LOCAL AND DOWNSTREAM IMPACTS OF WATER REUSE AT POWER PLANTS

BY

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THESIS

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ABSTRACT

Reclaimed water, treated effluent from a municipal wastewater treatment plant, is a viable resource for mitigating growing stress on water resources. One such application of reclaimed water is cooling thermoelectric power plants. Using reclaimed water along with recirculating cooling towers has a variety of benefits such as making use of an otherwise low-value waste stream and providing a reliable water source. However, consumption of water that would otherwise be returned to a surface waterway might cause negative impacts to downstream locations. This work presents a method that utilizes quantifiable metrics to assess the implications of constructing a consumptive water reuse system linking reclaimed water with power plant cooling. These metrics include de facto reuse (representing the incidental presence of wastewater in a surface water resource), infrastructure cost, power generation efficiency loss due to increased water temperatures, and downstream water quantity impacts. A case study of Chicago, Illinois, and the surrounding area is introduced to demonstrate the method’s applicability in jointly planning for water and energy. Findings reveal that the impacts of wastewater reuse are complex. While the infrastructure necessary for reuse is economically feasible, some power plants have high ratios of de facto reuse due to dense urban populations, which devalue the reclaimed water infrastructure investment. Additionally, the power generation efficiency gains made from the cooler and more reliable temperature of reclaimed water must be weighed against the inherent interbasin transfers that occur. These metrics summarize some of the considerations when sustainably managing both energy and water resources.
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CHAPTER 1: INTRODUCTION

"When we try to pick out anything by itself, we find it hitched to everything else in the Universe" - John Muir

Reliable energy and clean water are tantamount to a high standard of living in the modern age. As society tries to meet the growing demands for water and energy, it does so under increasing environmental and political stress.\textsuperscript{1,2} At the most fundamental level, water is required for drinking and growing food. As a civilized society, water is also used for bathing, manufacturing, raising livestock, a medium for transportation, and producing energy. The last use, energy production, is particularly connected to water. Water is involved at every stage of the energy production process. It plays numerous roles in the extraction and processing stages of fossil fuels, but most notably it cools thermoelectric power plants. Conversely, energy is used for the conveyance and treatment of water. Researchers continue to study energy and water resources independently as well as jointly to mitigate stress under these conditions.\textsuperscript{3} Previous work demonstrated that the energy and water sectors positively and negatively interact with each other, a connection commonly known as the energy-water nexus.\textsuperscript{3–16} In some cases, such as conservation or resource recovery, the two sectors can be synergistic.\textsuperscript{4,7,12,17} Conversely, tradeoffs can exist where efficiency in one area might increase consumption in the other, such as increased energy consumption for distributing reclaimed water (wastewater treatment plant effluent) through a network.\textsuperscript{18}

In the future, increases in socio-economic status, growing populations, climate change, and a greater respect for the environment threaten to increase the strain between energy and water.\textsuperscript{19,20} Increases in energy demands correlate to increases in water consumption. This increase is largely tied to water consumption at thermoelectric power plants. In 2009, about 88% of the nation’s energy was produced by thermoelectric power plants.\textsuperscript{21}

As the world’s resources become more stressed, engineers have sought sustainable solutions. Demand management seeks to reduce consumer consumption through strategies such as conservation campaigns and pricing. Alternatively, supply side solutions attempt to increase the
supply of resources through creative allocation and reuse. Integrated water management seeks to identify efficiencies by managing diverse water sectors, including stormwater, wastewater, and drinking water as an integrated system. Water reclamation, an integrated water management approach, reduces freshwater demands by reusing reclaimed water, or wastewater that has been treated to high standards, for beneficial purposes. Because roughly one-third of all water used in urban areas needs to be potable quality, based on the end use and likelihood of human contact, reclaimed water can be treated to reasonable levels of water quality and used for non-potable applications.

One suitable application is cooling thermoelectric power plants. The strengths of reclaimed water in power plant cooling applications include reliability and consistency of quantity and quality, without the environmental and legal risks of thermal pollution or entrainment and impingement issues for aquatic species. Constructing a reclaimed water cooling system, can be expensive and the impacts complex, prompting the need for well-informed decision-making. In the case of water and energy resources, spatial distribution often plays an important role, meaning the same reclaimed water system might be favorable in some situations but not in others. Currently, there is minimal guidance on evaluating reclaimed water systems, which motivates the following research questions:

- Given a specific scenario, is cooling power plants with reclaimed water beneficial?
- How can the costs and benefits of cooling power plants with reclaimed water be quantitatively assessed?
- How can the impacts downstream of the reuse be quantitatively assessed?
- What are the legal barriers and policy impacts of reuse?

To address these questions, this research employs scenario analysis to evaluate the implications of engineered water reuse compared to de facto reuse, defined by the incidental presence of wastewater in a water source. Originally developed to assess the percent of wastewater effluent at drinking water plants, the de facto reuse method is customized with temporal resolution to serve as a baseline in comparison to engineered reuse. Comparing engineered and de facto reuse, metrics of the financial cost, reliability, and generation capacity are presented in Chapter 3, and downstream impacts are assessed in Chapter 4 in order to aid decision-making in support of
sustainable energy and water resources management. Finally, legal and policy implications are discussed in Chapter 5 as they influence the efficient utilization of reclaimed water.
CHAPTER 2: BACKGROUND

“There are those who cannot remember the past are condemned to repeat it.”
- George Santayana

2.1 Reclaimed water

Though dual water systems were first introduced in the United States in the 1920s, water reclamation programs are not widespread. Water reclamation has been more widely adopted internationally; for example, 75% of the wastewater produced is reused in Israel, where water scarcity is a significant threat. On average, 32 billion gallons per day of wastewater are produced in the United States, and municipalities can save significant volumes of freshwater by integrating an otherwise underutilized resource in urban water resources systems. Reclaimed water is used for a variety of purposes. Urban, agricultural, industrial, municipal, and environmental demands all benefit from increased supply and reliability of water supplies. Currently, landscape and agricultural irrigation dominate the end uses, combining to represent approximately half of all deliberate reuse.

Most of the literature on reclaimed water is focused on the end use or largely qualitative. The work stemming from environmental engineering aims to provide reclaimed water to the customer safely. Due to quality concerns and the reliable nature of wastewater, there are certain applications that are better suited to utilizing reclaimed water. Large non-potable water consumers, such as irrigators and cooling towers, are particularly well suited. Research in this area is generally qualitative due to the vast heterogeneity that arises between reclaimed water systems, geographic areas, and demands. Although this disparity makes global claims about reclaimed water difficult (and foolish), methods should be developed to discern whether or not engineered reuse is beneficial in specific scenarios.

The federal government does not have enforceable statutes but rather guidelines concerning reclaimed water. Published by the U.S. Environmental Protection Agency (USEPA), these guidelines discuss quality, quantity, uses, existing state regulations, and how to develop programs.
The purpose is to assist state, regional, and municipal governments in designing regulations regarding reclaimed water. Since the first introduction of these guidelines, the focus has been on protecting the reclaimed water customer from quality issues. Currently, these guidelines are the best tool for assessing reclaimed water projects and policies; however, they fall short in quantifying external impacts.

2.2 Power plants

Thermoelectric power plants, the focus of this study, use steam to turn a turbine, which turns a generator that creates electricity. To avoid damaging the equipment, the steam has to be extremely pure; therefore, the boiler feed water is condensed and reused. There are a variety of methods for condensing steam; however, using another water source as a heat sink is the most common. Historically, this cooling process is done using large flow rates of less pure water, such as a river or lake, in a process known as open-loop or once-through cooling. The power plant transfers the heat from the extremely pure operational water (as steam) to the cooling water that is then discharged back to the waterbody at a higher temperature. These power plants often report zero water consumption via evaporation; however, the additional heat loading increases natural evaporation downstream.\(^{21}\) The alternative to open-loop cooling is closed-loop cooling that utilizes cooling towers or recirculating reservoirs. Cooling towers leverage the latent heat of vaporization, thereby evaporating the cooling water but requiring much smaller flow rates.

