ASSESSING DOWNSTREAM IMPACTS FROM AN ADDITIONAL CONSUMPTION OF RECLAIMED WASTEWATER EFFLUENT

by

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Assessing Downstream Impacts from an Additional Consumption of Reclaimed Wastewater Effluent

Thesis directed by Professor Joseph Kasprzyk

Consuming reclaimed wastewater effluent is becoming an increasingly popular alternative to consuming surface water or groundwater supplies. Although locally sustainable, impacts to downstream stakeholders require consideration prior to implementation of a proposed consumption. These downstream impacts are not typically evaluated in a quantitative manner, accounting for geospatial and systematic differences. Under certain statutory environments, downstream stakeholders may have a path towards legal recourse if additional consumption is determined to impact them. More broadly, the extent of downstream impacts is important in legal and policy contexts regarding the sustainability of reclaimed water projects.

In this thesis, a framework is presented to assess downstream impacts resulting from an additional consumption of reclaimed wastewater. This framework includes a scenario analysis of the region where the proposed consumption is conducted. This analysis is coupled with a pooled *t*-test on a transformation of streamflow data to determine the statistical significance in changes to mean streamflow. Further, potential lower streamflow is linked to impacts on downstream stakeholders through the use of stakeholder performance metrics. This framework is assessed in two distinct case studies in contrasting regions of the United States: 1) the Illinois River downstream from the greater Chicago, Illinois area, with a general abundance of water and large potential reclaimed water users, and 2) the Middle Rio Grande River downstream from Albuquerque, New Mexico, with high seasonal variability in water availability, ephemeral streamflow patterns, and prior appropriation water rights. In Illinois, impacts to barge transportation are assessed and determined to decrease with distance downstream of the proposed effluent consumption. In the Rio Grande, impacts to the Rio Grande silvery minnow are considered and determined to worsen with distance downstream of consumption, such that a proposed consumption would be unlikely to be established under federal regulations.

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Chapter 1. Introduction

Reclaimed water — municipal wastewater treatment plant effluent — can serve as an attractive alternative water resource due to its reliability and lower competition among freshwater demands. The U.S. Environmental Protection Agency (EPA) names water scarcity and the water-energy nexus as two of the primary motivators for increases in water reuse (U.S. Environmental Protection Agency, 2012). Utilizing reclaimed water has a great potential for expanding the quantity of water available, with an estimated 20 billion gallons of wastewater effluent discharged in the United States each day, often upstream of other users (National Research Council, 2012; US Environmental Protection Agency, 2008). As demands grow, reclaimed water presents an opportunity to better match various non-potable end uses with suitable water quality (Okun, 1997; Stillwell et al., 2011; Toze, 2006). Agricultural, industrial, municipal, and environmental water demands can benefit from increased supply and reliability of water supplies, with reclaimed water poised to satisfy many of these demands.

Presently, most municipal wastewater effluent is discharged to a waterbody that flows downstream to other users, known as de facto water reuse (Rice et al., 2015, 2013). In some cases, the percentage of wastewater present in waterways is quite high, approaching 100% during low flows (Rice and Westerhoff, 2015; Wiener et al., 2016). Despite this quantification of de facto reuse, the following questions remain: How might downstream flows change if the treated wastewater was diverted and consumed for some other purpose? In such a scenario, do downstream users have a legal right to the wastewater discharge?

To answer these questions in a socio-hydrology context, this thesis provides a method to quantitatively assess the impacts to downstream stakeholders using scenario analysis along with a two-sample *t*-test and stakeholder performance metrics. Results from these metrics, along with the local legal framework, can be applied to assess the relative merits of individual reclaimed projects, or more broadly, to design water resources policies that are more sustainable to all stakeholders. To demonstrate this method, several reclaimed wastewater effluent consumption scenarios are explored for two contrasting regions. The first scenario builds on previous work by Barker and Stillwell (2016) of reclaimed water consumption for thermoelectric power plant cooling in the greater Chicago, Illinois region. To analyze a contrasting scenario, reclaimed water consumption scenarios are assessed near Albuquerque, New Mexico along the Middle Rio Grande River. Each of these two regions represent differing water availability and streamflow patterns and contrasting water rights laws, with Illinois operating under regulated riparian water rights and New Mexico operating under prior appropriation. This thesis was adapted from a paper submitted to the Journal of Water Resources Planning and Management, co-authored by Zachary Barkjohn, Joseph R. Kasprzyk, and Ashlynn S. Stillwell.

Chapter 2. Background

2.1 Introduction

This chapter begins by discussing de facto water reuse, which refers to the fact that some water use is actually reusing existing wastewater effluent that represents a large portion of streamflow in many regions. Subsequently, the thesis discusses direct engineered water reuse, in which the wastewater effluent is used without being returned first to a waterbody. This chapter culminates with a discussion of legal considerations for reclaimed water reuse in the United States, and legal considerations should an additional consumption impact downstream stakeholders. A framework to assess these legal considerations can be found in the methods chapter.

2.2 Engineered and de-facto water use

Engineered or direct water reuse is the reuse of treated wastewater by directly transporting it from the treatment plant to the point of use (Binnie and Kimber, 2008). Engineered water reuse often replaces withdrawals from surface water or groundwater supplies. Although once considered a liability due to concerns over health and hygiene, wastewater is now viewed as a sustainable resource due to improvements in water treatment practices (Garcia and Pargament, 2015; Lazarova and Bahri, 2004). Due to the consistency of wastewater flows, certain applications are better suited for reclaimed water than others. For example, large non-potable water consumers, such as irrigators and industrial cooling towers, are particularly well suited for reclaimed water use (Asano et al., 2006; Stillwell et al., 2011; Stillwell and Webber, 2014).

Regardless of the end use application, most engineered reclaimed water projects represent consumptive uses such that the water is no longer available within the local watershed. Additional consumptions within a basin, such as a switch from open-loop to closed-loop cooling at thermoelectric power plants, are likely to reduce streamflow downstream (Barker and Stillwell, 2016; DeNooyer et al., 2016). Comparable to displacing groundwater or an inter-basin transfer source, an additional consumption of wastewater effluent reduces the downstream flows similar to introducing a new demand.

This additional consumption of wastewater effluent may limit the amount of de facto water available for use downstream. De facto water represents an important portion of the streamflow in many areas, particularly during dry conditions (Barker and Stillwell, 2016; Rice et al., 2013; Wiener et al., 2016). Determination of downstream impacts caused by a reduction in de facto water will ideally encompass the holistic function of rivers and streams, including instream ecosystem services and transportation, as well as serving as water sources for cities, industries, and agricultural operation. When evaluating a proposed reclaimed water project, important considerations should include quantifying the effects of displacing the original water source and downstream impacts associated with the change.

Currently, the portion of de facto water reuse downstream is an initial indication of the dependence of downstream users on wastewater effluent. Downstream users in reaches comprised of a large portion of de facto reuse are likely to be dependent on effluent. Previous research has quantified de facto use downstream. Different approaches in doing so range from determining the number of times water is reused in a single river reach (Vörösmarty et al., 2005) to basin-level analysis of the fraction of water reused (Le Van Chinh, 2012). Removing a portion of the de facto water available to be used may have quantifiable impacts to streamflow in the region and downstream stakeholders who rely on these flows.

2.3 Legal Considerations: Consuming Reclaimed Water

When assessing impacts from a proposed reclaimed water consumption, U.S. federal and state legislation concerning reclaimed water is limited. Guidelines published by the EPA (US Environmental Protection Agency, 2012), discuss quality, quantity, uses, existing state regulations, and development programs, with the intent to assist state, regional, and municipal governments in designing reclaimed water policies. Since the first introduction of these guidelines, the focus has been 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 and are not legally binding. When assessing the displacement of wastewater effluent, further consideration of the impacts to downstream users must be considered, which is discussed in the methods section.

2.4 Legal Considerations: Impacting Downstream Stakeholders

In the United States, both federal and state laws protect stakeholder interests against alterations to downstream streamflow. The impacted downstream stakeholder dictates which regulatory body has authorization to govern upstream consumptions.

Federal law takes precedent, and can be applied when direct interests of the federal government are involved (Getches, 2001). Such is the case in certain international compacts and court decisions, such as *Texas v. New Mexico et al.,* where the federal government can get involved for distinctively federal interests (Supreme Court Of The United States, 2018).

Similarly, environmental flow regulations to protect endangered species fall under federal jurisdiction (Appeals and Circuit, 1985; Ruhl, 1995). In each of these instances, the federal government has the authority to reject proposed reclaimed water projects that would reduce downstream flow.

When federal purposes are not involved, federal policy regarding reclaimed water in the United States is primarily in the form of guidelines rather than enforceable statutes (U.S. Environmental Protection Agency, 2012). Therefore, U.S. state laws reign supreme and should be investigated.

As of 2015, 22 states had statutes directly concerning reclaimed water use, (US Environmental Protection Agency, 2015), with most of those statutes governing reclaimed water quality and appropriate end use. When considering water ownership, each state varies in its legislation, precedents, and enforcement of water rights; therefore, understanding an individual state's water law becomes important. State water laws can generally be categorized as having riparian or prior appropriation water right doctrines, or a hybrid approach.

Prior appropriation doctrines issue water rights to users based on seniority or permit application date. States with these doctrines are often the most water scarce (Getches et al., 2015) and govern the difference between the quantity withdrawn from a source and the quantity discharged back to it. In-land cities often have return flow credits that require them to replenish a portion of their treated wastewater or acquire appropriate water rights (Scruggs and Thomson, 2017). Therefore, downstream users might have a legal right to the wastewater effluent, and the laws of the specific state should be considered.

Riparian water doctrines are less clear on ownership of reclaimed water since most policy approaches stem from judicial rulings. Common law riparian rights are typical in the eastern

United States where water is historically abundant (Getches et al., 2015), and do not typically have bearing on reclaimed water. Still, legislation at the state or local level might dictate how the rights of downstream stakeholders are considered in reclaimed water planning.

Chapter 3. Methods

3.1 Introduction

Considering a proposed reclaimed water consumption, the following methods quantitatively evaluate the downstream impacts of reduced streamflow using historical streamflow data. In this thesis, historical streamflow data are directly compared to a modified dataset representing the reclaimed water consumption scenario. To do so, observed streamflow for stream gages at varying downstream distances from the reclaimed water source is gathered, often collected from the United States Geological Survey (USGS) gage sources. The method can also incorporate probabilistic future streamflow predictions to augment the historical streamflow record.

3.2 Consumption Scenarios

Consumptive scenarios are dependent on the application of reclaimed water use. The scenarios can be uniform (equal consumption every day) or varied to mimic seasonal patterns. For instance, baseload thermoelectric power plants need a relatively constant, uniform supply of water (Peer and Sanders, 2016), while water demand for agricultural irrigation may vary depending on the season and crop distribution (Portmann et al., 2010). Effluent data from the wastewater treatment plant can be used to develop scenarios of reclaimed water, with assumptions being made as to the percentage of the reclaimed water that is consumptively reused.

The required timestep of the data is dependent on the downstream stakeholder being considered. For instance, many policies governing interstate or international water deliveries require a certain quantity of water to be delivered each year. When evaluating the ability of the governing party to meet these demands, a larger timestep can be applied than compared to when the considered stakeholder is susceptible to daily fluctuations in flow. In contrast, certain uses of streamflow, such as run-of-river hydropower plants, may require assessment on shorter timesteps.

Several techniques are available to modify the hydrologic timestep for the purposes of performing this analysis. To transform from a smaller to larger timestep, simple calculations of aggregation can be performed. Translating from a smaller to a larger timestep, however, can be more complicated. Daily streamflow data can be scaled down using hydrologic modeling (Waichler and Wigmosta, 2003). Using streamflow data derived from hydrologic models rather than observed flow may have other benefits beyond scaling the timestep of observations. Hydrologic models are able to generate synthetic streamflow records using historical or future climate predictions. This synthetic streamflow may include longer periods of high or low streamflow that may not have been observed in historical data. Assessing performance metrics using these extremes can be useful for planning purposes.

