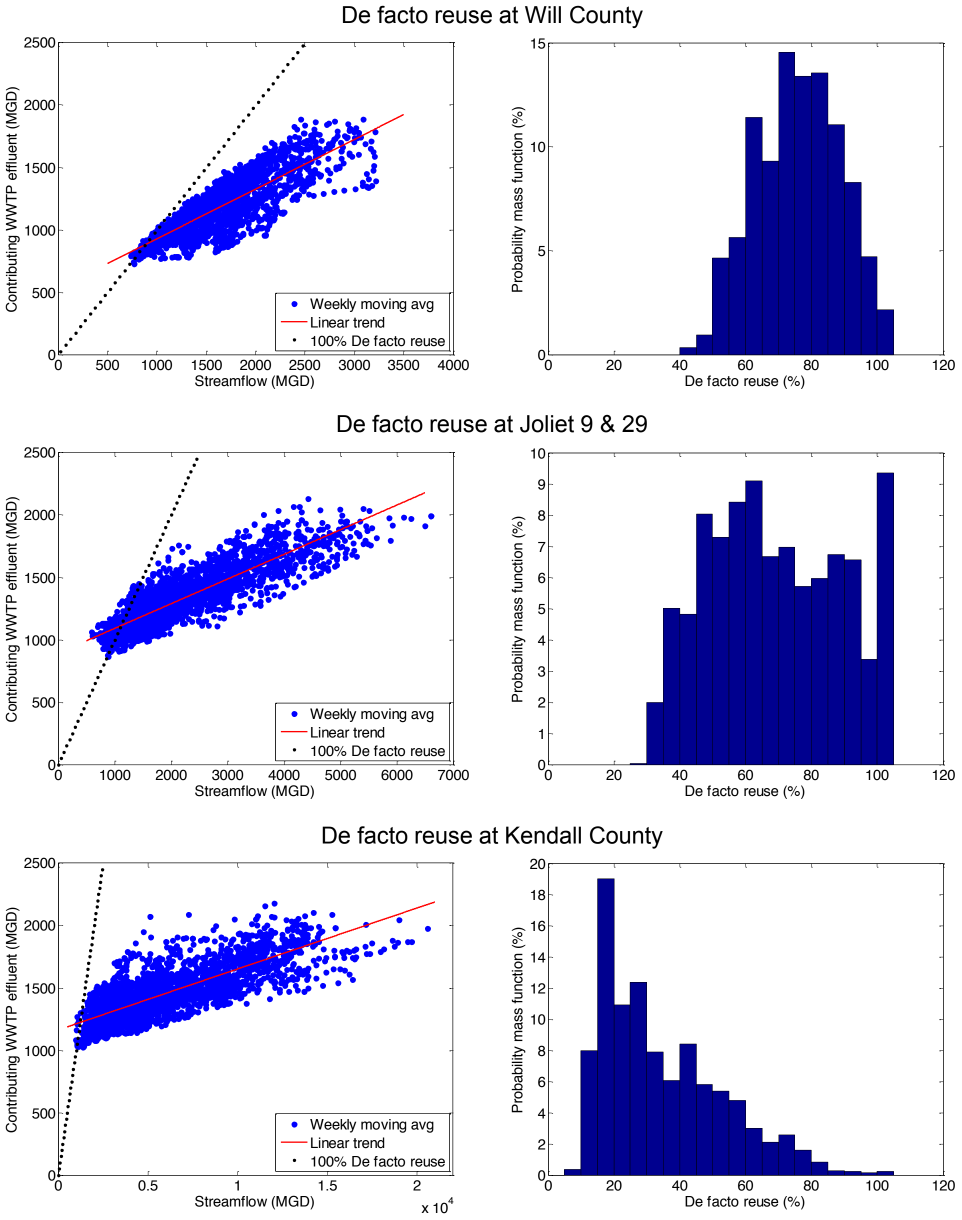


Figure 3. Conditioning to remove data that occurred on days with recorded combined sewer overflows, correlation exists between streamflow and wastewater effluent in the highly urban watershed of Chicago.

The regression plots in the left column of Figure 3 demonstrate that wastewater effluent and streamflow are in fact correlated due to the linear trend. Will County is the power plant nearest to the large wastewater treatment plants, which is reflected by the high slope of the trend line. The trend lines become flatter with increasing downstream distance, indicating the location-specific nature of de facto reuse. These findings reveal that the assumption made by Rice et al.

[13], that wastewater effluent is independent of streamflow is acceptable in most basins, but that assumption breaks down in highly urban environments, such as in the Chicago area.

Representing the de facto reuse as a probability mass function in the right column of Figure 3, we found that de facto reuse varies substantially. As with the median de facto calculation, these probability mass functions reflect the proximity to the large MWRD wastewater treatment plants. The de facto reuse at Will County is wastewater dominated while Kendall County is runoff dominated. At Joliet 9 and 29 the de facto reuse is more distributed.

Due to limited data availability for wastewater treatment plants in the Kankakee basin, no higher resolution analysis was performed. Since the two nuclear plants in this basin have such low preliminary de facto reuse percentages, a more precise analysis would likely reveal consistently low levels of de facto reuse.

Engineered reuse with reclaimed water at power plants

To compare the de facto reuse scenario to an engineered reuse scenario, we formulated an optimal system to supply reclaimed water to power plants. Combining a digital elevation model and land use rasters from the USGS, we created a cost scaling raster for the greater Chicago area. We expanded the cost scaling raster beyond the watershed boundary to allow the paths to traverse the least expensive route. Topography in the study area is relatively flat, such that the cost scaling raster reflects differences in urban density.