Previous work on this topic primarily focuses on quantifying the existing and future power plant water demand in a changing environment,\(^{14,21,37–46}\) with increasing focus on alternative water resources. In the United States, thermoelectric power plants account for 41% of the freshwater withdrawals and 3% of the consumption.\(^{47,48}\) As a result of these studies, renewable energy sources, such as wind and photovoltaics, which require no water for operation, are attractive from a water perspective.

Increased scrutiny on power plants has led to policy developments such as the Existing Facilities Rule and Clean Water Rule that build on the Clean Water Act, and the Clean Power Plan that sets performance-based standards for air emissions under the Clean Air Act.\(^{49–53}\) The Clean Water Act greatly hindered the construction of new open-loop cooled power plants under §316(b), but
grandfathered open-loop cooling at existing facilities. The thermal pollution along with the entrainment and impingement of fish were the primary motivators for the regulation. As the alternative, recirculating closed-loop cooling has become the standard for new construction or retrofitting power plants. Although the withdrawal rates are much lower, over 60% of the water that is withdrawn is consumed via evaporation. As open-loop power plants are retrofitted or replaced with closed-loop systems, these infrastructure changes might affect water availability and competition, motivating power plants to consider alternative water resources.

2.3 Reclaimed water for cooling

The USEPA names water scarcity, increasing urbanization, the water-energy nexus, and environmental protection the primary motivators for reuse. Given that the water-energy nexus, defined as the interdependency of the water and energy sectors, is a primary motivator for wastewater reuse, it is important to understand why. Although thermoelectric power plants typically require large freshwater withdrawals, this water is not required to be potable quality. Naturally, it has been suggested that cooling power plants with reclaimed water can be a beneficial practice since it is making use of an otherwise low-value resource.

Reclaimed water is poised as a viable alternative water resource for thermoelectric power plant cooling. Other common uses of reclaimed water include crop and landscape irrigation and dust control, with some areas of indirect potable reuse to augment drinking water supplies. The strengths of reclaimed water in power plant cooling applications include reliability and consistency of quantity and quality, without the environmental and legal risks of thermal pollution or entrainment and impingement issues for aquatic species. Reclaimed water also presents challenges of scale, corrosion, and biofouling, including danger of airborne bacteria that cause Legionnaire’s disease; however, these challenges can be minimized with proper planning and operations.

Power plants are a particularly adept end user of reclaimed water due to their large demands. Because building infrastructure is costly, it is generally more desirable to have a small number of large users rather than many small users. Power plants that currently operate using cooling towers would only require a pipeline from the wastewater treatment plant to utilize reclaimed water; however, not all power plants have closed-loop cooling systems. Many power plants still operate
open-loop cooling systems and are at risk for fines from the USEPA for environmental damage. Switching from open- to closed-loop cooling reduces the water withdrawals but increases consumption.

Work has been done on the economic feasibility of cooling power plants with reclaimed water. In this work the focus was on the benefits of drought mitigation in arid climates, such as Texas, and developed a geographic model for optimizing infrastructure for delivering treated wastewater to power plants. Further analyses (described in Chapter 3) built on the feasibility model by introducing comparison criteria to aid in assessing the merits of implementing a reclaimed water cooling system. Centered on comparing engineered reuse to de facto reuse, this work quantitatively assessed cost, reliability, and performance. These metrics represent useful values for comparison and can aid in persuading power plants to implement such systems; however, these localized metrics do not address regional downstream impacts.

2.4 Downstream Impacts

Regardless of the end-use, most engineered reclaimed water projects are similar in that they represent consumptive demands, meaning the water is no longer available within the local watershed. It is important to note that consumption is not a trait unique to reclaimed water. In many circumstances, the potential reclaimed water customer already consumes water from another source. The displacement of another water source is important in considering the sustainability of a project. Displacing a surface water source from the same basin does not change downstream flows. Conversely, displacing groundwater or an interbasin transfer source reduces the downstream flows similar to introducing a new demand. Reclaimed water should not be treated as a water source isolated from the environment. Most of the wastewater currently produced is discharged into waterways and is important to the aquatic ecosystem and downstream users. When considering a reclaimed water project, it is important to consider all impacts including the effects of displacing the original water source and downstream impacts along with the quality concerns normally attributed to reclaimed water.

Rivers and streams have many benefits and functions from instream ecosystem services and transportation to withdrawals that support cities, industries, and farms. The wastewater effluent
discharged into the waterway undeniably changes the flow and quality. In some cases the effects are negative due to inadequate treatment; however, with more stringent regulations and better treatment, these detrimental impacts have become less common. In many cases, the effluent positively affects the receiving water body due to the increased reliability of flows.\textsuperscript{35}

Some proponents of reclaimed water argue that the wastewater discharges are unnatural and, therefore, can be consumed. However, treated wastewater discharges are only one of the ways urbanization impacts downstream flows. Increased impervious areas impact flow regimes by reducing the time of concentration that runoff resides in the basin, effectively transforming the natural hydrograph to one with a higher peak and shorter tail, causing problems of flooding and lower flows. Green infrastructure, distributed and localized efforts to slow down the conveyance of water to mimic natural conditions, is currently a major research area.\textsuperscript{60} Considering the impacts of urbanization on the waterways holistically, wastewater discharges can either compound flooding concerns by combining with increased runoff, or counteract water scarcity by augmenting reduced baseflow during times of dry weather. Therefore, assessing the effects of reclaimed water on natural watershed conditions is non-trivial and requires consideration of impervious cover and urbanization.

From a legal perspective many states do not have legislation concerning reclaimed water use. In fact, only 22 states have statutes directly concerning reclaimed water. Further, very few state statutes mention consideration of downstream impacts; the remaining policies concern only the quality of reclaimed water and how it can be used. If a project receives federal funding, an environmental impact assessment might be required.\textsuperscript{36} As reclaimed water use increases, it will become necessary for states to address conflicts that might arise between local water reuse and regional water stakeholders.
CHAPTER 3: LOCALIZED IMPACTS

“If you choose not to decide, you still have made a choice” - Rush

3.1 Introduction

Constructing any large infrastructure, such as a reclaimed water cooling system, can be expensive, prompting the need for well-informed decision-making. In the case of water and energy resources, spatial distribution often plays an important role. Multi-criteria decision analysis tools have been developed to aid in this process.⁶¹,⁶² This work builds on this vein of research by combining novel analytical approaches to quantitatively assess the suitability of using reclaimed water for power plant cooling. Scenario analysis is employed to evaluate the implications of engineered water reuse compared to de facto reuse, defined by the incidental presence of wastewater in a water source. Originally developed to assess the percent of wastewater effluent at drinking water plants, the de facto method is customized with temporal resolution to serve as a baseline in comparison to engineered reuse.²⁵,²⁶ Through the analysis, metrics are presented quantifying the system financial cost, reliability, and generation capacity to aid decision-making in support of sustainable energy and water resources management.

3.2 Method

Since most power plants are downstream from municipal wastewater treatment plants, withdrawal of surface water sources for cooling leads to a degree of de facto water reuse. Quantifying the amount of de facto reuse establishes a baseline of existing hydrologic conditions at power generation facilities. In areas with significant levels of de facto reuse, the river channel acts as a natural conduit for transporting varying volumes of wastewater effluent. In such cases, construction of a reclaimed water distribution network might be less attractive than the de facto
conditions. In their work, Rice et al.\textsuperscript{25,26} quantified the percent of wastewater effluent present at a particular withdrawal point, shown in Equation 1:

\[
\% \text{ de facto reuse} = \frac{\sum_{i} q_{w,i}}{q_{s}} \tag{1}
\]

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. The Rice et al. analyses focused on drinking water treatment plants; similarly, this work quantifies de facto reuse at power plants, changing only the withdrawal point. Expanding on the existing method, this work uses finer resolution daily data (when available) with correlating time series, which allows the bypass of the previous assumption that streamflow and wastewater effluent are independent.