3.3 Engineered Streamflow

Streamflow following a proposed consumption is determined using historical data, gathered from the USGS and the United States Army Corps of Engineers (USACE). The resulting comparison between the historical streamflow and the amount of water removed via consumption is termed engineered streamflow, calculated using Equation (1),

$$E_t = D_t - r_t \quad (1)$$

where at each timestep (t), the engineered streamflow (E_t) is determined by reducing the observed streamflow (D_t), by the proposed consumption of reclaimed water (r_t). The magnitude and timing of r_t is constrained by the magnitude of effluent discharged from the wastewater treatment plant at time t.

Equation (1) assumes negligible travel time for the water discharged from the wastewater treatment plant to reach the gages. This assumption is valid for uniform consumption scenarios, short stretches of river, or long timesteps. If all of these criteria are not met, a lag in the timestep can be applied, which would depend on the routing of the river.

As discussed, this thesis uses the historical streamflow record for system analysis, but Equation (1) is broad enough to be amended to use synthetic streamflow. Probabilistic streamflows have the benefit of being able to reflect critical sequences of years with low or high runoffs that historical data may fail in capturing. Different methods such as autoregressive models (Hyndman and Athanasopoulos, 2018) or KNN disaggregation (Nowak et al., 2010) can be used to develop daily streamflows. These flows could be used to replace the observed streamflow (D_t) in Equation (1) if desired.

3.4 Statistical Significance

The statistical significance of changes to mean streamflow are determined and visualized to portray the impacts of reclaimed water consumption on streamflow at multiple downstream gages. To determine the statistical significance, a two-sample *t*-test comparing the historical and engineered data is conducted.

For the use of parametric tests, such as a two-sample *t*-test, the assumption of a Gaussian distribution must be met (Ghasemi and Zahediasl, 2012). To improve upon the assumption of normality in this study, a two-parameter Box-Cox transformation is utilized for both the observed and engineered streamflow. Box-Cox are a family of transformations commonly utilized to improve both the normality and heteroscedasticity of the observations (Box and Cox, 1964). Because of the presence of zero flow data, the two parameter Box-Cox is employed, where a constant shift parameter, λ_2, is added to each data point. The two-parameter Box-Cox transformation shown in Equation (2) is conducted on each datum (y).

$$y(\lambda) = \begin{cases} \frac{(y+\lambda_2)^{\lambda_1}-1}{\lambda_1}, & if\ \lambda_1 \neq 0; \\ \log(y+\lambda_2) & if\ \lambda_1 = 0. \end{cases} \quad (2)$$

An optimal value of λ_1 is determined for each stream gage using maximum likelihood estimation (Hyde, 1999), with the stipulation that for each stream reach the same values must be used to ensure the transformations are analogous.

Transforming streamflow data is common in hydrologic modeling and analysis because of the skewed nature of the observations (Bartczak et al., 2014; Wang et al., 2012). Sakia (1992) showed that hypothesis tests done on transformed data have good power properties; however, analysis must be done with consideration that the transformation of the data is being analyzed rather than the observed data (Osborne, 2010).

Histograms and quantile-quantile plots (QQ-plots) are visually analyzed following the transformation to confirm normality assumptions. The transformations are assessed at each stream gage. An example of the data pre and post transformation for the San Acacia gage can be found in figure 1. As illustrated by both the histogram and QQ-plot, the normality improves at

San Acacia following transformation. Further, a Kolmogorov-Smirnov (K-S) test is conducted to compare observed and engineered data to the data following the transformation. At each stream gage. The D statistics are presented in Table 1, with lower values representing distributions that more closely represent a normal distribution.

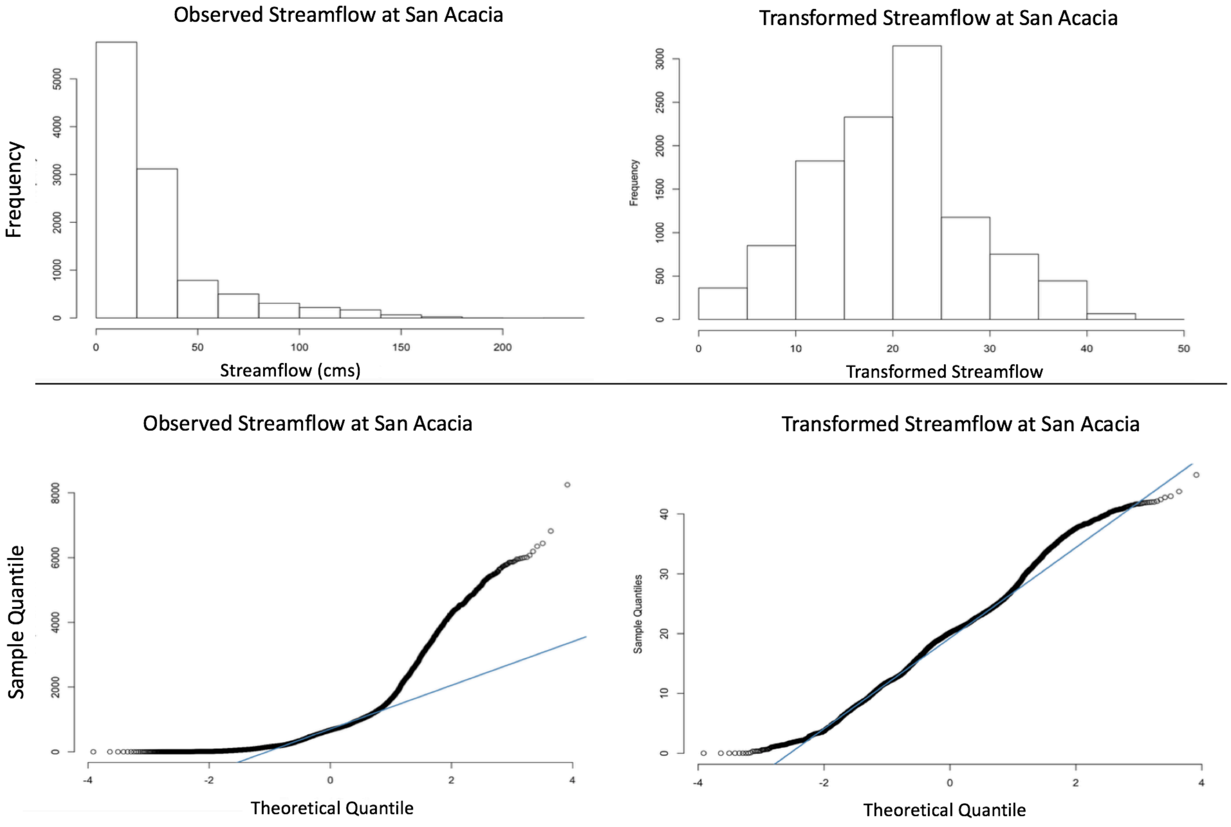

Figure 1: Histogram and QQ-plot at San Acacia prior to and following the Box-Cox transformation

Gage	Pre-Transformation D Value	Transformed D Value
Illinois River		
Dresden	0.1626	0.1027
LaGrange	0.1502	0.1071
Marseilles	0.1666	0.0738
Peoria	0.1449	0.0915
Starved Rock	0.1822	0.0971
Rio Grande		
Isleta	0.2597	0.1431
San Acacia	0.1793	0.0422
San Marcial	0.2170	0.0461

Table 1. The D statistic improves at each gage following transformation.

After the transformation is performed, a two-sample t-test is employed, which assumes a null hypothesis of no difference between the means of two datasets. Specifically, the test analyzes the transformed historical flow, represented by subscript (D), and engineered streamflow, represented by subscript (E). The result of the test is a t-statistic that represents the significance of the consumption on mean streamflow,

$$t = \frac{\bar{X}_D - \bar{X}_E}{\sqrt{\frac{\sigma_D^2}{n_D}} + \sqrt{\frac{\sigma_E^2}{n_E}}} \qquad (3)$$

where t = t-statistic, $\bar{X}$ = sample mean, σ = sample standard deviation, and n = sample size. Repeating this process for each gage and varying scenarios of reclaimed water consumption illustrates the effects to mean streamflow spatially. In the following sections additional calculations show the impact of these reduced flows to stakeholders.

3.5 Stakeholder Performance Metrics

Stakeholder performance metrics are used to determine the direct impact on individual stakeholders compared to some defined threshold. Thresholds are determined to define an acceptable streamflow versus an unacceptable streamflow. For example, a river stage threshold can be defined to delineate flows above the stage threshold versus those below. Each individual stakeholder may have a unique threshold, which can vary in both magnitude and timing.

Figure 2 is an illustrative example of how a streamflow record may perform relative to a threshold. In some periods, streamflow is below the required threshold. These periods of unsatisfactory streamflow vary in both the duration which they last and their magnitude below the threshold. Stakeholder metrics are used to quantitatively assess these failure periods by trying quantifying how often streamflow is failing, how long these failure periods are, and the severity of their failure.

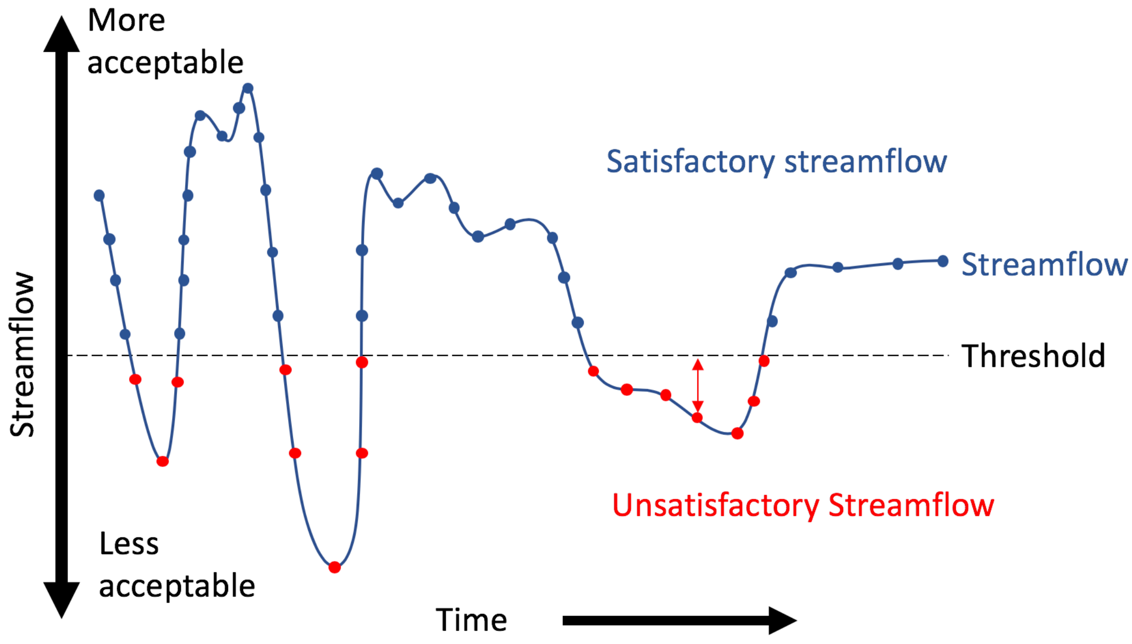

Figure 2: Cartoon example of a streamflow record relative to a streamflow threshold.