We simulated retrofitting power plants to use reclaimed water in recirculating cooling towers. Of the 6 power plants in the study area, only one (Kendall County) uses cooling towers; the remaining facilities operate open-loop systems, although Dresden and Joliet 29 have the necessary cooling towers on site. To determine the water withdrawal and consumption rates associated with retrofitting recirculating cooling, we used empirical and literature values specific to power generation in Illinois [17]. Under this assumption of cooling system retrofits, the Stickney, North Side (O’Brian), and Calumet WWTPs each have enough effluent to supply all power plant demands in the study area.

We found the least cost path between the wastewater treatment plants and power plants using the cost scaling raster with geographic information systems software (ArcMap by ESRI), displayed as the thin black lines in Figure 4. The genetic algorithm examines possible reclaimed water pipelines and selects the optimal solution, displayed as the thicker black line in Figure 4, representing piping reclaimed water from Stickney WWTP to each of the power plants.

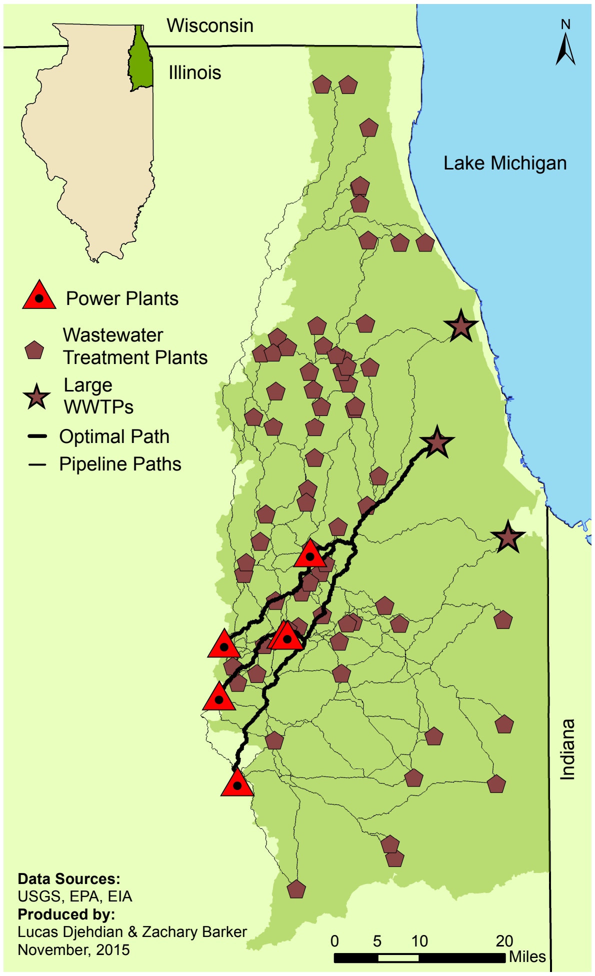


Figure 4. The least cost engineered reuse solution is a pipeline connecting the nearest treatment plant capable of providing all cooling demands.

Cost

To approximate the cost of retrofitting power plants to use reclaimed water (engineered reuse), we used the average of the low and high estimates from literature for each power plant in our study area, listed in Table 1. Due to the lack of data on the cost of cooling towers at nuclear power plants, there is high uncertainty in the retrofit cost estimate. The estimated pipeline construction cost is $356 million, or $23 million/yr using a 30-year amortization period and interest rate of 5%. The total length of pipe is estimated to be 93 miles long with diameters ranging from 0.5 to >6 ft. Similar feasible (yet sub-optimal) solutions for complete sourcing from the Calumet or Northside (O'Brian) WWTPs reveal estimated costs of $423 million and $615 million, respectively.

Combined, the total capital costs for the engineered reuse scenario is approximately $2.24 billion, with cooling tower costs representing 84% of the sum. This result is important when considering that the closed-loop cooling with de facto reuse scenario comprises the bulk of the capital costs required for engineered reuse. Naturally, de facto reuse with current cooling technologies, representing the baseline natural conditions, does not require any additional expense. These cost estimates represent a first-order approximation in motivating future in-depth studies.

Listed in Table 1, operation and maintenance costs for recirculating cooling, utilizing engineered reuse, are non-negligible. These costs comprise about one third of the total annual cost. This proportion is high due to the fouling and treatment costs associated with cooling with reclaimed water. We assume the operation and maintenance costs associated with open-loop cooling to be the baseline for comparison and, therefore, are zero. Due to lack of quality data, we cannot estimate treatment costs associated recirculating cooling utilizing de facto reuse. However, due to the high presence of wastewater, we expect the costs to be closer to the engineered reuse than zero.

Reliability

To calculate reliability, we quantitatively evaluated the likelihood of a power generation “failure” via a thermal variance event. We collected and organized documentation from the Illinois Environmental Protection Agency (IEPA) of thermal variances from 2003 to 2014 [19]. During this time period, 76 thermal variance days were recorded in the Chicago area out of 4,015 total days. Defining thermal variances as failures, we found that the system of power plants in our study area is 98% reliable under de facto reuse conditions; however, this computation does not consider future climate shifts. We account for anticipated increases in streamflow temperatures (likely leading to additional thermal variance days) by conditioning the data on the 80th percentile of seasonal ambient air temperatures, leading to a simulated power generation reliability of 91%. We conditioned on the 80th percentile because it correlates to a modest 2.5 °F increase in the Chicago area average air temperature [20].