Using the de facto quantification as a baseline, this work compares the current (de facto reuse) scenario with an engineered reuse scenario using reclaimed water in a piped network. Focused on power plants as possible reclaimed water customers this method is adaptable to include other consumers such as golf courses, agriculture, or industrial cooling. Stillwell and Webber\textsuperscript{33} introduced a geospatial model based on least cost path analysis to evaluate the feasibility of cooling power plants with reclaimed water using a nonlinear optimization approach for individual power plants. The cost of a pipeline is a function of length, diameter, and a cost scaler that accounts for terrain variability. To determine the cost-scaling factor, geospatial land use data are combined with digital elevation models (DEM) of calculated slope into a raster in a geographic information systems format. The least cost path is then found between each wastewater treatment plant and each power plant.

Advancing the Stillwell and Webber\textsuperscript{33} method, this analysis includes additional complexity by utilizing a genetic algorithm that considers all possible paths between wastewater treatment plants and power plants to select an optimal route. Practically, the genetic algorithm associated with MATLAB is employed; however, any genetic algorithm could be used. The cost of each pipeline is calculated using the same cost function from Stillwell and Webber\textsuperscript{33} with the flow, length, and cost scaler as inputs. The genetic algorithm treats the flows through each pipe as decision variables, constraining flows as non-negative, and minimizes the sum of all the pipe costs. Results with zero flow represent a pipeline that would be sub-optimal to construct. By formulating the optimization as a genetic algorithm, there is no need to assume any priority or water allocation rules. Although
the solution would likely be expensive, this formulation allows for one power plant to be supplied by multiple wastewater treatment plants or one wastewater treatment plant to supply multiple power plants.

The implications of transitioning from de facto reuse to engineered reuse using reclaimed water are evaluated using three feasibility metrics: cost, reliability, and performance. The cost of the generated reclaimed water network are approximated using construction constants. Additionally, the cost is estimated to retrofit cooling towers at power plants, since recirculating cooling is generally necessary when using reclaimed water. A first order approximation is completed of cooling tower costs based on a previously published method for evaluating economic feasibility of cooling system retrofits at power plants.\textsuperscript{63} Since only open- and closed-loop systems are compared without accounting for economic value of drought resilience, the original formulation is truncated as follows in Equation 2:

\[
A_C = P \left[ \frac{i(1+i)^t}{(1+i)^t-1} \right] + A_{O&M} G
\]  

where \( A_C \) is the annualized cost [$/yr], \( P \) is the present value of the construction [$], \( A_{O&M} \) is the annual operational cost per unit generation [$/MWh], \( G \) is annual generation [MWh/yr], \( i \) is the annual interest rate, and \( t \) is the amortization period [years]. Literature values providing low and high estimates for constructing cooling towers, along with an estimated operations and maintenance cost, are provided in Table 1.\textsuperscript{64,65} The actual retrofit costs associated with cooling towers are site specific and include factors such as space requirements, geography, operations, and water quality; therefore, this analysis represents an initial approach to support water resources planning and decision-making.
Beyond cost, reliability is an important metric to assess infrastructure. Reliability assesses the probability that a system is in a “satisfactory state” as defined by Hashimoto et al.\textsuperscript{66} Alternatively, reliability is defined mathematically, as shown in Equation 3:

\[ \text{Reliability} = 1 - P[\text{failure}] \]  

(3)

where failure is defined as an unsatisfactory state. Data on detailed power plant operations (especially curtailments or efficiency losses) are scarce in public databases. To cope with this limitation, failure is defined as the number of days that a power plant requires a thermal variance. The USEPA and state permitting agencies issue National Pollutant Discharge Elimination System (NPDES) permits to power plants regulating maximum cooling water effluent temperature(s), based on §316(a) of the Clean Water Act. On the occasion that a power plant cannot meet the temperature requirement, it is either fined or can request a temporary thermal variance from the state permitting agency. Although violations are public information,\textsuperscript{67} these data are often aggregated with no description of the cause of the fine. Consequently, failure is defined as the threshold under the influence of policy, that is, via granted thermal variance provisions. A change in administration or policy could change the granting of thermal variance requests or ramifications for violating discharge temperature limits, or could require other actions altogether. By assessing reliability, power plants and watershed managers are informed in planning for both policy and hydrologic changes.

---

**Table 1.** Estimated unit costs for retrofitting with cooling towers vary widely for different fuels.\textsuperscript{a}

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Capital Cost (US$/MW)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Coal</td>
<td>US$85,600</td>
<td>US$95,100</td>
</tr>
<tr>
<td>Nuclear</td>
<td>US$205,000</td>
<td>US$1,240,000</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Adapted from Stillwell & Webber (2012)\textsuperscript{33}
Finally, this method quantitatively evaluates power generation performance when using reclaimed water for cooling. Intake water temperatures affect cooling systems, and can vary substantially in natural systems due to climatic factors and external forcings (e.g., upstream heat loading). Reclaimed water, on the other hand, is more consistent in temperature and generally below the threshold temperature required for efficient cooling. Efficiency losses for the de facto reuse conditions and engineered reuse scenario are compared using a model introduced by Miara and Vörösmarty, which assumes an efficiency loss of 1.25% for every 1 kPa increase in the cooling system condenser pressure once a minimum threshold is reached. This minimum threshold is related to water temperature by the physical properties of water as a saturated liquid. The condensing temperature is related linearly to the wet bulb air temperature, which in situations with high humidity is assumed to be equal to the intake water temperature. Using historic averages of river temperature, the efficiency loss at each power plant (\( \eta \)) is estimated, which directly relates the power plant capacity (\( N \)) with generation capacity loss (\( N_{\text{loss}} \)), shown in Equation 4:

\[
N_{\text{loss}} = \eta N
\]  

(4)

In addition to any efficiency losses due to warm cooling water, parasitic pumping losses are included in the analysis of the reclaimed water (engineered reuse) scenario. Power plants are typically located next to a cooling water source such that cooling water pumping is approximated as negligible in the de facto scenario. Pumping large volumes of water considerable distances requires substantial energy to overcome changes in elevation, as well as major and minor friction losses in the distribution system. In the absence of a detailed pipe network, this method accounts for only major losses due to friction (using the Hazen-Williams equation; see section 3.3.5 for details) and elevation changes. Operationally, constant pumping rates over time are assumed, which is consistent with operations at baseload power plants.

### 3.3 Results

To illustrate the proposed method, a watershed in northeastern Illinois, U.S., including the City of Chicago and several surrounding suburbs, is analyzed. Shown in Figure 1, the study area is comprised of three Hydrologic Unit Code (HUC) 8 basins that drain to form the Illinois River. The Illinois River and the waterways within the study area are important for barge transportation,
connecting the Mississippi River to the Great Lakes. Of the river basins in the study area, Chicago is highly urbanized, the Des Plaines is suburban, and the Kankakee is primarily agricultural. The Chicago Area Waterways (CAW) are highly engineered, including several locks, dams, and diversions from Lake Michigan. Within the study area, there are 72 municipal wastewater treatment plants (WWTP) and 6 power plants. Figure 2 illustrates the median wastewater production and power plant withdrawals, with most of the wastewater treatment plants located upstream of the power plants.

**Figure 1:** The study area; the Greater Chicago Area includes 72 wastewater treatment plants and 6 power plants. It is comprised of three HUC 8 watersheds of varying degrees of urbanization.

**Figure 2:** Currently of the 6 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 area.
Cumulatively, the wastewater treatment plants discharge on average 1,600 million gallons per day (MGD) during dry years, with three facilities (Stickney, North Side (O’Brian), and Calumet) managed by the Metropolitan Water Reclamation District of Greater Chicago (MWRD) contributing 80% of the total discharge flow. The study area power plants, which are described in Table 2, employ primarily open-loop cooling systems and use a variety of fuels. The study area is situated such that the power plants are located near the mouth of the basin and downstream from many of the wastewater treatment plants.