3.5.1 Probability of Failure

The first stakeholder metric calculated is probability of failure. Probability of failure is used to determine how often a stakeholder is in a failing state. Using this defined threshold, the probability of failure represents the fraction of time that the streamflow falls below the stakeholders threshold (Hashimoto et al., 1982).

$$D_t^i = \begin{cases} X^i_{Threshold,t} - X^i_{Streamflow,t} & if\ X^i_{Threshold,t} \geq X^i_{Streamflow,t} \\ 0 & if\ X^i_{Threshold,t} < X^i_{Streamflow,t} \end{cases} \qquad (4)$$

$$P(f)^i = \begin{cases} \frac{No.of\ times\ D_t^i > 0}{n_t^i} & if\ No.of\ Failures > 0 \\ 0 & if\ No.of\ Failures = 0 \end{cases} \qquad (5)$$

At each gage (*i*), and for each timestep (*t*), satisfactory flow is characterized by a value of 0. Unsatisfactory flow, which is streamflow less than the threshold, is denoted by a value between 0 and the threshold (Sandoval-Solis et al., 2011). Large values indicate larger failures with respect to the threshold. The probability of failure, $P(f)^i$, is determined by the number of instances that streamflow is unsatisfactory ($No. of\ times\ D_t^i > 0$) over the total number of observations (n_t^i).

An advantage of this approach is that different failure thresholds can be considered, which can be used to model the needs of individual stakeholders. There are several conditions that could occur. When assessing downstream impacts to reductions in flow, the unacceptable condition is flow below a certain magnitude. This method can also be amended to assess impacts when streamflow is too large. Given an upper streamflow threshold, the greater-than and less-than signs on the D-statistic can be switched to capture failures above this upper threshold. Additionally, when the stakeholder is reliant on a river stage rather than streamflow, flows can be transformed to equivalent stage values using a rating curve. After this transformation is complete, Equation (5) can be used to calculate the number of timesteps in which the stage is violated.

3.5.2 Average Failure Duration

The average failure duration (AFD) is the average number of consecutive timesteps where streamflow is below the threshold. This value gives insight into the duration in which stakeholders are subjected to unsatisfactory flow. Longer periods of unsatisfactory flow stress the resilience of the downstream stakeholder.

Average failure duration is determined using Equation (6):

$$AFD^i = \begin{cases} \frac{(No.of\ times\ D_t^i > 0\ precedes\ D_t^i > 0) + (No.of\ times\ D_t^i > 0\ precedes\ D_t^i = 0)}{No.of\ times\ D_t^i > 0\ precedes\ D_t^i = 0} & if\ No.of\ Failures > 0 \\ 0 & if\ No.of\ Failures = 0 \end{cases} \quad (6)$$

where at each gage (i), the number of failures that precede a failure is added to the number of times a failure precedes a success. Dividing this sum by the number of times a failure precedes a success produces the average duration of a failure period. To ensure the final datum is included in the calculation should it be a failure, a success is assumed to occur on the timestep following the final datum.

3.5.3 Average Failure Magnitude

Average failure magnitude is an indication of the likely failure value when a failure occurs. Values can range from 0 to the failure threshold, with larger values representing larger magnitudes of failure. As the average failure magnitude approaches the failure threshold, streamflow or river stage is approaching a value of 0, or no flow.

$$AFM^i = \begin{cases} \frac{\sum D_t^i}{No.of\ times\ D_t^i > 0} & if\ No.of\ Failures > 0 \\ 0 & if\ No.of\ Failures = 0 \end{cases} \quad (7)$$

Determining the probability of failure, the average failure duration and average failure magnitude give a comprehensive assessment of the impact to downstream stakeholders. Each metric should be assessed with consideration of the other. For instance, a consumption scenario could increase the likelihood of failures, but both the average duration of the failures and the average magnitude of the failures might decrease.

3.6 Assessment of Legal Considerations in the United States

Two major considerations regarding legality of consuming reclaimed water are who owns the first rights to use this water and which stakeholders are affected by consumption of this water. The prior consideration is complicated, particularly in areas where jurisdiction of wastewater effluent is not explicit. Often water ownership of reclaimed water is unclear, and the latter consideration of what impacts are being caused must be assessed. The second consideration has direct implications to the stakeholder impacts laid out in the previous section. Through stakeholder metrics, if there is a clear impact imposed on a stakeholder, they may have the right to challenge the validity of a proposed consumption.

For consumption scenarios that impose downstream impacts, downstream stakeholders might have legal recourse due to changes in streamflow. To assess the potential for legal recourse, federal law is considered first. As discussed earlier, federal law takes precedent whenever federal interests, such as the ability to meet international compacts, are involved. When federal purposes are not affected, state water laws are considered. Major considerations for state laws revolve around water ownership, particularly in states that operate under prior appropriation water laws. In the absence of specific reclaimed water legislation, judicial precedents can be considered, but legal considerations in different states might be applied distinctively.

Chapter 4. Illinois Case Study

4.1 Illinois River Introduction

The Illinois River begins at the confluence of the Des Plaines and Kankakee Rivers. These headwaters are located in the greater Chicago area and receive the wastewater effluent from 72 wastewater treatment plants. The confluence of the Des Plaines and Kankakee Rivers also marks the outlet for the study area of previous work assessing the use of reclaimed water for power plant cooling (Barker and Stillwell, 2016).

As a tributary to the Mississippi River, the Illinois 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, as shown in Figure 3.

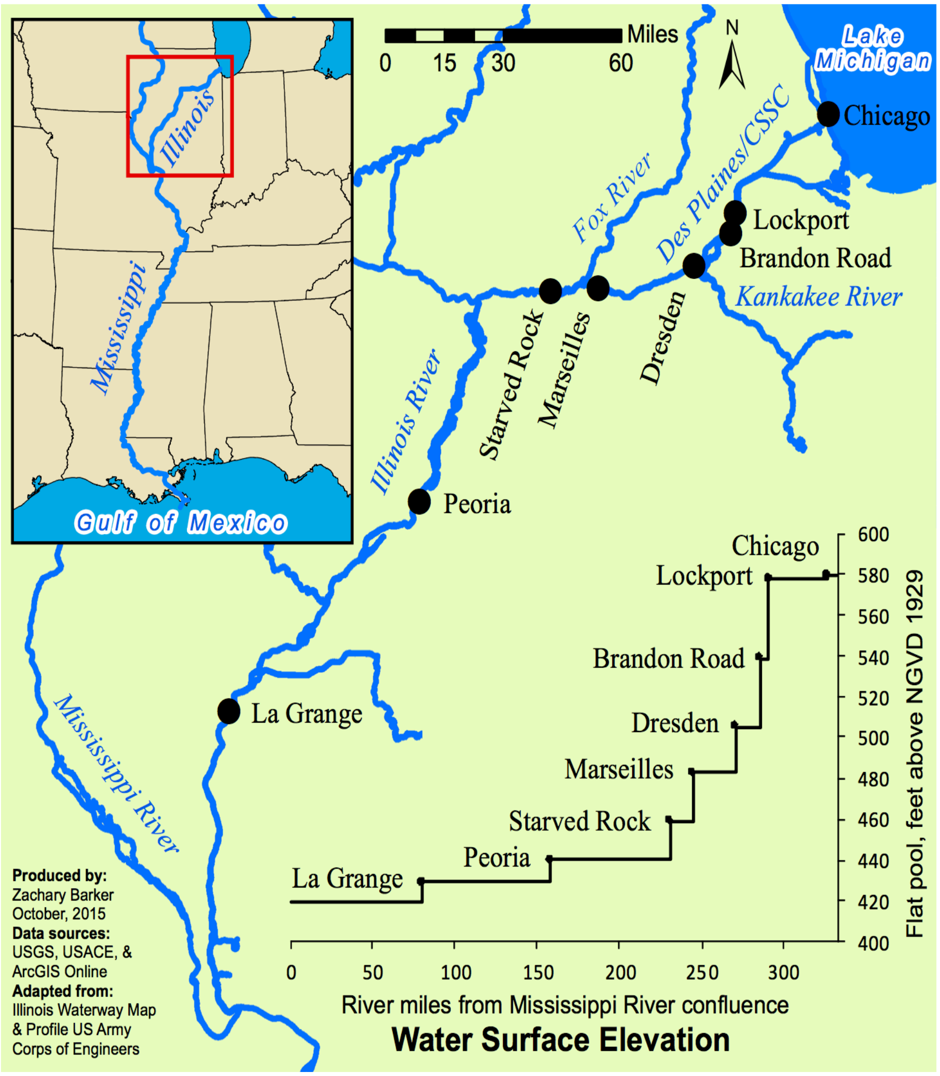

Figure 3: The Illinois River study area.

Comprised of three Hydrologic Unit Code (HUC)-8 watersheds, the headwaters of the Illinois River contain 6 power plants with a total power generation capacity of 7,900 MW. Thermoelectric power plants are particularly suitable for reclaimed water use due to their relatively large water demands. Cooling power plants does not require potable water, such that use of reclaimed water can be a beneficial practice for both electricity reliability and water resources sustainability (Li et al., 2011; Sovacool and Sovacool, 2009; Stillwell et al., 2011).

Many power plants still use open-loop cooling systems. Open loop cooling systems operate by withdrawing large amounts of water and circulating it once throughout the system. This water is then released into the natural environment at a higher temperature than it was withdrawn. Open loop cooling risks incurring fines from the U.S. EPA for environmental damage from intake structures and thermal discharge. Of the 6 facilities, 5 operate using open-loop cooling systems.

Many plants that operate with open-loop cooling have switched to closed-loop cooling. Switching from open-loop to closed-loop cooling systems reduces water withdrawals, and the associated environmental damage risk, but increases consumption via evaporation (DeNooyer et al., 2016). This additional consumption is supplemented by makeup water, often taken from bordering water bodies, and represents an additional consumption in the basin.

Barker and Stillwell (2016) demonstrated that the additional costs of cooling these power plants with reclaimed water could be rationalized by increases in power generation reliability and performance. The supply of wastewater effluent in the study area is very large due to high population densities and combined sewer infrastructure. The majority of the wastewater effluent is treated and released from the Stickney Water Reclamation Plant into the Chicago Sanitary & Shipping Canal, with an average daily flow (ADF) of 31 cms (700 MGD). The question becomes how does consumption of a portion of this ADF impact downstream users of the water.

Defining what uses of water are important downstream is critical for understanding the potential impacts caused by the consumption of reclaimed water. To make this determination, data from the Illinois Water Inventory Program and reports published by the Illinois State Water Survey are considered (Hlinka et al., 2011). Withdrawals from the Illinois River are divided into three categories: municipal, industrial, and power generation. Combined, these users withdraw less than 2% of the median flow at Dresden (see Figure 3). Due to the low amount of withdrawals in the study area, in-stream uses of streamflow were considered as a critical downstream stakeholder.

During times of drought, barge traffic on the Illinois River has lost productivity (Changnon, 1989; Harris, 2013). Barges are important to the region for cost-effective transportation of coal, petroleum, agricultural products, and other raw materials (Kruse et al., 2012). Since barge traffic relies on a channel deep enough to float, the focus of the analysis is on this critical stakeholder. Unique to this system is the source of water during dry periods. Lake Michigan diversions are already used as make-up water during low flows and are unlikely to increase due to international treaties (Espey et al., 2014).

4.2 Illinois River: Scenario Analysis

The baseline historical conditions are compared to a range of discrete water consumption scenarios. The minimum of this range is defined by zero consumption, or no change, and the maximum is defined as the consumption of 100% of the effluent ADF from Stickney Water Reclamation Plant, approximately 31 cms (One Water, 2015).

Additionally, three patterns for each consumption level are defined: Uniform (January–December), Winter (January–March), and Summer (June–August). These patterns are chosen to explore if consuming wastewater effluent during different times of the year changes the impacts to downstream stakeholders. Each pattern has the same maximum daily consumption but varies in the timing, with wastewater effluent only being consumed for the months stated. For the application of supplying cooling water for baseload thermoelectric power plants, a uniform consumption is reasonable since these power generators typically have fairly constant water demands. The formulation of water consumption in the model is flexible enough to accommodate any pattern that can be discretely represented.

Streamflow and stage data from the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers are used. The data at the locks and dams represent the tailwater side of the infrastructure and include 30 years of daily data. The data reported at these sites represent a baseline scenario and a selection of these data are displayed as flow duration curves in Figure 4. Using Equation (1), engineered water reuse scenarios are determined by subtracting the quantity of water consumption from all data points to shift the flow duration curves. Original exceedance probability is in bold and consumption scenarios are represented in gray.

