Linking Reclaimed Water Consumption with Quantitative Downstream Flow Impacts

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Abstract

Although reclaimed water --- municipal wastewater treatment plant effluent --- can serve as a locally sustainable alternative water resource, this additional consumptive use of reclaimed water may cause impacts downstream. This paper seeks to quantitatively assess these impacts by employing scenario analysis coupled with a two-sample *t*-test to evaluate the statistical significance of streamflow alteration. Further, the potential for lower volumes of streamflow is linked to impacts on downstream stakeholders through the use of stakeholder performance metrics. To demonstrate the applicability of this approach, two diverse regions are evaluated: 1) the Illinois River downstream from the greater Chicago, Illinois area, and 2) the Middle Rio Grande River downstream from Albuquerque, New Mexico. In Illinois, impacts to barge transportation are marginal and decrease with distance downstream of effluent consumption. In the Rio Grande, impacts to the Rio Grande silvery minnow worsen downstream such that a proposed consumption would be unlikely to be established under federal regulations. The extent of downstream impacts is important in legal and policy contexts regarding the sustainability of reclaimed water projects.

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 supply available. An estimated 20 billion gallons of wastewater effluent are discharged in the United States each day, equating to about 7% of the total freshwater use, and are 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. 2011b; 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.

De facto water reuse refers to discharges of municipal wastewater effluent into receiving waters. Studies of wastewater treatment plants serving more than 10,000 customers in the United States demonstrated that there is a wide variability in de facto water reuse, approaching 100% at some sites during low flow conditions (Rice et al. 2013a, 2015; 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?

This paper presents a framework to quantitatively assess the impacts to downstream stakeholders of engineered water reuse. The approach begins with an analysis of the regulatory framework, and then performs scenario analyses of proposed water reuse with a two-sample *t*-test of perturbed hydrology and calculation of a set of stakeholder performance metrics for each scenario and each considered stakeholder group. The paper presents two case studies to demonstrate the framework, which are chosen to illustrate differing water availability and streamflow patterns and contrasting water rights laws. The first scenario explores potential reclaimed water consumption for thermoelectric power plant cooling in the greater Chicago, Illinois region, building on previous work (Barker and Stillwell 2016). Illinois operates under regulated riparian water rights and represents a water abundant region. The second scenario demonstrates reclaimed water consumption scenarios for Albuquerque, New Mexico along the Middle Rio Grande River, which was chosen because it represents prior appropriation water law and relative water scarcity. The remainder of the paper first gives background on water reuse, provides the methodology for the framework, and discusses legal implications of water reuse. Subsequently, the two case study results are presented, ending with conclusions of the study.

Background

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. Utilizing reclaimed wastewater can reduce the required energy needed for transporting water, as wastewater effluent is often produced near the intended end-user. 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. 2011a; Stillwell and Webber 2014).

Water use regimes can be classified based on their relative proportion of withdrawals to return flows (Weiskel et al. 2007). Although there are different ratios of withdrawal to return flow with engineered reclaimed water use, the analysis presented herein explores uses that would be considered consumptive, such that the water is no longer immediately available in the originating watershed. For example, converting thermoelectric power plants from open-loop to closed-loop cooling increases evaporative consumption, likely reducing streamflow downstream (Barker and Stillwell 2016; DeNooyer et al. 2016). In this situation, additional consumption of wastewater effluent would reduce the downstream flows similar to introducing a new demand. Therefore, the analysis constitutes a highly conservative estimate, demonstrating how these increased consumptive uses would affect downstream flows.

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. 2013b; 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 operations. 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 stretches comprised of a large portion of de facto reuse are likely more dependent on effluent. Previous research has quantified de facto use downstream; different approaches for 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 will have quantifiable impacts.

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.

Methods

Considering a proposed reclaimed water consumption, the following methods quantitatively evaluate the downstream impacts of reduced streamflow using historical streamflow data. In this paper, historical streamflow data are directly compared to a modified dataset representing the reclaimed water consumption scenario. To do so, observed streamflow data are gathered for stream gages at varying downstream distances from the reclaimed water source.