**Table 2.** The study area power plants have different fuel and cooling characteristics.

<table>
<thead>
<tr>
<th>Name</th>
<th>Capacity (MW)</th>
<th>Fuel</th>
<th>Cooling system</th>
<th>Water source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will County</td>
<td>898</td>
<td>Coal</td>
<td>Open loop</td>
<td>Chicago SSC</td>
</tr>
<tr>
<td>Joliet 9</td>
<td>360</td>
<td>Coal</td>
<td>Open loop</td>
<td>Des Plaines River</td>
</tr>
<tr>
<td>Joliet 29</td>
<td>1320</td>
<td>Coal</td>
<td>Open loop&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Des Plaines River</td>
</tr>
<tr>
<td>Braidwood</td>
<td>2450</td>
<td>Nuclear</td>
<td>Open loop</td>
<td>Kankakee River</td>
</tr>
<tr>
<td>Dresden</td>
<td>2019</td>
<td>Nuclear</td>
<td>Open loop&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Kankakee River</td>
</tr>
<tr>
<td>Kendall County</td>
<td>1256</td>
<td>Natural Gas</td>
<td>Closed loop</td>
<td>Illinois River</td>
</tr>
</tbody>
</table>

<sup>a</sup> Has facilities to operate as closed-loop but primarily utilizes open-loop cooling.

### 3.3.1 De facto Reuse

Using flow data from the gaging stations shown in Figure 1 and wastewater effluent averages, the median de facto reuse at each power plant is calculated. Although a straightforward calculation, the spatial aspects of the data are important. For the 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 gage and power plant. Figure 3 illustrates one of these instances (panel (B)) where a wastewater treatment plant might discharge downstream from a stream gage. Under this condition, wastewater effluent is included in the numerator and denominator of the de facto calculation (using Equation 1) since the upstream gauge does not account for its flow. Similar mass balance logic is used for instances where two streams merge or the nearest gage is downstream from the power plant.
**Figure 3:** 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), there are not sufficient data to calculate de facto reuse during a CSO event; in response, data associated with CSOs are removed.

First, the median de facto reuse at each plant is calculated using the same technique as Rice et al.\textsuperscript{25,26} Shown in Figure 4, it is found that de facto reuse is very high compared to national averages and increases with proximity to the City of Chicago.
Figure 4: The de facto reuse, as calculated with the medians, increases with proximity to the large wastewater treatment plants. The two nuclear power plants have minimal de facto reuse percentages due to significantly less wastewater discharges in the Kankakee River basin.
The Will County power plant has the largest median de facto reuse at 65% while the Joliet 9 and 29 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 reuse 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. These results can be explained as a function of proximity to the large 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.

The daily wastewater effluent and stream data from the MWRD and the U.S. Geological Survey (USGS), respectively, between the years 2007 and 2014 are analyzed. Daily data for the remaining wastewater treatment plants are unavailable; therefore, approximate daily effluent flows from reported annual averages are used. In the 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. The study area scale is sufficiently small to avoid time lag challenges; similarly, infiltration, evaporation, or unaccounted withdrawals do not appear to be of concern. This result can be explained by the highly engineered and complex system of dams controlling the waterways. The modeling and research of these waterways is extensive, ongoing, and beyond the scope of this work.\textsuperscript{69–71} Therefore, a one-week moving average is employed before calculating the de facto reuse. Representing the de facto reuse visually by depicting wastewater effluent (numerator in Equation 1) against streamflow (denominator in Equation 1), is shown in Figure 3 (a1, b1, & c1). Although the one-week moving average smoothing does not eliminate all the points greater than 100%, it reduces their number and magnitude. The remaining percentages greater than 100, left of the dotted line in Figure 3, are within the margin of error.
Figure 5: Correlation exists between streamflow and wastewater effluent in the highly urban watershed of Chicago.
The regression plots in Figure 3 (a1, b1, & c1) 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 that wastewater effluent is independent of streamflow is acceptable in most basins, but that assumption breaks down in highly urban environments.

Representing the de facto reuse as a probability mass function in Figure 3 (a2, b2, & c2), 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 is performed. Since the two nuclear plants in this basin have such low preliminary de facto reuse percentages, a more precise analysis would likely reveal similar results.

3.3.2 Engineered Reuse

To compare the de facto reuse scenario to an engineered reuse scenario the optimal system to supply reclaimed water to power plants is formulated. Combining a digital elevation model and land use rasters from the USGS, a cost scaling raster is created for the greater Chicago area, shown as the background in Figure 6. Refining this method, the cost scaling raster is expanded beyond the watershed boundary to allow the paths to traverse the least expensive route, with darker areas of Figure 6 indicating more expensive areas to build a pipeline. Topography in the study area is relatively flat, such that the cost scaling raster reflects differences in urban density.

Retrofitting power plants to use reclaimed water in recirculating cooling towers is also simulated. 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, empirical and literature values specific to power generation in Illinois are used. 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.

Shown in Figure 6, the cost scaling raster combines land use and slope data. Using the created raster, the least cost path between each power plant and each wastewater treatment plant is found. To determine which pipeline paths should represent the engineered reuse solution, the scalers associated with each pipeline are exported via the Python library associated with ArcMap. This method employs a genetic algorithm rather than a non-linear solver to avoid subjective prioritization in reclaimed water allocations and to create a more robust optimization to minimize total cost. Inputs are the lengths and cost scalers for each pipeline path and the solution is constrained by the supply and demands of reclaimed water. The decision variables are the diameters of each pipe; therefore, a diameter of zero represents a pipeline not built. Note that the genetic algorithm does not include an accounting mechanism for overlapping pipes that would likely be combined into one larger pipe in practice. The advanced computational power of the genetic algorithm provides sufficient flexibility to capture straightforward and more complex results such that the method is broadly applicable in other locations.

The least cost path between the wastewater treatment plants and power plants is displayed as the thin black lines in Figure 7. The genetic algorithm examines possible reclaimed water pipelines and selects the optimal solution, displayed as the thicker black line in Figure 7, representing piping reclaimed water from Stickney WWTP to each of the power plants.
Figure 6: Retrofitting the power plants to closed loop cooling systems reduces the water demand such that, using the cost scaling raster, the least cost path between wastewater treatment plants and power plants can be found.
Figure 7: The least cost engineered reuse solution is a pipeline connecting the nearest treatment plant capable of providing all cooling demands.
3.3.3 Cost

To approximate the cost of retrofitting power plants to use reclaimed water (engineered reuse), the average of the low and high estimates from Table 3 are used for each power plant in the study area, listed in Table 2. 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 (see Stillwell and Webber\textsuperscript{33} for additional explanation). The estimated pipeline construction cost is $356 million, or $23 million/yr using a 30-year amortization period and interest rate of 5%. Similar feasible (yet sub-optimal) solutions for complete sourcing from the Calumet or Northside (O’Brien) WWTPs reveal estimated costs of $423 million and $615 million, respectively. Combined, the total capital costs for the engineered reuse scenario exceeds $2 billion. De facto reuse, 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. Of particular note is the cost of the reclaimed water pipeline compared to the cost of retrofitting power plant cooling systems. In this study, the cost of constructing cooling towers at the Braidwood nuclear plant is half of the total cost, compared to 15% for the reclaimed water pipeline.