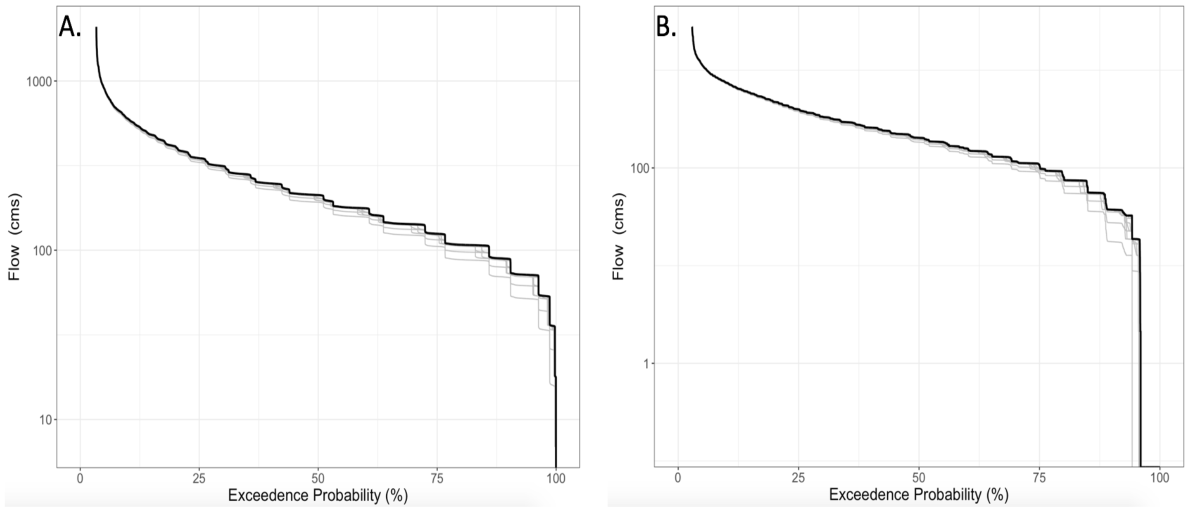

Figure 4: Flow duration curves at two downstream gages, Dresden (A.) and Marseilles (B.). The black line represents the baseline flow duration curve, with additional consumption scenarios represented by light grey,

Lower reclaimed water consumption rates show similar shifts, but the magnitude is less detectable. At all of the streamflow gages shown in Figure 3 and for all consumption rates and patterns, the flow duration curves shift left, illustrating lower streamflow. While all of the flow duration curves depict the same reductions in streamflow, gages further downstream have larger contributing drainage areas, and, therefore, the flow regime shift appears smaller.

Because barge transportation is reliant on-stream stage rather the streamflow directly, rating curves are developed for each of the downstream gages. Ideally, rating curves would define the relationship between stage and flow; however, these curves are not available or accurate for low flows at the study gauges. To establish a relationship between streamflow and stage, linear regression is used. 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 the focus is on low flows that put downstream users at risk, only the lower 50th percentile of streamflow is used in developing the rating curve. The linear regression based on the full data 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, the stage is shifted using Equation (8):

$$l'_t = l_t - mr_t \qquad (8)$$

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, stakeholder impacts are assessed relative to the threshold of 9 feet at each gauge. An example rating curve developed for the La Grange stream gage can be found in Figure 5. Additionally, the R^2 value, which measures how well the river stage observations fit the linear regression, is displayed in Table 2.

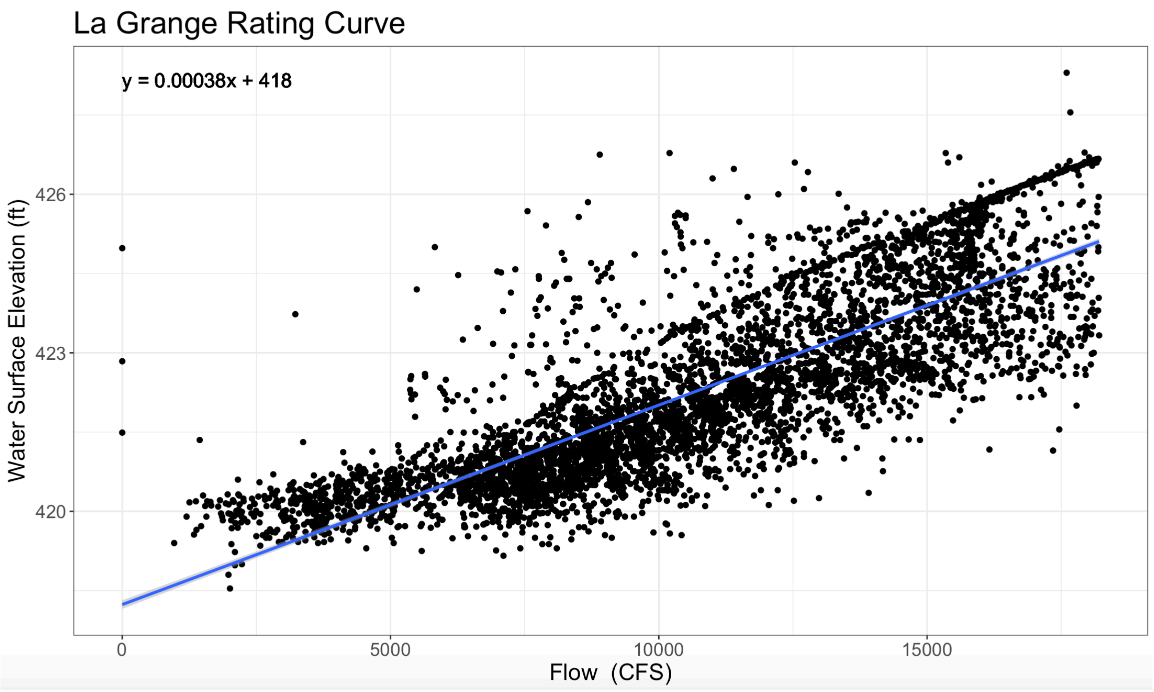

Figure 5: Rating curve at the La Grange stream gage.

Gage	R^2
Dresden	0.374
LaGrange	0.679
Marseilles	0.084
Peoria	0.044
Starved Rock	0.240

Table 2. The R^2 value for each rating curve along the Illinois River.

4.3 Illinois River: Statistical Significance

To quantify the difference in flow regimes illustrated by the flow duration curves in Figure 4, statistical techniques are used to estimate the difference in means between the baseline scenario and each engineered water reuse scenario. As discussed in the methods section, each of the scenarios are transformed using a two-parameter Box-Cox transformation with matching λ_1 and λ_2 values. A two-sample *t*-test is then conducted on the transformed data. The results are displayed in Figure 6.

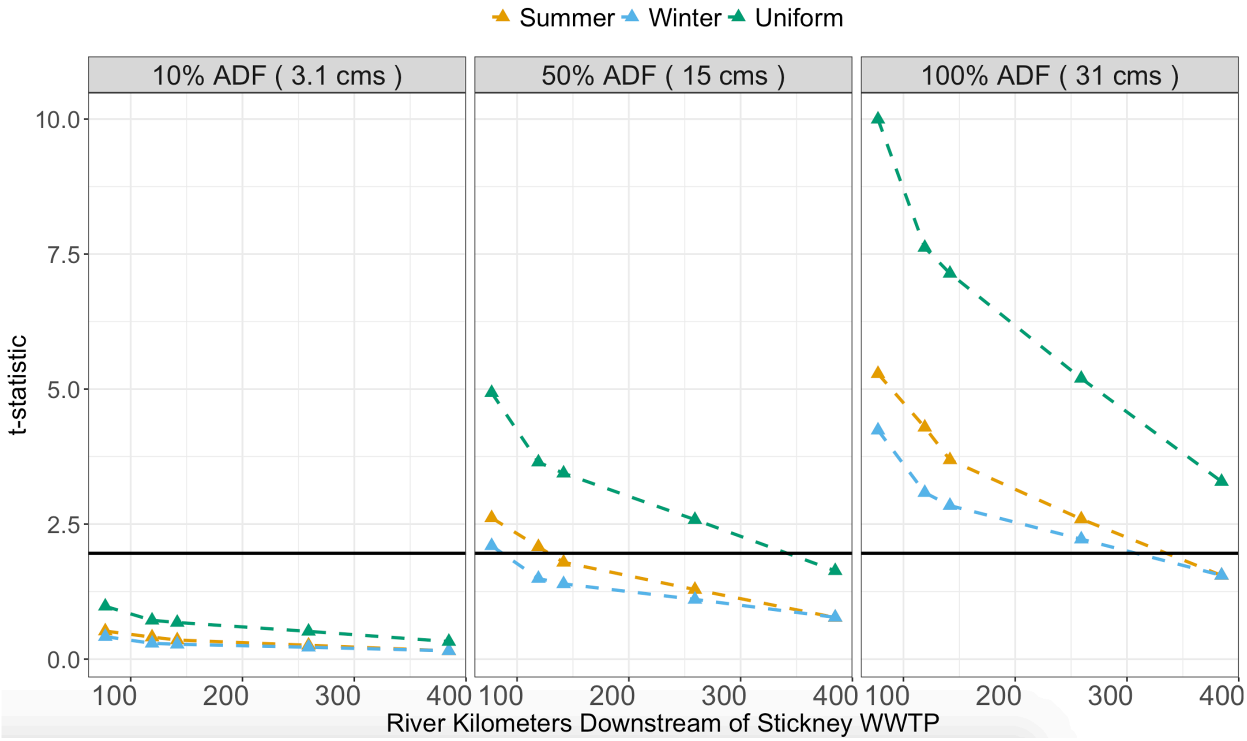

Figure 6: Illinois River statistical significance in reduction to mean streamflow.

The significance in mean streamflow reductions increases with additional effluent consumption for each consumption scenario. These impacts diminish with distance downstream and are below the significance level ($\alpha = 0.05$), represented by the black line in Figure 6, for each consumption pattern in the 3.1 cms (10% ADF) scenario. The impacts to mean streamflow are smaller downstream because of the larger contributing drainage area, reflected in the flow duration curves.

The statistical significance gives insight into which consumption scenarios are most likely to impact downstream stakeholders. For instance, mean streamflow along the Illinois River is greater in the winter than mean streamflow in the summer. Further, consuming reclaimed water in only the winter generates consistently lower differences in mean streamflow compared to consuming reclaimed water in the summer months. To assess the negative impacts of reclaimed water consumption on downstream stakeholders, the effect on downstream barge traffic is further investigated.

4.4 Illinois River: Stakeholder Metrics

Defining barge transportation as the downstream stakeholder, river stage is assessed rather than streamflow. The U.S. Army Corps of Engineers aims to maintain a minimum depth of 2.74 meters (9 feet) along the Illinois River, which is used as the threshold. An example of a stage time series for a selected period of time is displayed in Figure 7, with the 9 ft. threshold shown in red. Any stage below that 9 ft. is considered a failure. Stakeholder metrics aim to quantify how these periods of failure are changing following consumption by assessing how often the stage if failing, how long the average failure lasts and how severe the average failure is.