We further grouped the variances into seasons for comparison to a seasonal climate metric, represented as the deviation from the seasonal average air temperature, illustrated in Figure 5. Most thermal variances occurred during the drought of 2012; however, Dresden nuclear plant also had variances during 2005. Unlike the current de facto reuse conditions used to calculate reliability, reliance on engineered reuse introduces negligible power generation reliability concerns due to the relatively consistent quality and temperature of reclaimed water. The tradeoff with a reclaimed water system is the reliance on critical pipeline infrastructure that is also at risk for failure, but leaving the existing cooling water intake structures as a backup can mitigate that risk.

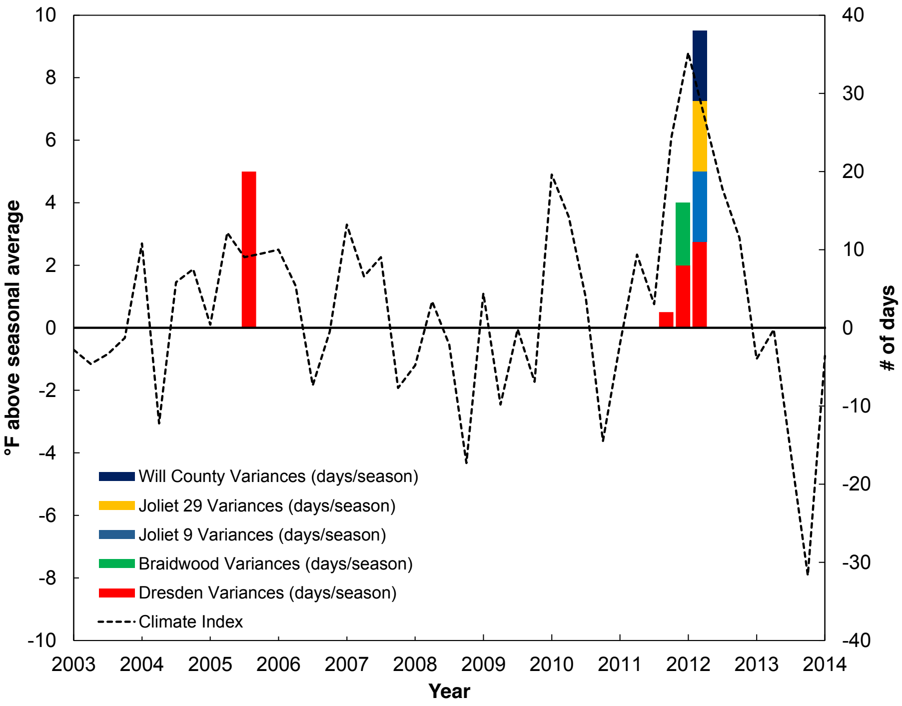


Figure 5. Without power plant operational data, we use thermal variances as a proxy for failure. Warmer seasons produce more thermal variances that have negative ramifications for the power plant and environment.

Performance

To assess the power plants' operational performance under the de facto and engineered reuse scenarios, we modeled the capacity loss due to warmer cooling water and power consumed during reclaimed water pumping. Using reported average monthly intake temperatures from the Energy Information Administration for the years 2010 through 2013, we applied a capacity loss model for each of the power plants. Since we did not have detailed operational information on these power plants, we used estimates from literature for the threshold at which the intake temperature begins to affect capacity [21]. Shown in Figure 6, the modeled capacity loss at each power plant is compiled (illustrated as stacked bars) to represent the total generation capacity loss for our study area. A peak capacity loss of 250 MW occurs for our de facto reuse scenario compared to a peak capacity loss of 400 MW for the engineered reuse scenario. The capacity loss under the de facto reuse scenario is due to the increased temperatures along the river, ranging from 26 to 29 °C. The maximum temperature of wastewater effluent, as reported by MWRD, is 23 °C, which is equal to the modeled threshold for efficiency loss in power plant cooling. Capacity loss in the engineered reuse scenario is the result of additional power demands for cooling tower operations.