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Capital Cost (US$)</th>
<th>Annual O&amp;M (US$)</th>
<th>Total Annual Cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will County</td>
<td>US$81,000,000</td>
<td>US$2,120</td>
<td>US$5,278,000</td>
</tr>
<tr>
<td>Joliet 9</td>
<td>US$33,000,000</td>
<td>US$850</td>
<td>US$2,119,000</td>
</tr>
<tr>
<td>Joliet 29</td>
<td>US$119,000,000</td>
<td>US$3,120</td>
<td>US$7,761,000</td>
</tr>
<tr>
<td>Braidwood</td>
<td>US$1,770,000,000</td>
<td>US$5,780</td>
<td>US$115,146,000</td>
</tr>
<tr>
<td>Dresden</td>
<td>--</td>
<td>US$4,760</td>
<td>US$4,760</td>
</tr>
<tr>
<td>Kendall County</td>
<td>--</td>
<td>US$2,960</td>
<td>US$2,960</td>
</tr>
</tbody>
</table>

3.3.4 Reliability

To calculate reliability, the likelihood of a power generation “failure” via a thermal variance event is quantitatively evaluated. Documentation from the Illinois Environmental Protection Agency (IEPA) of thermal variances from 2003 to 2014 is collected and organized.\textsuperscript{72} During this time
period, 76 thermal variance days were recorded in the Chicago area out of 4,015 total days. Using Equation 2 and defining thermal variances as failures, 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. This method accounts 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 as an arbitrary approximation, leading to a simulated power generation reliability of 91%.

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 8. Most thermal variances occur 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 existing cooling water intake structures can mitigate that risk.

Figure 8: Without power plant operational data, thermal variances are used as a proxy for failure. Warmer seasons produce more thermal variances that have negative ramifications for the power plant and environment.
3.3.5 Performance

To assess the power plants’ operational performance under the de facto and engineered reuse scenarios, the capacity loss due to warmer cooling water and power consumed during reclaimed water pumping is modeled. Using reported average monthly intake temperatures from the Energy Information Administration for the years 2010 through 2013, the capacity loss model (described in section 3.2) is applied for each of the power plants. Since detailed operational information on these power plants is not available, estimates from literature for the threshold at which the intake temperature begins to affect capacity are used. Shown in Figure 9, the modeled capacity loss at each power plant is compiled (illustrated as stacked bars) to represent the total generation capacity loss for the study area. A peak capacity loss of 250 MW occurs for the de facto reuse scenario compared to a peak capacity loss of 50 MW for the engineered reuse scenario. The large 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 threshold for efficiency loss in power plant cooling.

![Figure 9: Capacity loss due to the intake of warm cooling water during the summer months is much greater than the cumulative parasitic loss due to pumping reclaimed water year round.](image)

Although the engineered reuse scenario causes less capacity loss from elevated cooling water temperatures, the pumping and distribution of reclaimed water from the wastewater treatment plant is quantified. Power for reclaimed water pumping is estimated using conservation of energy, and accounts for major (friction) losses with the Hazen-Williams equation shown in Equation 5: \[73\]
where \( q_w \) is the flow of reclaimed water [gpm], \( C \) is the Hazen-Williams roughness coefficient, \( D \) is diameter [feet], \( h_l \) is the head loss [feet], and \( L \) is the length of pipe [feet]. The life span of the system is assumed to be greater than 30 years; therefore, a conservative \( C \) value of 100 is used. The diameter of each pipe is calculated assuming a hydraulic slope, representing the ratio between head loss and length, of 0.003. Combining elevation changes and major friction losses, the power requirements for reclaimed water pumping are estimated using Equation 6:

\[
P = k \frac{q_h}{\eta}
\]

where \( P \) is the pumping power [MW], \( k \) is a units conversion constant equal to 331,041.912, \( \gamma \) is the specific weight of water [lb/ft\(^3\)], \( q \) is flow [gpm], \( h \) is the total head required [feet], and \( \eta \) is the combined efficiency of the pump and motor. The power associated with pumping reclaimed water to the power plants is less than 1 MW. In comparing de facto reuse conditions and the engineered reuse scenario, reclaimed water for power plant cooling is preferable due to substantially lower capacity losses 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\(^{74}\) and assuming the study area power plants would be operating at full capacity, a first order approximation of revenue loss of about $32 million/year due to cooling inefficiencies under de facto reuse conditions is calculated, which exceeds the initial cost estimate for reclaimed water pipeline construction.
CHAPTER 4: DOWNSTREAM IMPACTS

“Do unto those downstream as you would have those upstream do unto you”
- Wendell Berry

4.1 Introduction

Whether reclaimed water is utilized in an engineering sense or not, it still affects society and the environment. In the past, wastewater was considered a liability due to its low quality; however, in the face of better technology and water scarcity, it is now being considered a resource. Reclaimed water has great potential for expanding the quantity of water available. It is estimated that about 20 billion gallons per day of wastewater effluent are discharged in the United States upstream of other users. As demands grow, society has the opportunity to match end uses with suitable water quality without wasting resources on over-treating.

Using reclaimed water can be sustainable at a local level (as shown in Chapter 3), but downstream impacts are less understood. Presently, most wastewater effluent is discharged to a waterbody that then flows downstream to another user, known as de facto reuse. In some cases, the percentage of wastewater is quite high. The question remains: What happens to the flow if the treated wastewater is diverted for some other purpose? Additionally, in such a scenario, do the downstream users have a legal right to that discharge? To answer such questions a method is proposed for quantifying changes in streamflow using scenario analysis along with pooled t-tests and conditional probability. Results from these metrics, along with the local legal framework, can be applied to assess the merits of individual reclaimed projects or more broadly to design policies that are beneficial to all stakeholders.
4.2 Method

4.2.1 Scenario analysis

Considering a proposed consumptive reclaimed water system, this study is interested in quantitatively measuring the downstream impacts using historical flow data. The goal of this analysis is to compare the historical, or de facto, data to a modified version representing the scenario in which reclaimed water is consumed. By using historical data, hydrologic stationarity is assumed, but this assumption could be amended to represent expected changes. The data required are daily average flow data for gauges at varying distances from the wastewater treatment plant from which the reclaimed water is to be diverted. The multiple stream gauges aid in the analysis by describing the effect that distance has on the severity of impact.

To construct the simulated engineered reuse streamflow data, a simple transformation is performed on the historical data. For all data points, the amount of proposed reclaimed water consumption is subtracted, shown in Equation 7:

\[ E_t = D_t - r_t \] (7)

where \( E_t \) is the hypothetical flow downstream, \( D_t \) is the flow reported at the same location, and \( r_t \) is the proposed reclaimed water consumption, with each value from the same time step in days. In essence, the transformation shifts the flow duration curve left so that the same exceedance probability returns a lower streamflow. Formulating the shift in this manner allows the reclaimed water consumption to be either static or dynamic. Subtracting a set amount from all data points assumes that reclaimed water consumption would be constant. Static consumption is a good assumption for baseload power plants but not for agriculture, which typically has a seasonal demand pattern.

A major tool of the hydrologist is the flow duration curve, which graphically depicts the historical flows similar to a cumulative distribution frequency graph.\(^{73}\) Plotting the historical data compared to the engineered reuse scenario in this manner can give intuition on the downstream impacts of reclaimed water consumption.
4.2.2 Statistical significance

Quantifying the significance of the change in streamflow using difference of means further illustrates whether or not the regime shift due to reclaimed water consumption is important. Specifically, the pooled variance $t$-test is employed. This metric assumes a null hypothesis of no difference between the means of the historical flow data and the engineered reuse scenario. To calculate, Equation 8 is used:

$$ t = \frac{\bar{X}_D - \bar{X}_E}{\sigma \sqrt{\frac{1}{n}}} $$

(8)

where $t$ is the $t$ statistic, $\bar{X}_D$ is the sample mean from the de facto flow data, $\bar{X}_E$ is the sample mean from the engineered reuse scenario, $\sigma$ is the standard deviation of the historical data, and $n$ is the number of samples. Because the engineered reuse scenario is built from the historical data, the scenarios share the same standard deviation and sample size, thus the typical pooled $t$-test equation is greatly simplified.