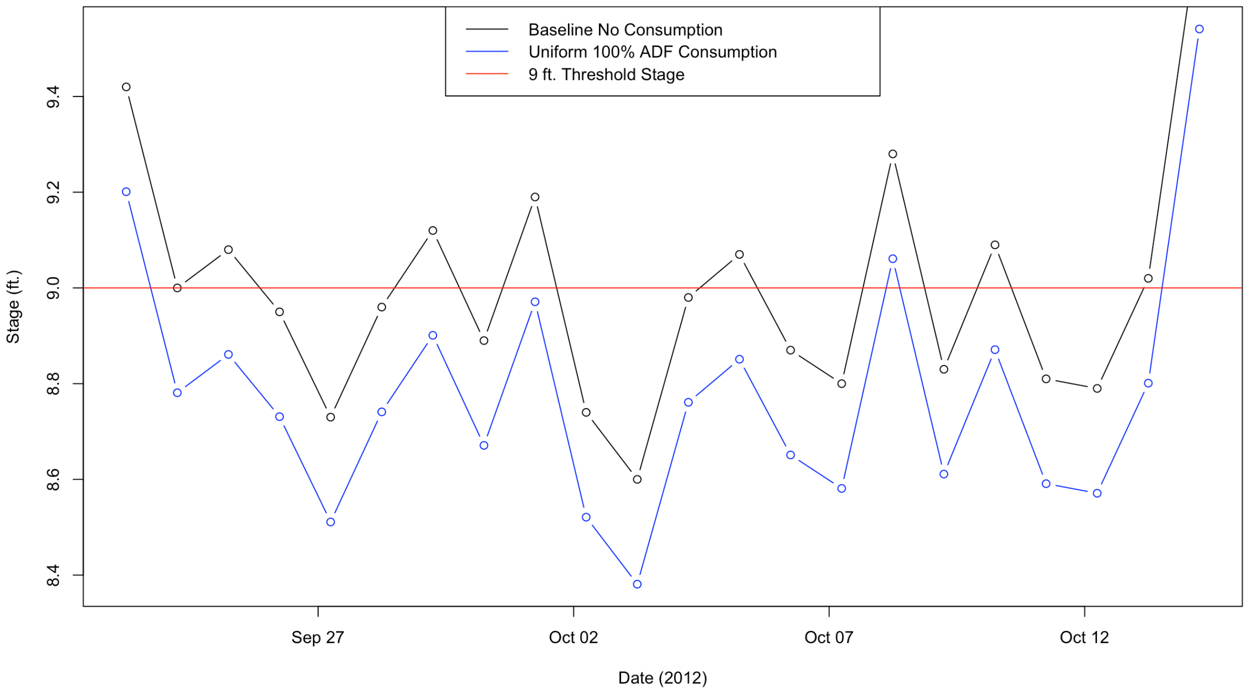

Figure 7: Representative time series of stage at Starved Rock with and without consumption.

The first metrics calculated is the probability of failure, or how likely it is that stage is below 9 ft. The current probability that the minimum stage is not met is found using the reported stage and streamflow data immediately downstream from each lock and dam with Equation (4). All five gages have some non-zero, low (less than 1%) probability of failure in the baseline (de facto) scenario, represented by the black lines in Figure 8.

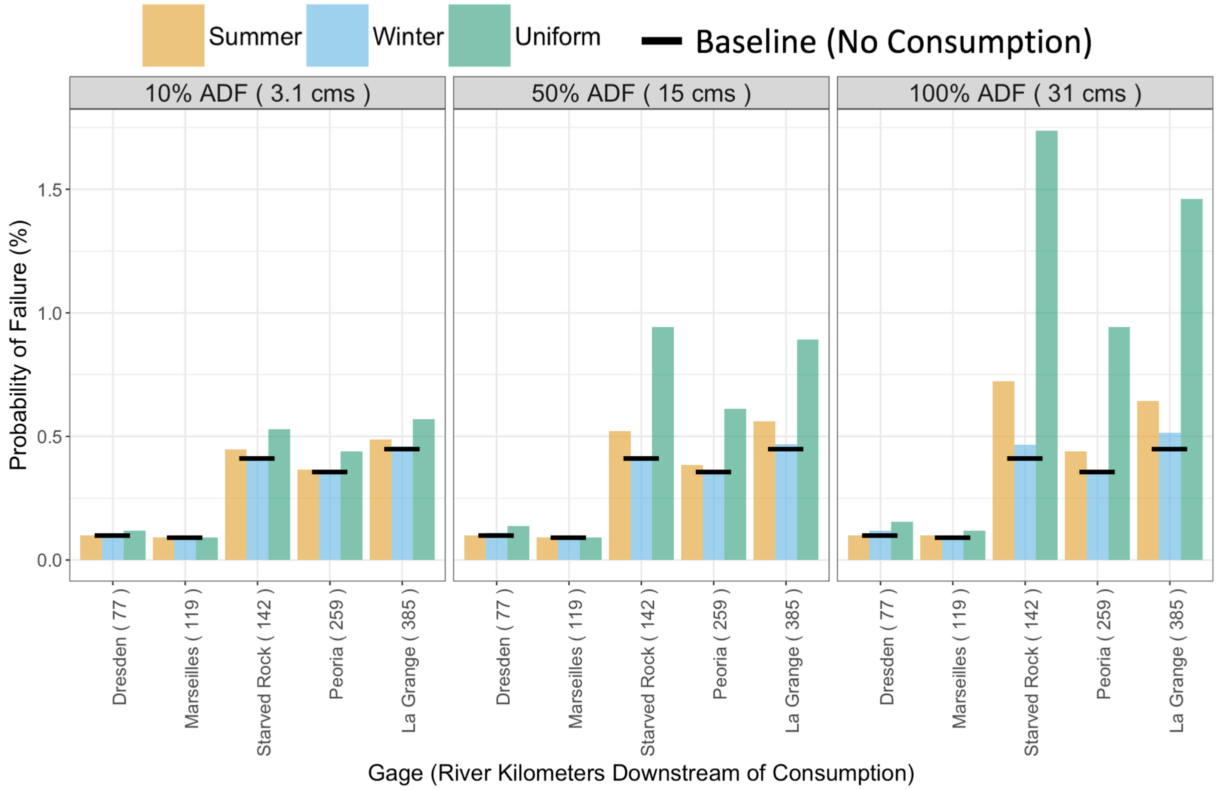

Figure 8: Illinois River probability of failure.

Figure 8 displays the increase in the probability that river stage falls below the 2.74-m threshold. For each consumption scenario, the probability of failure increases in severity compared to its baseline value. Considering the timing of consumption, there is an increase in probability of failure when consumption occurs during the summer months compared to consumption in the winter months. Probability of failure does not monotonically increase with distance from the Mississippi River confluence, as would be expected by the trend of the *t*-statistic. Because the failure threshold for barge traffic is dependent on stage rather than streamflow, river characteristics beyond streamflow will affect stage. These variations in river characteristics at each gage can lead to the spatial disagreement between the *t*-statistic and probability of failure.

An increase in the likelihood that the stage falls below the 2.74-m (9-ft) minimum will increase the operating costs of barge companies due to lost days of available transit and/or reduced shipping weights. Increasing the probability of failure from 0.5% to 1.5%, which occurred at two of the gages in the uniform, 100% ADF scenario, would represent approximately 4 more days of the year that barge traffic could not travel through the channel.

To determine the expected length of failure periods, the average failure duration (Figure 9), is calculated for each of the consumption scenarios. Larger durations indicate larger continuous time periods that barge traffic will be affected by lower flows. Continuous days of insufficient stream stage put shipping companies at higher risk of missing required delivery dates.

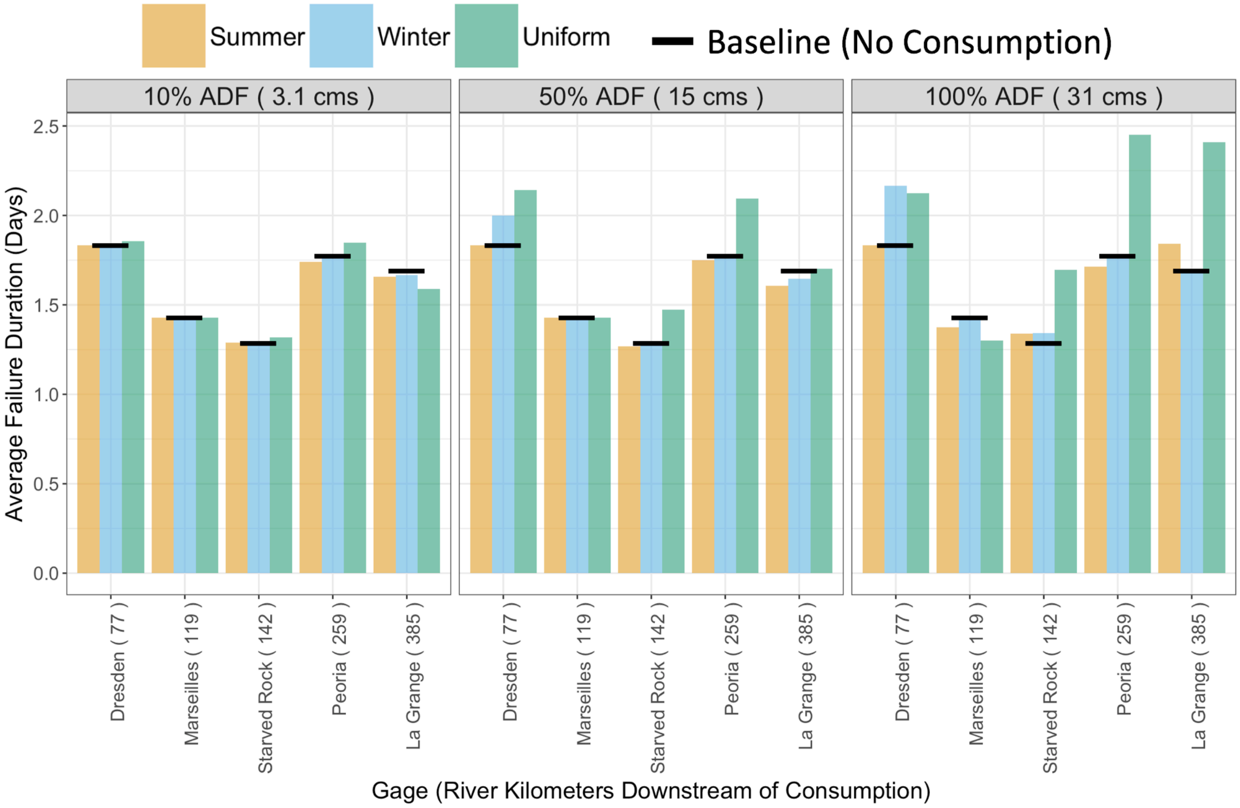

Figure 9: Illinois River average failure duration

Temporal changes to consumption have contrasting impacts to average failure duration at different gages, with changes best represented by the 100% ADF consumption scenarios. The Dresden, Starved Rock, and La Grange gages each observe an increase or no change to their average failure duration for every consumption scenario explored. The opposite is observed for the Marseilles gage. Effects to the Peoria gage are dependent on the consumption scenario, with uniform consumption increasing failure duration and summer consumption decreasing failure duration.

Lastly, the average failure magnitude is calculated to determine the severity of the average failure. The failure magnitude (Figure 10) indicates how far the stage falls below the 2.74-m failure threshold. Larger failures reduce the allowable load a barge can transport to ensure the barges do not run aground (Meyer et al., 2016).