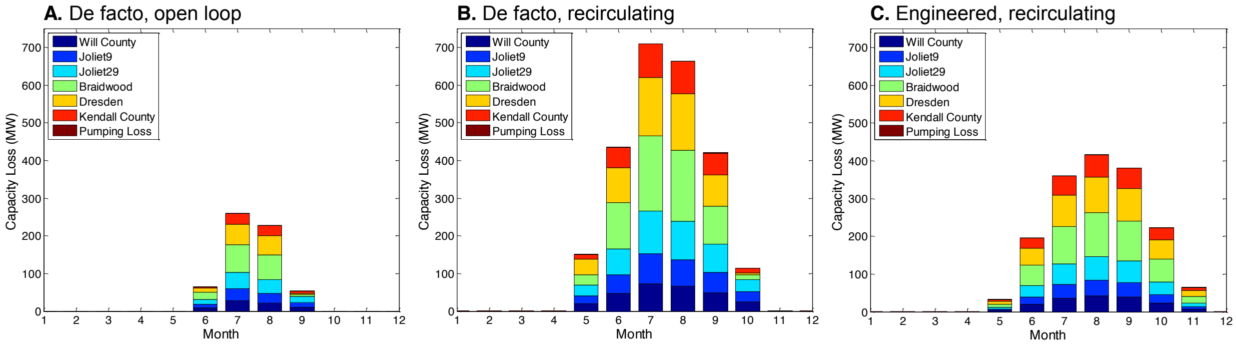


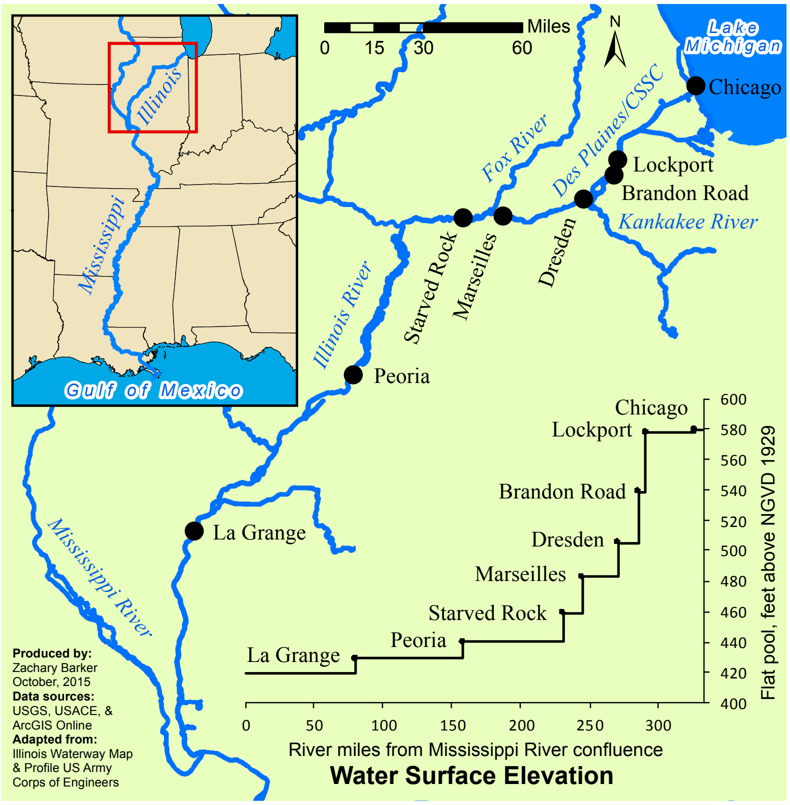
Figure 6. Capacity loss is greatest during the summer months due to the intake of warm cooling water. While recirculating cooling with cooling towers (B,C) introduces additional capacity loss compared to open-loop cooling (A), the impact is less pronounced in the engineered reuse case (C).

Although the engineered reuse scenario causes less capacity loss from elevated cooling water temperatures than the de facto scenario with recirculating cooling towers, we accounted for the pumping and distribution of reclaimed water from the wastewater treatment plant. We found the power associated with pumping reclaimed water to the power plants to be less than 1 MW. In comparing de facto reuse conditions with recirculating cooling (Figure 6(B)) and the engineered reuse scenario (Figure 6(C)), reclaimed water for power plant cooling is preferable due to substantially lower capacity losses due to consistency of water temperature, even when accounting for reclaimed water pumping. Notably, the capacity gains using reclaimed water, observed during summer months with peak electricity demand, are on the same scale as a small power plant. Using an electricity price of $0.08 per kWh [22] and assuming the study area power plants would be operating at full capacity, we calculated a first order approximation of revenue loss of about $62 million/year due to cooling inefficiencies under engineered reuse compared to current de facto conditions. However, compared to de facto reuse with cooling towers, there is a net savings of $47 million/year, which exceeds the initial cost estimate for reclaimed water pipeline construction. That is, when retrofitting to use cooling towers, engineered reuse with reclaimed water provides economic advantages via improved performance.

Overall, our results indicate that use of reclaimed water for power plant cooling has strategic advantages and tradeoffs. The engineered reuse with recirculating cooling scenario reveals advantages compared to de facto baseline conditions in terms of reliability. These reliability gains are due to the predictable temperature of reclaimed water and its use in recirculating cooling towers, mitigating the need for thermal variances. When comparing recirculating cooling scenarios, engineered reuse with reclaimed water has lower capacity loss (that is, better performance) than recirculating cooling under de facto reuse conditions. These improvements in reliability and performance, however, come at the tradeoff of increased infrastructure cost, yet estimated revenue loss from power plant derating is comparable to these investment costs. Consequently, use of reclaimed water for power plant cooling might be a strategic infrastructure investment to benefit both energy and water resources.

Downstream impacts of consumptive water reuse

To quantify the dynamic downstream flow impacts of consumptive water reuse, we created a model extending beyond the original study area to include the downstream Illinois River, shown in Figure 7. The Illinois River, a tributary of the Mississippi River, provides a navigable waterway to Chicago and Lake Michigan via the Des Plaines River and the Chicago Sanitary & Shipping Canal. Along the route, there are eight locks and dams operated by the U.S. Army Corps of Engineers. While drastically reducing cooling water withdrawals, retrofitting power plants in the area to use reclaimed water in cooling towers would increase total water consumption by an estimated 200 million gallons per day (MGD). Fortunately, the supply of wastewater effluent in the study area is very large due to high population densities and combined sewer infrastructure, with the total amount of treated effluent typically exceeding 1,800 MGD.



Produced by:
Zachary Barker
October, 2015
Data sources:
USGS, USACE, &
ArcGIS Online
Adapted from:
Illinois Waterway Map
& Profile US Army
Corps of Engineers

Figure 7. The Illinois River connects Lake Michigan with the Mississippi River and is downstream from the proposed consumptive use of reclaimed water.