Comparing the $t$ statistic to a critical value that represents the region for rejecting the null hypothesis demonstrates whether or not the difference in means is statistically significant. Critical values are determined by the $t$ statistic that correlates to the region representing the significance, $\alpha$, under the tail of a $t$ distribution with the same number of degrees of freedom as the flow data. An $\alpha$ of 0.05 is commonly used as a threshold for significance. When the $t$ statistic is greater than the critical $t$ value, the null hypothesis is rejected and there is evidence that the difference between the scenarios is statistically significant.

Repeating this process for each gauge and varying levels of consumption provides a clear picture about the effects of consumption spatially. Testing for statistical significance is a good way to prove reclaimed water consumption has less impact than the uncertainty in the river itself. However, when consumption returns statistical significance, other methods must be used to further determine if the downstream impacts are large enough to forgo the reclaimed water consumption.

4.2.3 Probability of failure

To determine the implication of significance, a metric is employed that represents the fraction of time that the flow might fall below a threshold. Each stakeholder should define this threshold so
that the most susceptible water user (individual or group) can be evaluated. Similar to consumption, this threshold could also be dynamic. Therefore, a definition of risk, or probability of failure, that assesses each datum individually against an appropriate threshold is used.\(^6\) Hence the probability that the streamflow is not above the required threshold is calculated using Equation 9:

\[
P(f) = \frac{f}{n} \tag{9}
\]

where \(P(f)\) is the probability of failure, \(f\) is the number of data points that are deemed unsatisfactory, and \(n\) is the total number of data points. This calculation is performed on both the historical, de facto, flow data to gain insight into the current situation. In many cases, there might already be significant shortfalls. Repeating this calculation for the data transformed to represent the engineered reuse scenario allows comparison and a way to quantitatively assess how consumption will impact downstream flows.

### 4.2.4 Value

Determining the increase in probability of failure is important in understanding the impacts of reclaimed water consumption, but it does not necessarily inform the decision makers about the ramifications. To understand the ramifications, one must understand the value that the stakeholders receive from the flow. Users value the streamflow differently; therefore, it is necessary to use stakeholder engagement to balance the rights of the upstream and downstream.

The value agriculture and industry receive from the flow can be quantified by using the rate of withdrawals and the cost of the next best alternative water source. Simply put, the value of production that would be lost if withdrawals were curtailed due to reduced flows should be used to balance the claims. Municipal demands can have inherently high value due to basic water needs such as drinking and bathing, yet other low-value demands such as outdoor irrigation also depend on municipal water. Approximately half of nationwide municipal demands are expended for outdoor use such as landscape irrigation.\(^47\) Consequently, downstream municipal water users can represent high-value stakeholders, but significant conservation and efficiency gains are typically possible as well.
On major waterways, shipping and barge transportation have an important stake in downstream flows. Barges can carry much more weight than trucks or trains for the same amount of fuel, making waterborne transportation both economically and environmentally efficient.\textsuperscript{80} Additionally, barges do not compete with cars for highway capacity, thereby reducing congestion. Conversely, barges can only traverse areas where the rivers and canals are large enough and properly maintained. Typical of barge routes are locks and dams. Dams keep water levels at navigable depths and locks allow the barges to traverse the dams. In the United States, the Army Corps of Engineers is most often the lock and dam operator, and in doing so keeps public records of the tonnage and type of commodities that pass through on barges. Reported as yearly values, these tonnages are important to quantifying mass of specific commodities transported annually on the waterway downstream.

Environmental valuation is a complex and difficult to quantify economic challenge that is beyond the scope of this work. However, legislation such as the Clean Water Act\textsuperscript{51} has given authority to governmental agencies to prohibit jeopardizing waterways. During any discussion of consumptive water reuse, it is assumed that the agencies in charge of protecting downstream flows would be able to articulate necessary requirements without having to define monetary value. Furthermore, in the case of cooling power plants that have traditionally operated as open-loop cooled facilities, concerns over streamflow would most likely be trumped by concerns over thermal pollution.

4.2.5 Legal ownership of reclaimed water

In the case that consumptive reclaimed water use impacts downstream users and an agreement cannot be reached, ownership should be investigated. To assess reclaimed water consumption as it relates to downstream users, the statutes and precedents are considered. In the case of prior appropriation doctrines that are based on consumption, such as in California, the law is definite in that downstream users have a right to the wastewater effluent.

Without direct legislation regarding reclaimed water, water law must be extrapolated. Water law varies from state to state; however, water rights systems generally follow one of two approaches: riparian and prior appropriation rights. Common law riparian rights are normally associated with states in the eastern United States where water has been historically abundant, with policies stemming from judicial rulings rather than legislation. This doctrine entitles landowners to water
that flows over or adjacent to their property. Conversely, the states in the western United States, where climate is typically drier, often follow the prior appropriation doctrine. This legislation was enacted to resolve water conflicts by assigning a priority structure for users based on seniority.

Each state varies in its legislation, precedents, and enforcement of water rights; therefore, it is important to understand the local water law. Applying the existing water law to reclaimed water primarily hinges on the ownership of water once it is extracted from the environment. If the water is private property at this point, it will most likely be the will of the owner on what to do with that water, as long as any discharge meets certain environmental requirements. If the wastewater treatment plant has no legal right to the effluent, then no further analysis is needed because downstream water users are legally entitled to the discharge.

Since water law, especially in a riparian regime, often relies on decisions from the court system, it is imprudent to assume judgments regarding a specific scenario would be applied ubiquitously. The courts demonstrate routinely that conflicting rights should be balanced. This balance between water users means that in the absence of clear legislation regarding reclaimed water rights, water reuse developments should consider any stakeholders that might value the reclaimed water in situ.

4.3 Results

4.3.1 Case Study

To demonstrate the techniques described, a real scenario is analyzed in which reclaimed water could be utilized for power plant cooling. For this purpose, Chapter 3 provides a useful study location. Comprised of three HUC 8 watersheds (Chicago, Des Plaines, and Kankakee River basins), these basins form the headwaters for the Illinois River. Located within the study area are 6 power plants and 72 wastewater treatment plants. The power plants have a total capacity of 7,900 MW, with 5 of the 6 power plants operating open-loop cooling systems. While drastically reducing withdrawals, retrofitting to cooling towers would increase total consumption for power generation to less than 200 MGD. The supply of wastewater in the study area is very large due to high population densities and combined sewers. The total amount of treated effluent discharged in our study area typically exceeds 1,800 MGD. As shown in Chapter 3, the costs of cooling power plants in the area could be rationalized by the increases in reliability and performance. Since additional
concerns arise regarding downstream impacts, the study area is expanded to include the Illinois River. Shown in Figure 10, the Illinois River begins at the confluence of the Des Plaines and Kankakee Rivers.

![Map of the Illinois River](image)

**Figure 10:** The Illinois River connects Lake Michigan with the Mississippi River and is downstream from the proposed consumptive use of reclaimed water.

This confluence also marks the outlet for the study area previously used to assess reclaimed water for power plant cooling (see Chapter 3). The Illinois River, a tributary of the Mississippi River,
provides a waterway to Chicago and then 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 Army Corps of Engineers.

Defining who or what is important downstream is critical for understanding the impacts. For the Illinois River, the most critical stakeholder is barge traffic. The Illinois River does not sustain large fishing operations or support a large number of water withdrawals. There are a few power plants that currently rely on the Illinois River for cooling water; however, these facilities are not considered in this analysis because they would not be affected by the changes proposed. Barges are important to the region for inexpensive transportation of raw materials, coal, petroleum, and agricultural products. Since barge traffic relies on a channel deep enough to float, this analysis focuses on waterborne transportation as the primary 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.81,82

4.3.2 Scenario analysis

To quantitatively assess the downstream impacts of reclaimed water consumption, scenario analysis is employed, comparing the proposed scenario to the current conditions. Primarily, this study is interested in the effects of consuming 200 MGD of reclaimed water for cooling power plants. Further, this analysis aims to understand 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, a uniform demand of reclaimed water on a daily and seasonal timescale is assumed. Since this analysis specifically considers using reclaimed water for thermoelectric power plant cooling, this assumption remains valid due to the fairly constant water demands.