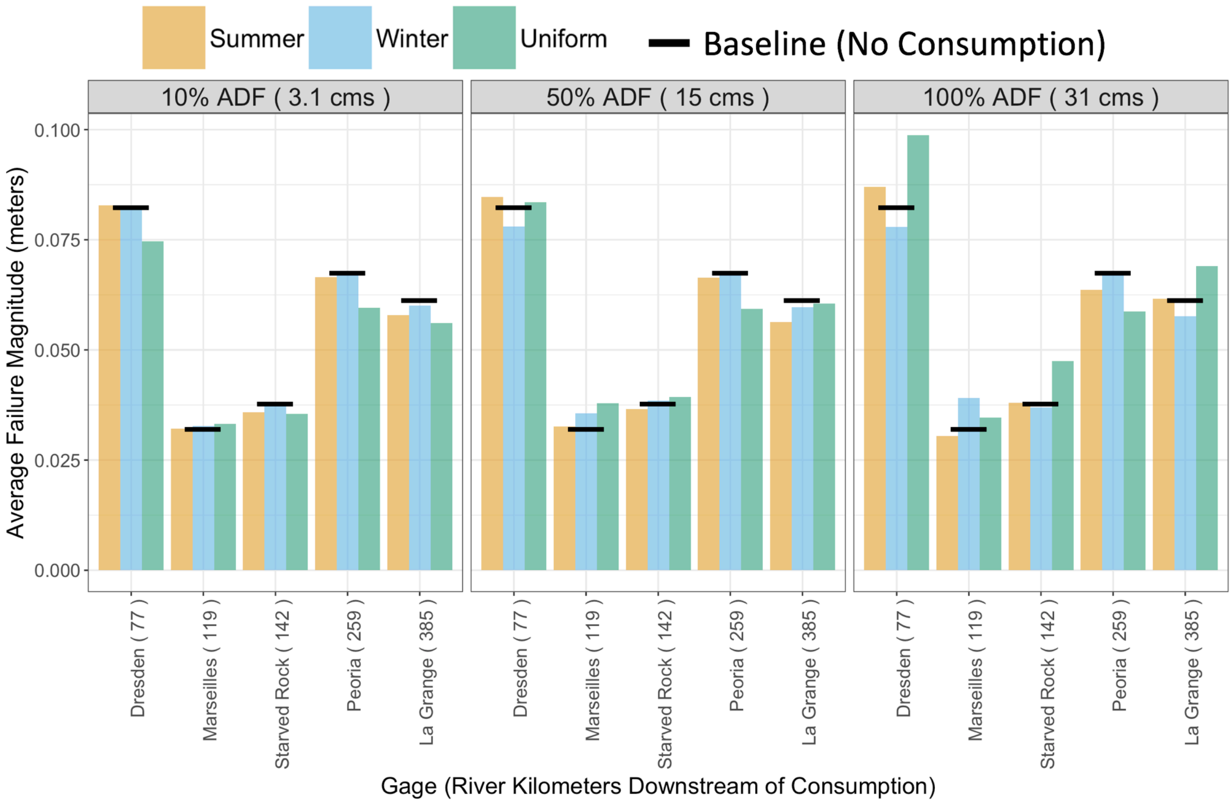

Figure 10: Illinois River average failure magnitude.

For informed decision making, each of the stakeholder metrics should be assessed with consideration to the others. Each metric provides additional detail as to how the stakeholder will be affected by a consumption scenario. For barge traffic along the Illinois River, average failure duration and failure magnitude indicate lower impacts to the downstream stakeholder. To understand why an additional consumption would cause these metrics to improve, probability of failure must be assessed. The gages that experience improved performance for average failure duration and magnitude experience a large increase in the probability of failure. The relationship between lower failure magnitude and duration and a larger probability of failure indicates an increase in smaller, single event failures. It is the responsibility of decision makers to determine if these smaller failures are acceptable.

4.5 Illinois River: Legal Considerations

The state of Illinois does not directly govern reclaimed water in legislation. To understand the legal concerns surrounding reclaimed water consumption in the greater Chicago area, the framework for water law in Illinois is used as a starting point for future resource management discussions. The system of water governance stems from a riparian common law of torts. Consequently, water rights are included with property rights, as opposed to prior appropriation where the two rights are severed (Getches et al., 2015). More specifically, a landowner would have the right to "reasonably" use water that borders his/her property. The term "reasonable" comes from civil litigation [*Evans v. Merriweather*] (Illinois Supreme Court, 1842) where the court decided that riparian rights only extend so as not to obstruct another user's right to also make reasonable use.

Reclaimed water presents a challenge in this water law structure because reclaimed water is not considered part of the surface water until it is discharged. When water is lawfully removed from the natural system in Illinois, that water then becomes private property (Illinois General Assembly, 2013). As private property, the owner may use or sell it in any manner that does not violate environmental regulations such as the Environmental Protection Act [415 ILCS 5] (Illinois General Assembly, 2013). 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 is unreasonable (Illinois Supreme Court, 1842), which is unlikely with municipal water withdrawals.

Chapter 5. Rio Grande Case Study

5.1 Rio Grande Introduction

Impacts from reclaimed water consumption are assessed along the Middle Rio Grande downstream of Albuquerque, New Mexico (Figure 11). Albuquerque is adjacent to the Rio Grande and the effluent from the local wastewater treatment plant, Southside Water Reclamation Plant (SWRP), is discharged directly into the river following treatment.

Produced by:
Brendan Purcell
November, 2018

Data sources:
ESRI, USGS,
US EPA

Figure 11: The Middle Rio Grande stretches from Albuquerque, New Mexico to the Elephant Butte Reservoir.

The Rio Grande basin starkly contrasts that of the Illinois River. New Mexico is characterized as a region with semi-high aridity and a wide variation in seasonal water availability (Tidwell et al., 2004). A large portion of the Rio Grande's streamflow is derived from snowmelt originating in the San Juan Mountains, with low flows in the summer being supplemented by the San Juan Charma diversion (Flanigan and Haas, 2008).

Agricultural land neighboring Albuquerque is irrigated by both groundwater from surrounding aquifers and surface water diverted from the Rio Grande. The majority of this water use is in the form of gravity-fed flood irrigation for alfalfa (Benson et al., 2018). The irrigation withdrawals are primarily seasonal, with most of the demand occurring in summer months. This seasonal withdrawal coincides with the Rio Grande's lower streamflow.

The larger demand for water during months with lower streamflow leads to a large quantity of water withdrawals from proximate aquifers. Past research has shown that many of these aquifers are hydrologically isolated from the river (US Department of Interior et al., 2005). The use of reclaimed water for irrigation has long been proposed as a substitute to groundwater withdrawals (Kinney et al., 2009). Because the aquifers are isolated from the river, the switch from groundwater to reclaimed water would represent an additional consumption from the Rio Grande basin.

Two stakeholders are considered for the purpose of this study. The first is the ability for New Mexico to adhere to its obligatory water deliveries as required by the Rio Grande Compact. The second is the conservation of the Rio Grande silvery minnow (*Hybognathus amarus*), an endangered fish species (U.S. Fish & Wildlife Services, 2018).

New Mexico is required to deliver a portion of the Rio Grande's annual streamflow into Elephant Butte reservoir. This required delivery is part of an interstate agreement between

Colorado, New Mexico, and Texas, as well as an international agreement between the United States and Mexico. In accordance to the Rio Grande Compact, New Mexico's required deliveries are based on measured streamflow at the Otowi stream gage upstream of Santa Fe (Hill, 1974). Measured streamflow is exclusive of flow in the months of July, August, and September.

The second stakeholder considered is the conservation of the silvery minnow. The population of the silvery minnow is at risk due to both fragmentation of the river from the multiple dams and reservoirs, as well as decreased flows from irrigation diversions along the river (Alò and Turner, 2005). The Rio Grande silvery minnow is only found in small portions of the river stretching between Albuquerque and Elephant Butte reservoir, which represents just 5% of the fish's original range (Ward and Booker, 2006). For the conservation of the species, the recommended minimum streamflow in this stretch of river is 1.42 cms (50 CFS) (US Department of the Interior, 2001).

5.2 Rio Grande: Scenario Analysis

Similar to the Illinois Case Study, a modified data set is created to compare the historical streamflow data with scenarios simulating reclaimed water consumption. Water consumption scenarios ranged from the lowest consumption scenario representing 0 consumption, or no change, to an upper bound of 2.55 cms of wastewater effluent consumption, which represents the average daily effluent from Southside Water Reclamation Plant (Albuquerque Bernalillo County Water Utility Authority, 2010)[1]. Consumption of 1.28 cms (50% ADF) and 0.255 cms (10%

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[1] This analysis assumes that the engineered streamflow considered consumes water that would have made up a portion of the Rio Grande streamflow, but potentially upstream reservoirs could release water to meet these additional demands created by the consumption.

ADF) are also considered to illustrate the potential effects to the downstream stakeholders for a range of possible consumption scenarios.

Additionally, three patterns are considered for each consumption level: Uniform (January–December), Winter (January–March), and Summer (June–September). Similar to the Illinois River case study, each pattern has the same maximum daily consumption but varies in timing. For the proposed application of agricultural irrigation, summer or uniform consumption scenarios are most likely. The summer consumption also coincides with when the de facto water percent is highest downstream of Albuquerque. For the 2012 calendar, the average de facto water percentage just downstream of the Southside Water Reclamation Plant was 16.8%. But in the summer months, the de facto percentage was 52% and occasionally accounted for 100% of the streamflow in this reach. A winter consumption scenario is included to determine if the impact on downstream stakeholders could be mitigated by temporal changes in consumption.

Average daily streamflow data obtained from the USGS were used in the analysis. The three gage sites used for the study are Isleta Lakes, San Acacia, and San Marcial (see Figure 11), located along the Rio Grande between the Southside Water Reclamation Plant and Elephant Butte reservoir.

5.3 Rio Grande: Statistical Significance

The statistical significance to reduction in mean streamflow is determined, shown in Figure 12. Unlike the Illinois Case Study, reduction in mean streamflow generally increases with distance downstream from Albuquerque. Although there is still a large contributing area further downstream, there are also multiple water diversions used for irrigation (Figure 11). This downstream increase is likely due to those large diversions of water downstream from the wastewater treatment plant, which already limit the streamflow in those reaches. Supporting this proposition is the fact that the increase is greater for the uniform and summer consumption scenarios, when diversions are largest. The *t*-statistic value is consistently lower for winter consumption compared to summer or uniform consumption. This lower value indicates impacts to stakeholders may be mitigated with consumption only in the winter months.

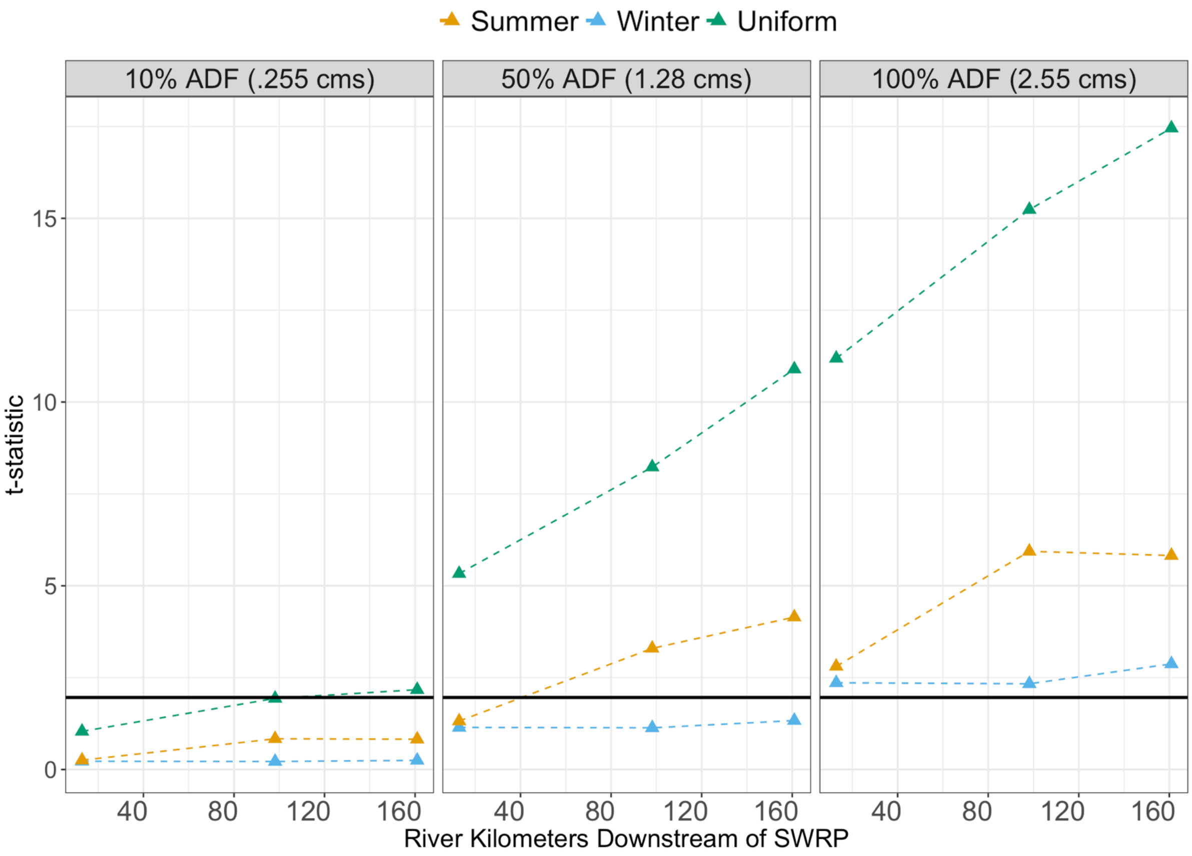

Figure 12: Rio Grande statistical significance in reduction to mean streamflow.