Defining what uses of water are important downstream is critical for understanding the impacts of water reuse. For the Illinois River, the most critical downstream stakeholder is barge traffic. The Illinois River does not sustain large fishing operations or support a large amount of water withdrawals. A small number of power plants downstream from the original study area currently rely on the Illinois River for cooling water; however, these facilities are not considered in this analysis because their operations would not be affected by the simulated changes in the flow regime. Barges are important to the region for cost-effective transportation of coal, petroleum, agricultural products, and other raw materials. Since barge traffic relies on a channel deep enough to float, we focused our analysis on this critical stakeholder. Unique to this system is the source of water during dry periods. Lake Michigan diversions are already used to act as make-up water during low flows and could not be increased due to international treaties.

Scenario analysis

To quantitatively assess the downstream impacts of reclaimed water consumption, we employed scenario analysis, comparing the proposed scenario to the current baseline (de facto) conditions. We were primarily interested in the effects of consuming 200 MGD of reclaimed water for cooling power plants; however, many other water reuse applications are possible and could be evaluated with this methodology. To explore these possibilities, we examined how the system changes due to the entire range of possible reclaimed water consumption levels. The minimum of this range is defined by zero consumption, or no change, and the maximum is defined as the total consumption of the 1,800 MGD of wastewater produced in the Chicago region. For this analysis, we assumed a uniform demand of reclaimed water on a daily and seasonal timescale. Since our main application is cooling baseload thermoelectric power plants, this assumption is reasonable because these power generators typically have fairly constant water demands.

We used streamflow and stage data from the USGS and the U.S. Army Corps of Engineers. The data at the locks and dams represent the tailwater side of the infrastructure and include 25 years of daily data. The data reported at these sites represent our baseline (de facto) scenario and a selection of these data are displayed as flow duration curves in Figure 8. We simulated our engineered water reuse scenarios by subtracting the quantity of water consumption from all data points to shift the flow duration curves. The 200 MGD consumption scenario, representing cooling study area power plants with reclaimed water, is illustrated in Figure 8.

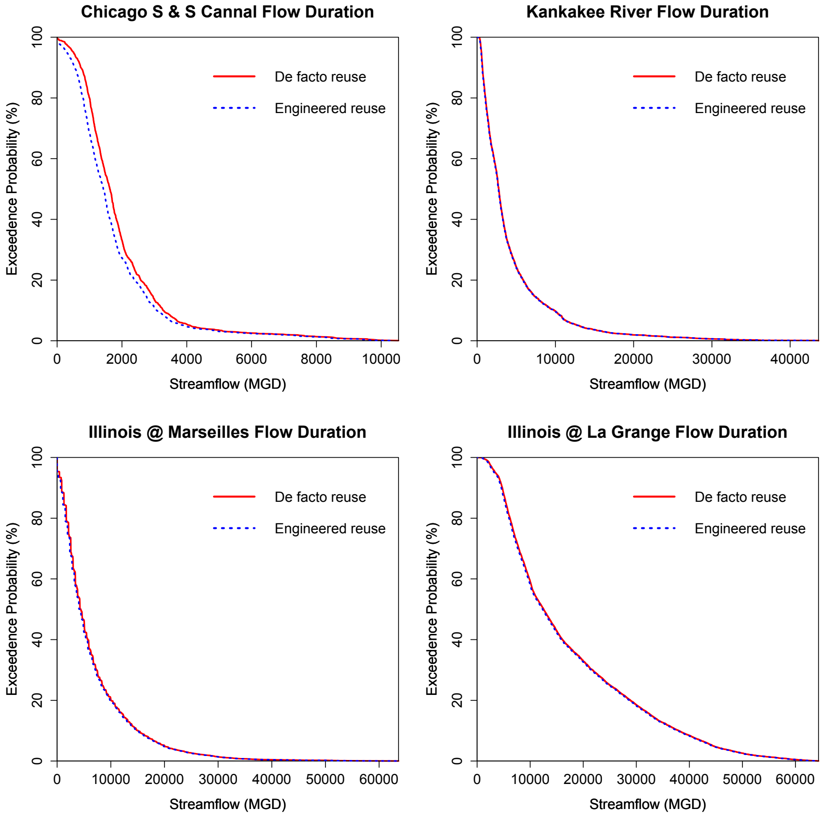


Figure 8. Consuming reclaimed water upstream shifts the flow duration curves downstream.

At all of the streamflow gauges shown in Figure 7, excluding the Kankakee River, the flow duration curve shift is to the left, illustrating lower streamflow. The flow duration curve for the Kankakee River, however, shifts to the right signifying more streamflow in the engineered reuse scenario than in the de facto scenario. In the engineered reuse scenario, two power plants that currently withdraw water from the Kankakee River instead consume reclaimed water that is produced on the Des Plaines branch of the Illinois River headwaters. While all of the flow duration curves in Figure 8 depict the same 200 MGD reduction in streamflow, gauges further downstream have larger drainage areas, and, therefore, the flow regime shift appears smaller.

Statistical significance

To quantify the difference between flow regimes illustrated in Figure 8, we used statistical techniques to estimate the difference between means between the baseline (de facto) scenario and each engineered water reuse scenario. We calculated *t*-statistics to quantify the statistical significance of the difference between streamflow means for each gauge. A significance level of 0.05 was used for α, which correlates to a *t*-statistic threshold of approximately 2. Test statistic results greater than this threshold were considered statistically significant; that is, a statistically significant difference exists between the mean baseline (de facto) streamflow and streamflow with upstream consumptive water reuse at *t*-statistic values greater than 2.