The data used for this analysis are streamflow and stage data from the USGS and Army Corps of Engineers. The data at the locks and dams represent the tail water side and include 25 years of daily data. The data reported at these sites represent the de facto scenario and a selection are displayed as flow duration curves in Figure 11. Using Equation 7, engineered reuse scenarios are
calculated by subtracting the quantity of consumption from all data points to shift the flow duration curves. The 200 MGD consumption is represented in Figure 11.

**Figure 11: Consuming reclaimed water upstream shifts the flow duration curves downstream.**

At all of the gauges except on the Kankakee River, the flow duration curve shift is to the left. The Kankakee River curve shifts to the right, signifying more streamflow in the engineered reuse scenario than in the de facto scenario. This increase in flow under engineered reuse conditions is due to the retrofit of two power plants that currently withdraw water from the Kankakee River to
instead consume reclaimed water that is not produced in that basin. Note that while the other three flow duration curves all depict the same 200 MGD reduction in streamflow, gauges further downstream have larger drainage areas; therefore, the shift appears smaller.

4.3.3 Statistical significance

Applying the difference in means statistical test to compare the de facto scenario with each engineered reuse scenario, the $t$ statistics for each gauge are calculated. A value of 0.05 is used for $\alpha$, which correlates to a $t$ statistic threshold of just under 2. Results greater than this threshold are considered statistically significant.

Using a water reuse simulation step size of 10 MGD for the range of consumption (0 to 1,800 MGD), the maximum level of consumption without having a statistically significant impact is calculated. Although the entire range of consumption scenarios are calculated, only up to 500 MGD are displayed in Figure 12.

![Diagram showing t statistics and significance](image)

**Figure 12:** Consumption above 100 MGD would lead to statistically significant changes in downstream flow.
From the results, the 200 MGD scenario for power plant cooling is significant at the first two gauges downstream from the wastewater treatment plant. An important, although previously unquantified, conclusion is that impacts of reclaimed water consumption diminish with distance.

Reclaimed water consumption could approach 100 MGD and not cause any statistically significant change in streamflow in the study area. While reclaimed water consumption of 100 MGD would not provide sufficient cooling water to all six power plants in the study area, a few could be cooled without ramification of any quantifiable downstream impacts. Also shown in Figure 12 is the threshold for $\alpha$ of 0.01, representing a more relaxed threshold for significance. Increasing this threshold allows the maximum reclaimed water consumption to increase to 150 MGD. Since 200 MGD returns statistically significant differences in means for gauges directly downstream, further investigation is needed to determine the amount of impact reclaimed water consumption would have downstream.

4.3.4 Probability of failure

Defining barge transportation as the most at-risk downstream stakeholder, this study is more concerned with stage than in-stream flow. The Army Corps of Engineers aims to maintain a minimum depth of 9 feet along the Illinois River. Using the reported stage and flow data immediately downstream from each lock and dam in Equation 9, the current probability that the minimum stage is not met is found. All five gauges have some very low (<1%) probability of failure in the de facto scenario.

Since the threshold is defined as a stage, the reclaimed water consumption must be converted from a reduction in flow to a reduction in stage. Ideally, rating curves would be utilized to relate streamflow to stage; however, rating curves are not available or are inaccurate for low flows at the study gauges. To establish a relationship between flow and stage, linear regression is used. Nonlinear relationships could also be used; however, for the highly engineered operation of the Illinois River, nonlinear models do not produce more accurate results. This study is concerned with low flows that put downstream users at risk, hence only the lower 50th percentile of flows are used in the linear regression model. Figure 13 depicts this process for one of the gauges and is
representative of the method for each location. The result of using the entire data set for the regression is also illustrated for completion.

**Figure 13:** Without rating curves, linear regression is used to estimate the relationship between flow and stage.

The full data regression does not accurately represent the range of low flows. Further the lower slope would underrepresent the reduction in stage from upstream consumption. Using the slope from the rating curve the stage is shifted using Equation 10:

\[
l_t' = l_t - mr_t
\]

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, with each value for the same time \(t\). By shifting the stage, similar to the shifting of the flow duration curve, the number of data points that fall below the threshold of 9 feet at each gauge can be assessed. The probability
of failure, calculated using Equation 9, can then be used to find the expected failure rate for each downstream gauge at varying levels of reclaimed water consumption.

Figure 14 displays the results for each gauge on the Illinois River. The 200 MGD consumption scenario simulating reclaimed water use for power plant cooling represents very small 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%. Even if the full supply of reclaimed water produced in the Chicago area was consumed (1800 MGD scenario), the probability of failure would increase to a maximum of 15% at Peoria. This analysis, however, does not capture the seasonality of precipitation. In Illinois, the precipitation is higher during the first half of the year than the second. For this reason, the probability of failure is conditioned based on time of year, repeating the same analysis for January through June (spring) and July through December (fall) data. The results show similar trends comparing gauges; however, the magnitudes are significantly different. During the spring, the wet season, failure probabilities are less than 4% in all scenarios, including total reclaimed water consumption of 1800 MGD. During the fall, the dry season, probabilities of failure approach 25% for total reclaimed water consumption; however, the 200 MGD scenario remains below 2%.
Figure 14: The probability that stage falls below the necessary 9 foot channel depth is very small under current conditions (no reclaimed water [RW] consumption) and increases marginally under the proposed consumption scenario of 200 MGD.
4.3.5 Value

To put the effect of decreased navigability of the Illinois River into perspective, this analysis considered the relative value of barge transportation. The Army Corps of Engineers reports the tonnage and type of commodity that passes through each lock. Using these data for the years 1999 through 2014, the amount of commodities passing through each lock via barge can be assessed. The average, shown in Figure 15, is representative of the larger annual trends. Most importantly, locations further downstream observe more traffic in terms of tonnage, with the difference attributed mainly to food and farm products. On average the most upstream gauge, Lockport, observes roughly half of the tonnage of the most downstream gauge, La Grange. This increase in tonnage at downstream locations is favorable for using reclaimed water to cool power plants in the Chicago area, since the consumptive affects diminish with downstream distance.

![Figure 15](image_url)

*Figure 15: The average tonnage recorded passing through the locks on the Illinois River increase 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, the Commodity Flow Survey and the associated Freight Analysis Framework (FAF³) are used. These data include tabulated 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, it is assumed the percentage of tonnage distributed by mode and commodity stays relatively constant. From the data, the waterborne market share of transportation is calculated; however, it might include other waterways not downstream of the consumptive reuse. To accurately account for the Illinois River, the unit value of each commodity is calculated, given by Equation 11:

\[ \text{Unit Cost} = \frac{V}{T} \]  

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 the spatial variability between different sections of a waterway.

From the FAF³, waterborne transportation accounts for 5% of the total tonnage. Trucks, by comparison, account for about 70% of the tonnage. Comparing the waterborne tonnage reported by the FAF³ and the Army Corps of Engineers data for the locks, barges on the Illinois River account for about one-third of the total waterborne tonnage. This fraction appears reasonable given that waterborne transportation could serve the state of Illinois via the Mississippi River, the Ohio River, or Lake Michigan without traversing the Illinois River. Comparing the total value of commodity flows through, to, or from Illinois, barge traffic on the Illinois River accounts for about 1%. Year to year this fraction might vary; however, this analysis reveals that barge traffic on the Illinois River has a small impact on overall statewide commodity transportation.

4.3.6 Legal ownership of reclaimed water

Illinois does not manage reclaimed water directly in legislation. To understand the legality of reclaimed water, the framework for water law in Illinois must be interpreted. The system of water governance stems from a riparian common law of torts, meaning water rights are included with property rights, as opposed to prior appropriation where the two rights are severed. More specifically, the landowner would have the right to “reasonably” use water from a surface water resource that borders the property. The term “reasonable” comes from civil litigation [Evans v.
Merriweather], where the court determined that riparian rights only extend so as not to obstruct another user’s right to also make reasonable use.