5.4 Rio Grande: Stakeholder Metrics

5.4.1 Ability to Adhere to the Rio Grande Compact

Each of the downstream stakeholders have unique failure thresholds and their impacts are determined at different timesteps. Upholding the Rio Grande Compact is assessed annually, and the failure threshold varies each year depending on streamflow at the Otowi gage. Because both the threshold and the metric are determined yearly for the Rio Grande compact, a one-year time step is used for the determination of probability of failure.

Per the Rio Grande compact, New Mexico is required to deliver a certain portion of streamflow to Elephant Butte Reservoir. The portion required to deliver is determined using a proportion of inflow into the state, measured at the Otowi stream gauge, and deliveries into the Elephant Butte Reservoir, measured at the San Marcial stream gauge.

The yearly required delivery by New Mexico determined at the Otowi gauge is calculated excluding July, August, and September flows. This required delivery is compared to observed streamflow at the San Marcial stream gauge to determine if New Mexico is meeting their obligations of the compact. Engineered streamflow at the San Marcial is then determined using the same consumption scenarios laid out in the Rio Grande: Scenario Analysis section. Impacts to New Mexico's ability to adhere to the compact are assessed using a time series (Figure 13).

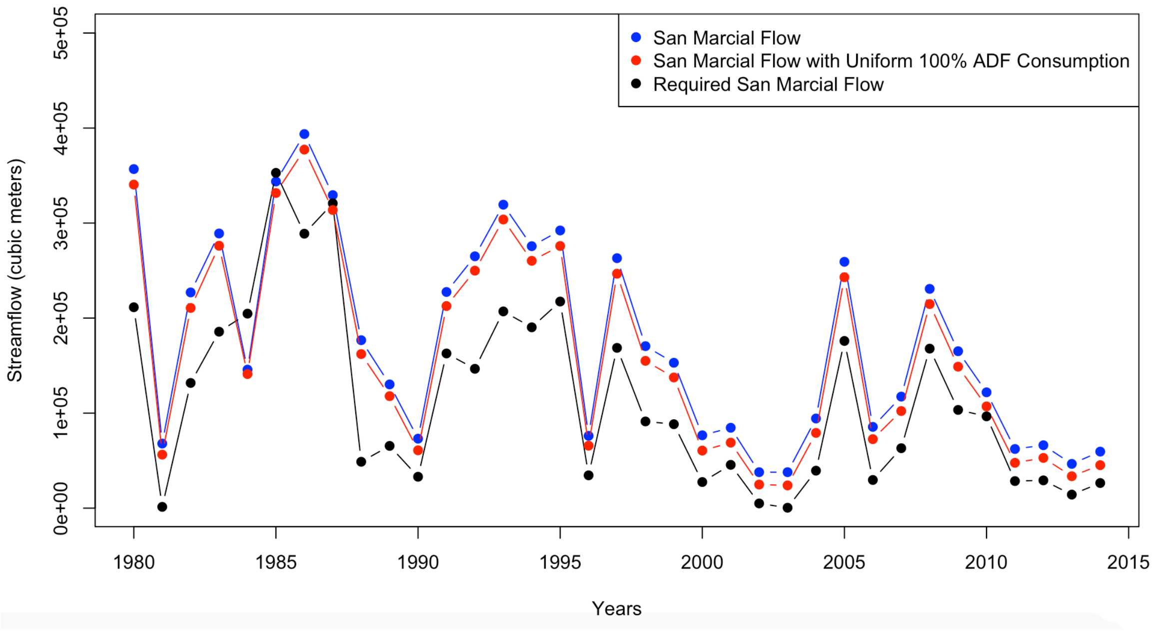

Figure 13: Time series representation of New Mexico's ability to meet the requirements of the Rio Grande Compact

A failure occurs when the San Marcial flow falls below the required San Marcial flow. An additional failure is determined when the required San Marcial flow falls below the San Marcial flow, but above the San Marcial flow following consumption. Each of the consumption scenarios are assessed, and the only one found to have an additional failure is the uniform 100% ADF consumption scenario.

The 100% ADF consumption scenario causes an additional failure only once in the thirty-five-year period assessed. The compact operates under a debit and credit system such that the impacts from only a single failure are marginal as the insufficient flow can be abated by credited flows in future years (Hill, 1974). More broadly, each of the proposed consumptions would be unlikely to impact New Mexico’s ability to adhere to the Rio Grande Compact.

5.4.2 Rio Grande Silvery Minnow

In addition to the Rio Grande compact, the conservation of the Rio Grande silvery minnow is considered as an additional downstream stakeholder. The US Fish and Wildlife Service recommends a minimum threshold flow of 1.42 cms (50 CFS) in the river. Using the reported streamflow data, the current probability of failure at each stream gage is determined, represented by the black lines in Figure 14. This baseline probability of failure is then compared with each of the consumption scenarios (Figure 14).

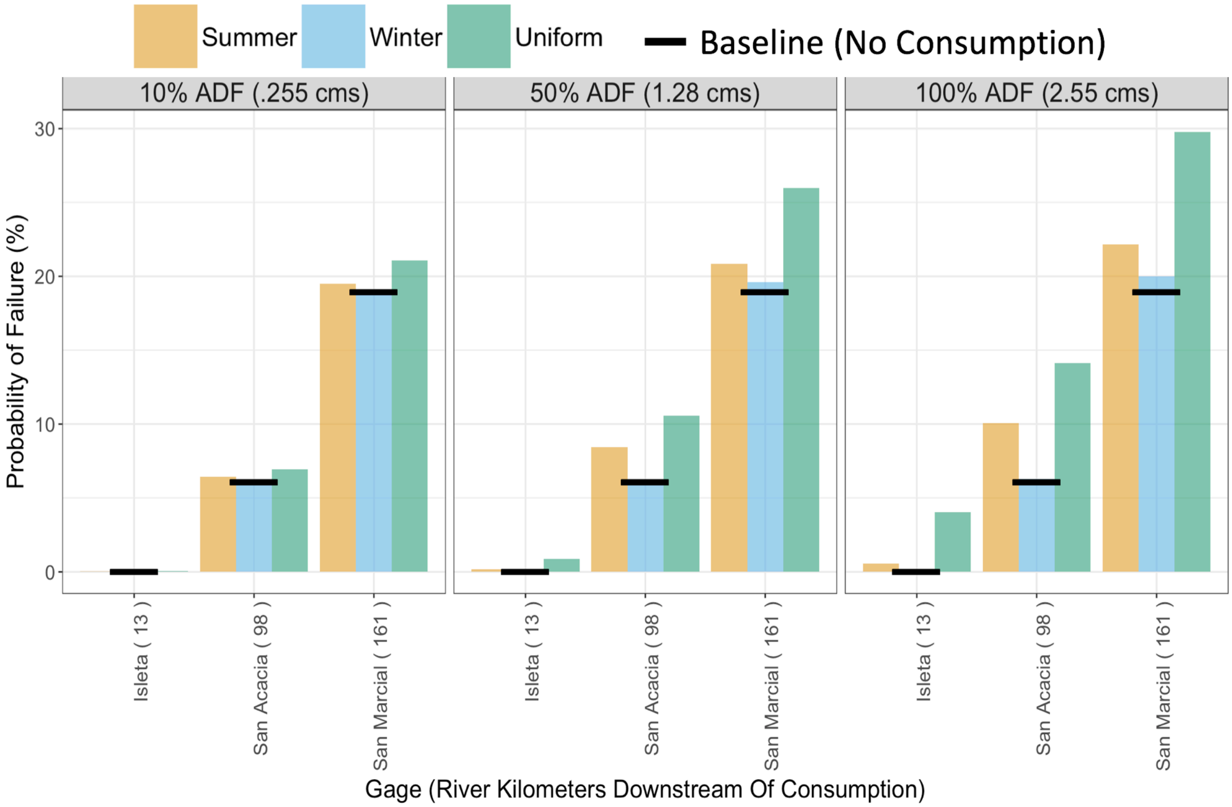

Figure 14: Rio Grande probability of failure.

Some patterns become evident by assessing the Rio Grande probability of failure. Probability of streamflow being below the 1.42 cms threshold increases with additional consumption at each gage but there are seasonal and spatial differences. Summer consumption patterns consistently cause a larger probability of failure than reclaimed water consumption in the winter. Also, the probability of streamflow being below the threshold increases with downstream distance from the wastewater treatment plant.

Average failure duration (Figure 15) is calculated to determine how long negative impacts to the silvery minnow persist. Longer failure durations are generally harder for a stakeholder to overcome. If the average failure duration in the Rio Grande increases, the resilience of the silvery minnow becomes pertinent.

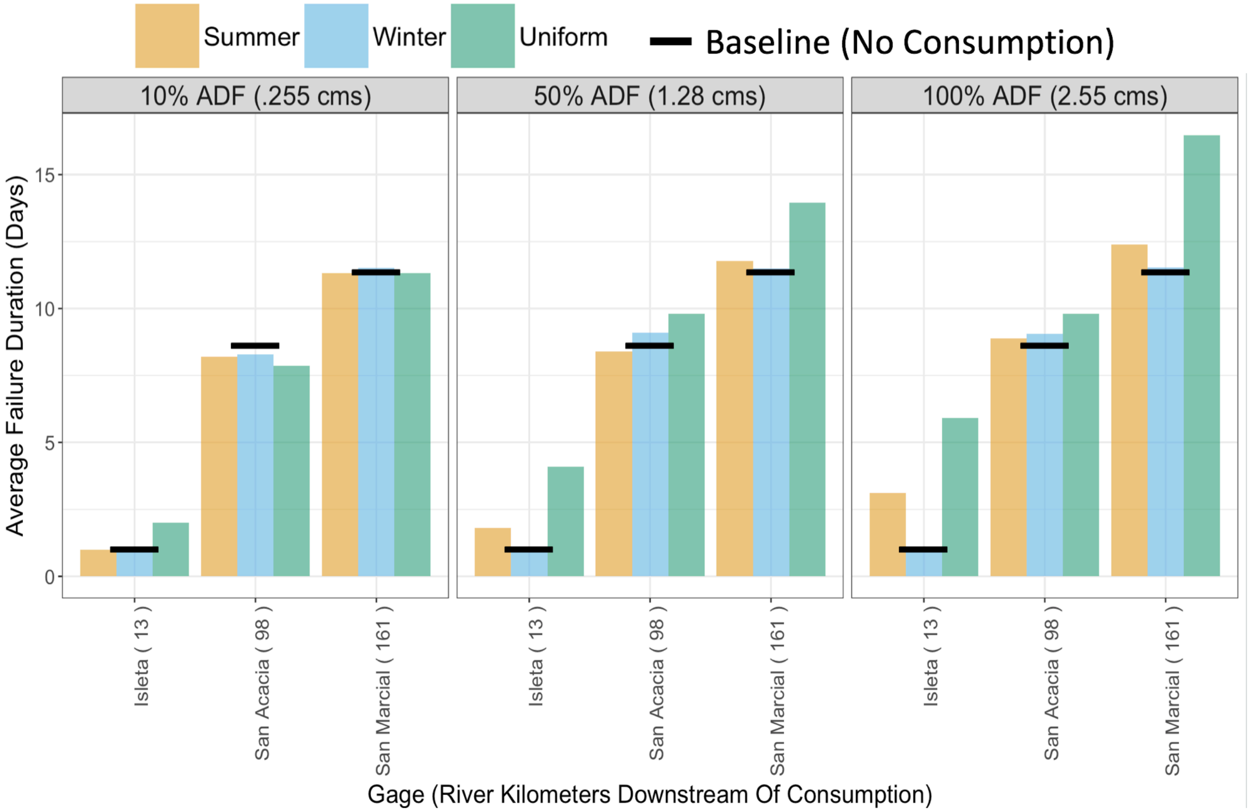

Figure 15: Rio Grande average failure duration

Within the Rio Grande, the average failure duration stays relatively constant for lower reclaimed water consumption scenarios. Larger consumptions (50% ADF and 100% ADF) produce larger periods of failure for the Rio Grande. These changes are especially prevalent at the Isleta Gage, where the average failure period increases from 1 day with 0% ADF consumption (existing de facto conditions), to 7 days with the 100% ADF, uniform consumption.