Using a step size of 10 MGD for the range of reclaimed water consumption (0 to 1800 MGD), we evaluated the maximum level of water reuse (consumption) possible without observing a statistically significant simulated downstream impact. Although the entire range of consumption scenarios were calculated, scenarios up to 500 MGD reclaimed water consumption are displayed in Figure 9. From these results, the 200 MGD scenario for power plant cooling has a significant impact on streamflow at the first two gauges downstream from the wastewater treatment plant. These impacts of reclaimed water consumption diminish with distance downstream, becoming insignificant by 50 river miles downstream.

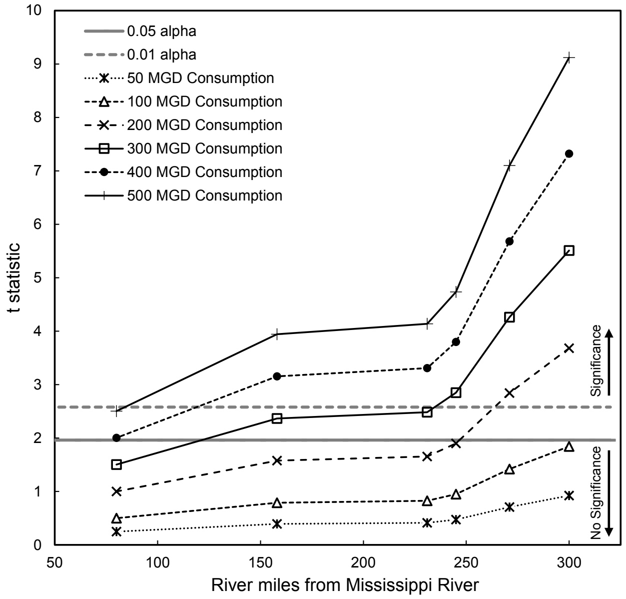


Figure 9. Reclaimed water consumption above 100 million gallons per day (MGD) would lead to statistically significant changes in downstream flow, with impacts varying with distance. The right hand side of the figure represents the Chicago area (300 river miles from the Mississippi River) and the left hand side is near the confluence.

Reclaimed water consumption could approach 100 MGD in this simulation and not have a statistically significant impact on downstream flow. While this amount of water reuse would not provide cooling water to all six power plants in the study area, a few could be cooled without ramifications of any significant downstream impacts. Also shown in Figure 9 is the level of significance threshold for α of 0.01, representing a more relaxed threshold for significant downstream impacts. Increasing this threshold (by decreasing the value of α) allows the maximum reclaimed water consumption to increase to 150 MGD. Since the *t*-test for 200 MGD reclaimed water consumption returns a statistically significant difference in means for streamflow gauges directly downstream, we further investigated the negative economic impacts that reclaimed water consumption might have on downstream barge transit.

Probability of failure

Defining barge transportation as the most at risk downstream stakeholder, we focused on river stage instead of streamflow directly. The U.S. Army Corps of Engineers aims to maintain a minimum depth of 9 feet along the Illinois River. Using the reported stage and streamflow data immediately downstream from each lock and dam, we found the current probability that the minimum stage is not met. All five gauges have some low but non-zero probability of failure in the baseline (de facto) scenario.

Since we have defined our threshold as a stage, we converted the reclaimed water consumption from a reduction in streamflow to a reduction in stage. Ideally, rating curves would define this relationship; however, these curves were not available or accurate for low flows at the study gauges. To establish a relationship between streamflow and stage, we used linear regression. Nonlinear relationships could also be used; however, for the highly engineered operation of the Illinois River, nonlinear models did not produce more accurate results. Since our focus is on low flows that put downstream users at risk, we used only the lower 50th percentile of streamflow in developing the rating curve. Figure 10 depicts this process for one of the gauges and is representative of the method for each location. Also illustrated in Figure 10 is the linear model result from using the entire data set for the regression. The full data linear regression does not accurately represent the range of low flows of interest. Further, the lower slope would underrepresent the reduction in stage from upstream reclaimed water consumption. Using the slope from the rating curve, we shifted the stage using Equation 2:

$$l_t' = l_t - mr_t \tag{2}$$

where l_t' is the stage given reclaimed water consumption, l_t is the reported stage, m is the slope of the rating curve, and r_t is the amount of reclaimed water consumption; all for the same time t. By shifting the stage, similar to the shifting of the flow duration curve, we assessed the number of data points that fell below the threshold of 9 feet at each gauge. We then calculated the probability of failure to find the expected failure rate for each downstream gauge at varying levels of reclaimed water consumption.