Reclaimed water presents a challenge because it is not part of the surface water resource until it is discharged. In Illinois, when water is removed from the natural system, assuming it was removed lawfully, the water becomes private property. As private property, the owner may use or sell it in any manner that does not violate the environmental regulations such as the Environmental Protection Act [415 ILCS 5/1]. These statutes regulate pollutants entering the waters rather than the quantity of water. Under this construct, reclaimed water is considered private property of the wastewater treatment plant. Contesting this ownership would require proving the initial withdrawal from the environment was unreasonable, which in the case of municipalities, would be a difficult argument to make.

Additionally, the source of water would have to be natural waters, meaning upstream of the party challenging ownership. Chicago sources its potable water from Lake Michigan; therefore, it is considered a “developed” water source because it is not in the same river basin as the Illinois River. Developed waters are generally considered exempt from downstream considerations because the source of water could be terminated at any time.85 Therefore, consumption of the reclaimed water that originates from Lake Michigan would likely be legally protected.
CHAPTER 5: POLICY IMPLICATIONS

“If the grass is greener on the other side, you can bet the water bill is higher”
- Unknown

5.1 Open-loop cooling

From the power plant perspective, there is debate on whether or not current practices are legal. The state of Illinois issues temporary thermal variances for power plant cooling water discharges. The Clean Water Act, which regulates effluents, includes the ability to receive variances given that criteria are met that ensure minimal environmental risk. These variances become part of the permit indefinitely.

The Clean Water Act developed the NPDES permitting system, which delegates authority to states to regulate the temperature of the cooling water discharged into waterways. In the state of Illinois via the IEPA, provisional thermal variances include exceptions for unreasonable hardship, a provision not included in the Clean Water Act or the NPDES permitting structure. In practice, the IEPA has accepted the claim that converting to closed-loop cooling would merit an excessive financial burden and presents a hardship. This conclusion favors the power plants; however, Micha argued that the policy might not be in accordance with federal laws. Provisional variances might violate the Clean Water Act because they essentially alter the water quality standards approved by the USEPA.

Given the questionable legality of this practice, in the future power plants might have to convert to closed-loop cooling if the temporary variances are discontinued. Retrofitting to cooling towers would cause increased consumption without regard for downstream impacts. If retrofitting becomes a requirement, stakeholders downstream could be negatively affected, regardless of the location of the water withdrawal and consumption (i.e., natural surface water resources or wastewater treatment plants).

Understanding the grey area in which power plants receive thermal variances is important in assessing the suitability of reclaimed water. Retrofitting a power plant to incorporate cooling
towers is expensive; however, reclaimed water use in conjunction with cooling towers has additional reliability and performance benefits, as demonstrated in this analysis (see Chapter 3). Considering the possibility of an intervention by the USEPA, power plants might not be able to rely on provisional thermal variances in the future. In such a future, engineered water reuse at power plants might be increasingly attractive from a policy perspective.

5.2 Reclaimed water

Of the many uses for reclaimed water, power plants are able to capitalize on some of the properties that other users do not. Increased reliability and performance are realized due to the consistency in quantity and temperature. When other proposed reclaimed water uses are better suited due to proximity or other factors, the methods presented in this analysis are still applicable. For example, if the treated wastewater does not meet quality requirements necessary for cooling towers, there are still beneficial applications. Agriculture might be better suited for reclaimed water use, and could benefit from increased nutrient levels such as nitrogen and phosphorous. Additionally, seasonal demands for water could align with seasonally low demand downstream, making reuse acceptable. Flexibility in consumption is another important consideration. Some applications of reclaimed water allow for greater variability in consumption. For example, groundwater recharge has the ability to curtail reclaimed water consumption in times that would otherwise jeopardize downstream users. Applications that are not dependent on timing can more easily meet the downstream threshold described in the method in Chapter 4 by formulating consumption as a function of flow. Understanding the physical benefits and constraints in a regulatory setting is important to crafting effective policies.

Wastewater reuse within the confines of the legal environment can be difficult. Traditional water rights vary state to state as well as the local statutes concerning reclaimed water. The method presented in this analysis provides a framework for addressing the ambiguity. In states where it is not obvious that downstream users have a legal claim to wastewater discharges, the methods from Chapter 4 present quantitative metrics to support stakeholder engagement and address potential conflicts.
An additional consideration regarding the suitability of engineered water reuse is the price of the reclaimed water. Reported reclaimed water rates vary widely, with many wastewater utilities setting rates less than drinking water prices to encourage use. In this study area in Illinois, offering reclaimed water to power plants at little to no cost might incentivize cooling towers and protect against high thermal discharges in the summer. However, questions arise regarding ownership of wastewater effluent, especially in other geographic locations. In several western states, prior appropriation water rights laws account for return flows (wastewater discharges), such that downstream users might depend on wastewater effluent.
CHAPTER 6: CONCLUSIONS

“There are 86,400 seconds in a day. It's up to you to decide what to do with them” – Jimmy Valvano

Under the increasing stress on water resources, new tools are needed to determine the merits of seemingly sustainable solutions. This analysis provides methods for assessing local and regional impacts of reclaimed water consumption for cooling power plants.

Chapter 3 reveals important insights regarding water reuse, both under existing de facto conditions and in a simulated engineered reuse scenario. Reclaimed water use for power plant cooling incurs high infrastructure investment costs for pipeline construction and cooling system retrofits. These investments, however, mitigate the risk of power generation reliability concerns from thermal variances and capacity loss due to elevated water temperatures. When considering factors such as the environment or public policy, cooling power plants with reclaimed water can minimize the risk of the unknown. Understanding and quantifying these benefits and tradeoffs can help support sustainable water reuse and power generation.

Demonstrated in Chapter 4, the method provides clear and quantifiable ways of determining regional downstream impacts from consumptive water reuse, along with accounting for the legal structure of the state. Reclaimed water consumption in the Chicago region of 200 MGD would result in a statistically significant difference in streamflow within 50 river miles, but would be insignificant further downstream. The maximum probability of failure would increase from about 1% to 2%; however, barge traffic along the Illinois River accounts for less than 1% of the value of commodities shipped in Illinois, making the difference in streamflow relatively minor in terms of economics. Overall, in the model of cooling power plants with reclaimed water in Chicago, there are minimal downstream impacts (lower river stage) on an already insignificant industry (waterborne transportation).
It is important to use quantitative metrics because the merits of a reclaimed water system change with geographic factors. As reclaimed water becomes more necessary for resource management, policy makers have the opportunity to define simple rules for handling reclaimed water conflicts before they arise. By allowing uncertainty about reclaimed water outcomes to persist, the region might be sub-optimally allocating resources. Enabling a system where customers can buy reclaimed water without sacrificing other stakeholder’s rights to water creates a more economically efficient and environmentally sustainable society.

The following primary research questions were answered for the case study of the greater Chicago area of Illinois:

- *Given a specific scenario, is cooling power plants with reclaimed water beneficial?* In cases where the supply is sufficient to meet demand, the reliability of water supply and lower water temperature might warrant the high infrastructure costs.

- *How can the costs and benefits of cooling power plants with reclaimed water be quantitatively assessed?* Given accurate information, geospatial assessment tools, reliability metrics, and generation performance models can be used to accurately estimate the costs and benefits.

- *How can the impacts downstream of the reuse be quantitatively assessed?* Scenario analysis, along with *t* tests and conditional probability, can quantitatively assess downstream impacts.

- *What are the legal barriers and policy impacts of reuse?* The current legal environment concerning reclaimed water is not well formed; however, policy can be shaped to allow for efficient utilization with minimal risk.

More broadly, the methods presented are a necessary evolution in sustainable resource management. Reclaimed water, along with other seemingly sustainable propositions, requires holistic spatial and quantitative analyses that include stakeholder engagement. Moving forward, the techniques described should be expanded and others introduced so that projects and polices can be objectively evaluated to determine the local, distant, and future impacts.
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