Lastly, average failure magnitude is calculated to measure the discrepancy of an average failure below the 1.42 cms threshold (Figure 16). Higher magnitudes represent more severe failures. In the Rio Grande, larger average failures increase the likelihood of creating isolated instream pools, which can separate the silvery minnow from a required continuous food supply, putting the population at a greater risk for adverse effects (Ward et al., 2006).

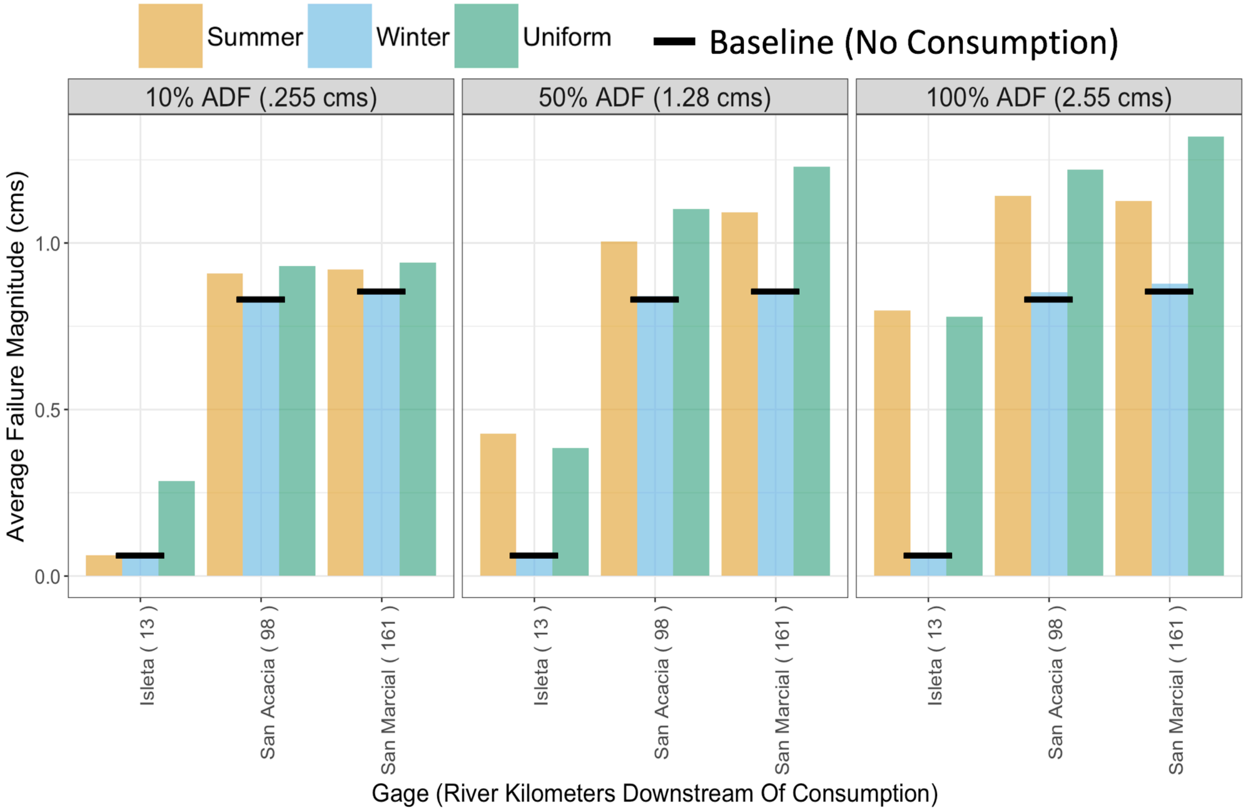

Figure 16: Rio Grande average failure magnitude.

The average failure magnitude follows the same pattern as the probability of failure and failure duration. At all three downstream locations, failure magnitude increases with an additional consumption of reclaimed water. This impact is notably larger in the summer and uniform consumption scenarios compared to winter consumption.

Assessing all of the stakeholder metrics together allows for a comprehensive assessment of the downstream impacts to the Rio Grande silvery minnow. Increases to probability of failure, average failure duration, and average failure magnitude at each downstream location are all smallest for the winter consumption scenario, indicating that impacts could be reduced with consumption in only the winter months.

5.5 Rio Grande: Legal Considerations

Water rights surrounding international treaties and endangered species both fall under federal policy. As previously discussed in the probability of failure section, impacts to deliveries required by the Rio Grande Compact would be minimal for any of the proposed consumption scenarios. As a result, it is unlikely the federal government would have justification to oppose any of the reclaimed water consumption scenarios for the purpose of meeting the compact's required water deliveries.

Conversely, there were measurable impacts to the streamflow to support the Rio Grande silvery minnow. Sections 7(a)(1) and 7(a)(2) of the Endangered Species Act require federal agencies to aid in the conservation of endangered species and ensure actions do not jeopardize the continued existence of the species, including preventing "destruction or adverse modification of habitat" (*Endangered Species Act of 1973*, 1973). If the U.S. Fish and Wildlife Service determine the calculated impacts would put the silvery minnow at risk, a proposed consumption could be rejected.

In New Mexico, the New Mexico Office of the State Engineer has the authority to require surface water releases due to decreased streamflow resulting from groundwater withdrawals (Supreme Court of New Mexico, 1962). The required return flow is determined based off of a numerical groundwater model operated by the State Engineer's office. Currently, a portion of Albuquerque's wastewater return flows are used to supplement streamflow that is lost due to groundwater pumping for drinking water (Albuquerque Bernalillo County Water Utility Authority, 2016). Any consumption of reclaimed water that inhibited Albuquerque's ability to meet their required return flows would be unlikely to be approved by the New Mexico State Engineer.

Additionally, New Mexico operates under prior appropriation water laws such that earlier permit holders have the first right to water. This water rights priority would become pertinent if upstream consumption of water was deemed to impact the ability of a downstream stakeholder with a more senior permit to make required withdrawals. Additional downstream stakeholders, such as those relying on instream diversions for irrigation, were not assessed in this case study but could have legal recourse concerning an additional consumption of water.

Chapter 6. Discussion, Limitations, Conclusions and Future Work

6.1 Discussion

In Illinois, results show that there would be a minimal downstream impact from the consumption of reclaimed water. Based on the analysis presented, the largest possible water consumption in the Chicago region (100% ADF from the Stickney Wastewater Reclamation Plant) would lead to a statistically significant difference in mean streamflow immediately downstream but would become less significant further downstream. The maximum probability of failure for waterborne transportation — defined as the likelihood of observing a river stage below 2.74 meters — would increase from about 0.5% to 1.75%; however, the failures would occur for short durations and low failure magnitudes. These impacts would be unlikely to affect a proposed reclaimed water consumption project in Illinois under riparian water rights.

In New Mexico, there are significant impacts downstream of Albuquerque for the proposed reclaimed water consumption. In the summer months, large diversions of water increase the significance of these impacts at further distances. For the 1.28 cms consumption scenario (50% ADF from the Southside Water Reclamation Plant), the probability that streamflow would drop below the threshold increases from 18% to 26%. This increase in the probability of failure is coupled with larger average failure magnitudes and longer average failure durations. These impacts increased with larger consumption magnitudes. Proposals may be rejected by the federal government because of their adverse impacts to endangered species (Houck, 1993). Due to the protection of the Rio Grande silvery minnow under the Endangered Species Act, it is unlikely a proposed reclaimed water consumption of 1.28 cms would be permitted.

Spatial patterns from the statistical significance in reduction to mean streamflow closely matched those from the stakeholder metrics for the Rio Grande case study but not the Illinois River case study. As previously mentioned, impacts to mean Rio Grande streamflow increased with distance downstream of consumption. This same trend is found when analyzing the impacts to the silvery minnow, particularly the probability of failure. Along the Illinois River, impacts to barge transportation are greater further downstream of consumption while the significance in streamflow reduction is greater close to the point of consumption. This indicates that assessing changes to mean streamflow may not be sufficient when stakeholders are reliant on stage rather than streamflow.

Whether assessing a stakeholder that is reliant on stage or streamflow, each downstream metric must be assessed with consideration to each other and with consideration to the requirements of the stakeholder for informed decision making. As discussed in the Illinois case study, considering only some of the metrics can lead to misinformed conclusions about the downstream impacts. Moreover, the importance of each individual metric might vary depending on the stakeholder. Certain stakeholders might be resilient to more failures but susceptible to larger magnitudes of failure. Additionally, a stakeholder might be unable to function at any capacity under a determined threshold, such that the magnitude of failure is less significant than the probability of failure.

Flexibility in water consumption is another important consideration, since some reclaimed water applications allow for greater variability in consumption. For example, artificial groundwater recharge could 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 this method by formulating water consumption as a function of flow.

6.2 Limitations

As previously discussed, the analysis conducted in the described case studies uses historical stream gage data. This method inherently assumes stationarity and no changes to historical operation in the basin. Additionally, the use of historic streamflow data assumes no changes in reservoir operations to minimize downstream impacts. In highly managed regions such as the Rio Grande Basin, it is likely that upstream water could be released in order to supplement streamflow during low flow periods. As mentioned in the methods section, the analysis could be amended for probabilistic forecasts and changes to operation policy in lieu of historical streamflow data.

Additional research to quantify the implications of reclaimed water use on downstream water quality could complement the proposed framework. The consideration of water quality could be done with the same spatial and temporal consumption patterns employed in this method and would provide additional metrics for water managers to evaluate a proposed reclaimed water consumption.

6.3 Conclusion

Impacts to downstream stakeholders are an important consideration when evaluating an additional consumption of reclaimed wastewater effluent. Use of reclaimed water is becoming more prevalent due to concerns over water scarcity and the water-energy nexus. This consideration is increasingly important as reclaimed water becomes a more popular alternative to surface water and groundwater withdrawals.

As demonstrated in the analysis of the Illinois River and Rio Grande case studies, the methods quantitatively assess the impacts to downstream stakeholders for a proposed consumption of reclaimed water. This quantification, coupled with local legal considerations, can aid decisionmakers in the evaluation of proposed reclaimed water consumption.

More broadly, the methods presented are a necessary evolution in sustainable resource management. Water reuse, along with other seemingly sustainable propositions, requires holistic spatial and quantitative analyses that include stakeholder engagement to determine the relative sustainability of different options within socio-hydrology. Moving forward, decision makers can use such techniques to objectively and consistently evaluate projects and polices to predict the local, regional, and probable future impacts.

6.4 Future Work

To improve upon the assumption that reservoir operations will be unaffected by the consumption of effluent, further analysis in the Rio Grande basin will be done using the simulation model RiverWare (Zagona et al., 2001). Through the use of this model, upstream reservoir releases to supplement effluent consumption can be reflected. This is likely to influence downstream stakeholder performance metrics as well as the reservoir operations upstream. Additional stakeholders and metrics may also be assessed using this model, including energy generation at upstream reservoirs.

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