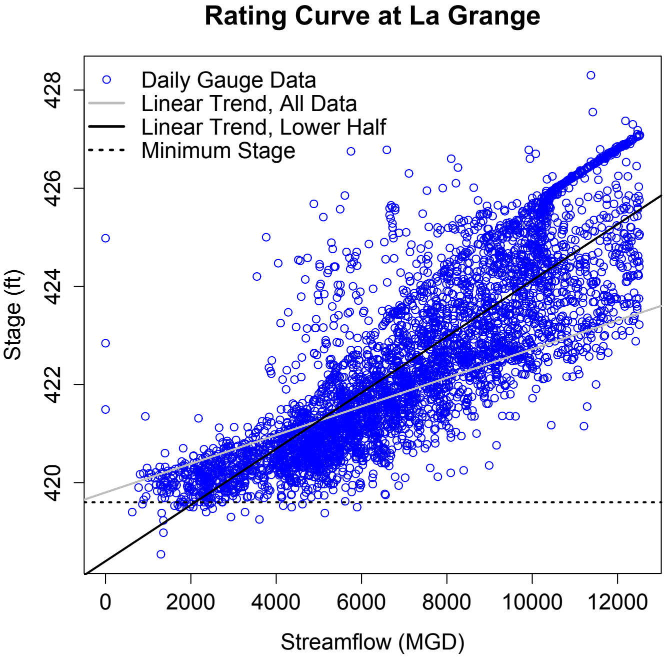


Figure 10. In the absence of accurate rating curves, we used linear regression to estimate the relationship between streamflow and stage.

Figure 11 displays the probability of failure results for each gauge on the Illinois River. The 200 MGD consumption scenario representing water reuse for power plant cooling reveals minor increases in probability of failure with all gauges less than 1%. At Peoria, the most extreme change, the probability of failure increases from 0.39% to 0.99%. In the scenario with consumption of all of the reclaimed water produced in the Chicago area (1800 MGD), the probability of failure would increase to a maximum of 15% at Peoria. While illustrating the potential downstream impacts of water reuse on an annual basis, this approach does not capture the seasonality of precipitation. In Illinois, precipitation is higher during the first half of the year than the second. To account for these seasonal precipitation patterns, we conditioned the probability of failure on the time of year, repeating the same analysis with two datasets: 1) data from January through June (spring), and 2) data from July through December (fall). The results show similar findings comparing gauges to each other; however, the magnitudes are significantly different. During the spring, the wet season, failure probabilities are less than 4% even for total reclaimed water consumption at 1800 MGD. During the fall, the dry season, probabilities of failure approach 25% for total reclaimed water consumption; however, the 200 MGD scenario (representing water reuse for power plant cooling) is still below 2%.

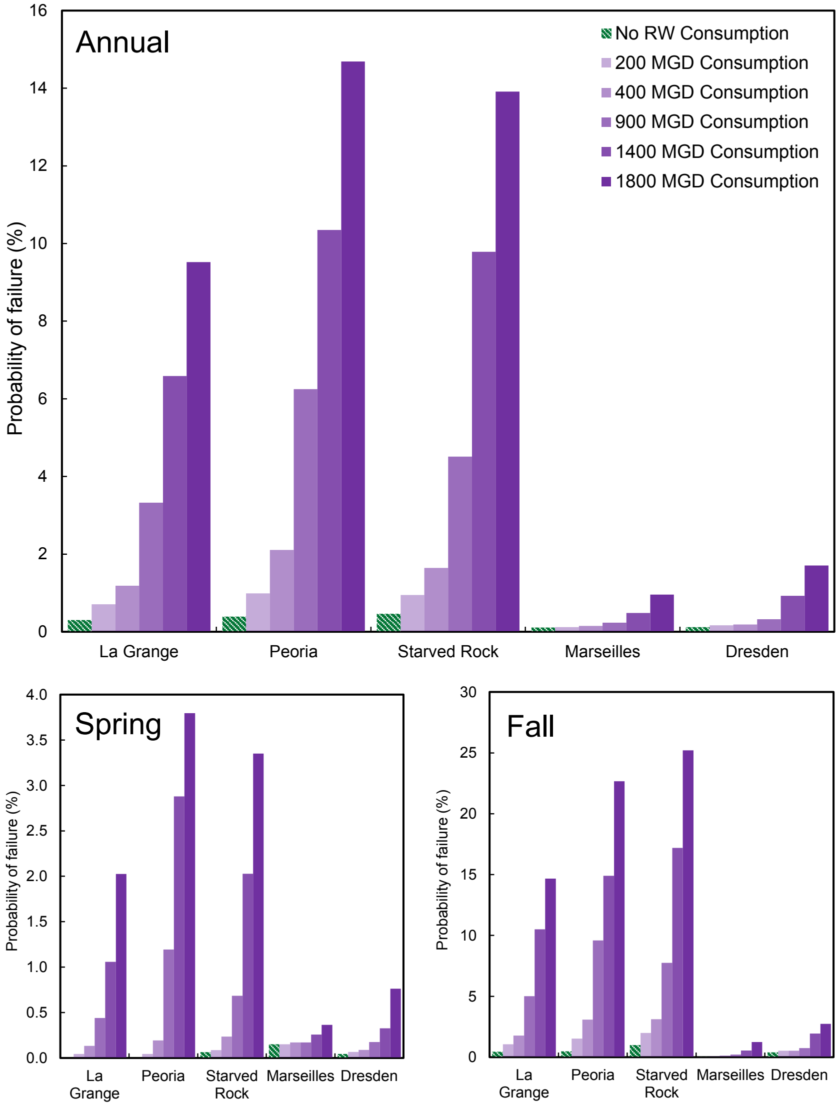


Figure 11. The probability that the stage at each gauge falls below the 9-ft minimum channel depth is small under current conditions (no reclaimed water [RW] consumption) and increases marginally under the proposed consumption scenario of 200 million gallons per day (MGD).

Value

To quantify the effect of decreased navigability of the Illinois River in an economic perspective, we calculated the relative value of barge transportation. The U.S. Army Corps of Engineers reports the tonnage and type of each commodity that passes through each lock [23]. Using these data for the years 1999 through 2014, we assessed the amount of commodities passing through each lock via barge. The average, shown in Figure 12, is representative of the larger trends in movement of commodities along the waterway. Most importantly, the data reveal that areas further downstream see more barge traffic, with the difference associated mainly with food and farm products. On average, the most upstream gauge, Lockport, sees roughly half of the tonnage of the most downstream gauge, La Grange. This increase in commodity movements downstream is favorable for cooling Chicago area power plants with reclaimed water since the consumptive affects diminish with downstream distance.

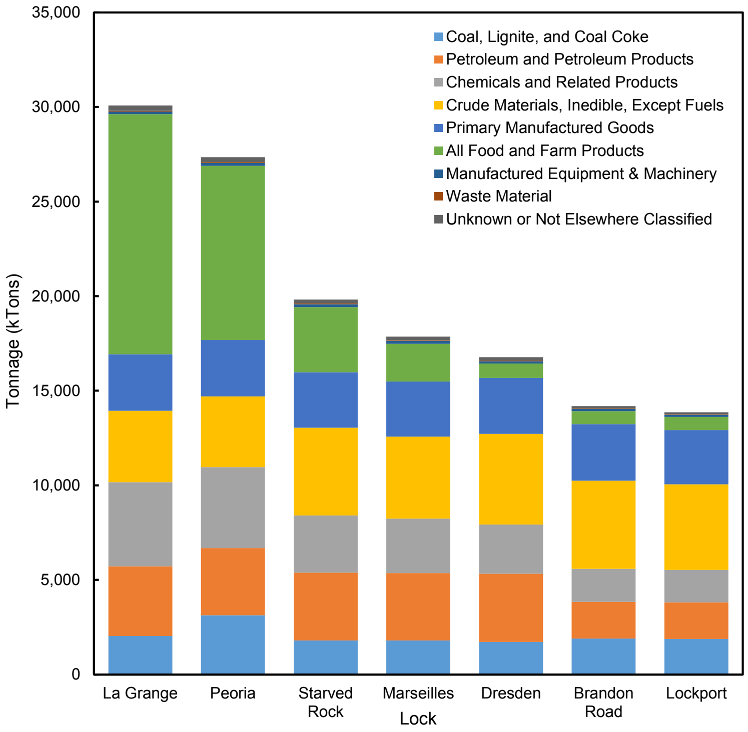


Figure 12. The average tonnage recorded passing through the locks on the Illinois River increases with proximity to the confluence with the Mississippi River. (La Grange is the gauge furthest downstream and Lockport is the furthest upstream in the study area.)

In order to assign value to barge traffic, we used the Commodity Flow Survey and the associated Freight Analysis Framework (FAF^3) [24], which tabulate commodity flows by mode of transportation and origin/destination. Combining all flows to and from Illinois gives a snapshot of the total transportation portfolio. Although these numbers represent a single year of commodity flows, we assumed the percentage of tonnage distributed by mode and commodity stays relatively constant. From these data, we directly calculated the waterborne market share of transportation; however, these values might include other waterways not downstream of the proposed consumptive water reuse. To account for these spatial considerations, we estimated the unit value of each commodity given by Equation 3:

$$Unit\ Cost = \frac{V}{T} \tag{3}$$

where V is the value and T is the tonnage. Multiplying the unit cost by the tonnages reported at each downstream gauge yields not only a value associated with barge traffic but also reflects the spatial variability between different sections of a waterway.

From the FAF^3, waterborne transportation accounts for 5% of the total tonnage of commodities transported in Illinois. Trucks, by comparison, account for about 70% of the total tonnage. Comparing the waterborne tonnage reported by the FAF^3 and the U.S. Army Corps of Engineers data for the locks, we found that barges on the Illinois River account for about one-third of the total waterborne tonnage. Comparing the total value of commodity flows through, to, or from the state of Illinois, barge traffic on the Illinois River accounts for about 1% of the total. This fraction varies annually; however, barge traffic on the Illinois River represents a small subset of overall transportation in the state.

Based on our results, we demonstrated that water reuse for power plants – using reclaimed water from wastewater treatment plants to cool thermoelectric power generators – can be a sustainable energy and water management approach both locally and regionally. Electric power generators can benefit from increased reliability when using reclaimed water for cooling. The downstream flow impacts from additional upstream consumption become statistically insignificant within 50 river miles downstream, illustrating the negligible change to downstream flow regimes. Water reuse can be beneficial at local and regional levels.

PROJECT TEAM

The project team included PI Ashlynn Stillwell, Assistant Professor, and co-PI Zachary Barker, M.S. student and Graduate Research Assistant, both in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign. Additional research support came from Undergraduate Research Assistant Lucas Djehdian, who was funded by the CEE Research Experiences for Undergraduates program.

PUBLICATIONS

Details of the results were published in Zachary Barker's thesis, *Local and downstream impacts of water reuse at power plants*, available at https://www.ideals.illinois.edu/handle/2142/88999. Results of the first two objectives (quantifying de facto water reuse and engineered reuse with reclaimed water) appeared in a manuscript that is under consideration with *Environmental Science & Technology* (initial reviews were favorable, and the revised manuscript has been resubmitted). Results of the third objective (simulating downstream impacts) are in preparation for submission to a peer-reviewed journal during the spring 2016 semester. Excerpts of these manuscripts are included here.

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