The resulting comparison between the historical streamflow and the amount of water removed via consumption is termed adjusted streamflow, calculated using equation (1),

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

where, at each timestep (t), the adjusted streamflow (A_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.

Consumptive scenarios are dependent on the application of reclaimed water use. The scenarios can be uniform (equal consumption each timestep) or varied to mimic seasonal patterns. For instance, baseload thermoelectric power plants need a relatively constant, uniform supply of water (Peer et al. 2016; 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 compared to when the considered stakeholder is susceptible to daily fluctuations in flow.

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 (European Commission and Directorate-General for the Environment 2015). If these criteria are not met, a lag in the timestep can be applied, which would depend on the routing of the river. The subsequent sections introduce the major methodological components of the analysis: statistical significance tests and metric analysis.

Statistical Significance

A two-sample *t*-test comparing the historical and adjusted data is conducted, to determine the extent to which consumption scenarios will significantly change the mean of the daily streamflow distribution at a particular location along a river. For the use of parametric tests, such as a two-sample *t*-test, the assumption of a Gaussian distribution should 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 adjusted streamflow. Box-Cox are a family of transformations commonly utilized to improve both the normality and homoscedasticity 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),

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

is conducted on each datum (*y*). 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 gage 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 performed 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 QQ-plots are visually analyzed following the transformation to confirm normality assumptions. Both the visual analysis of the QQ-plots and several other normality statistical hypothesis tests can be found in the supplemental information (Table S1 and Figures S6 – S13).

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 adjusted streamflow, represented by subscript (A). The result of the test is a *t*-statistic that represents the significance of the consumption on mean streamflow:

$$t = \frac{\underline{X}_D - \underline{X}_A}{\sqrt{\frac{\sigma_D^2}{n_D}} + \sqrt{\frac{\sigma_A^2}{n_A}}} \qquad (3)$$

where t = t-statistic, $\underline{X}$ = 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.

Stakeholder Performance Metrics

Quantitative performance metrics are presented here to depict how stakeholders might be impacted by reduced streamflow. The framework uses multiple metrics to provide a diverse view of these impacts.

Probability of Failure

Following Hashimoto et al. (1982), the probability of failure calculation requires a threshold to dictate acceptable versus unacceptable streamflow. For example, assume a stakeholder requires river streamflow to be above a given threshold value. A deficit can be calculated:

$$D_t^i = \{\ X^i_{Threshold,t} - \ X^i_{Streamflow,t} \ \ 0\ if\ \ X^i_{Streamflow,t} \le X^i_{Threshold,t}\ if\ X^i_{Streamflow,t} > X^i_{Threshold,t} \qquad (4)$$

where D_t^i represents the magnitude by which the streamflow is less than the desired threshold, at a gauge *i* and time *t*.

Probability of failure represents the fraction of time that the streamflow falls below the threshold:

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

Equation (5) therefore ignores the magnitude of the failure and instead gives the sum of the number of times that this *D* value is non-zero across a timeseries, divided by the total length of the timeseries, n_t^i. Lower values are desired, with a value of 0 indicating that the variable is always above the threshold. Equation (5) can be modified for different thresholds depending on the stakeholder, or combined with extra calculations such as transforming streamflow to river stage or other variables.

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. Average failure duration is determined using equation 6:

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

$$0\ if\ No.of\ Failures = 0 \qquad (6)$$

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.

Average Failure Magnitude

Average failure magnitude (Equation 7) 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, the average streamflow or river stage during a failure is approaching a value of 0, or no flow.

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

Determining the probability of failure, the average failure duration, and average failure magnitude gives a holistic 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.

Legal Considerations in the United States

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. When changes in streamflow do not affect federal purposes, state water laws are considered.

Federal law takes precedence in situations where federal purposes 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 because the outcome may impact the United States' ability to adhere to the Rio Grande Compact (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 (US Environmental Protection Agency 2012). Therefore, U.S. state laws 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.

In the absence of specific reclaimed water legislation, judicial precedents can be considered, but legal considerations in different states might be applied distinctively. Additional information on legal precedents can be found in the discussion section.

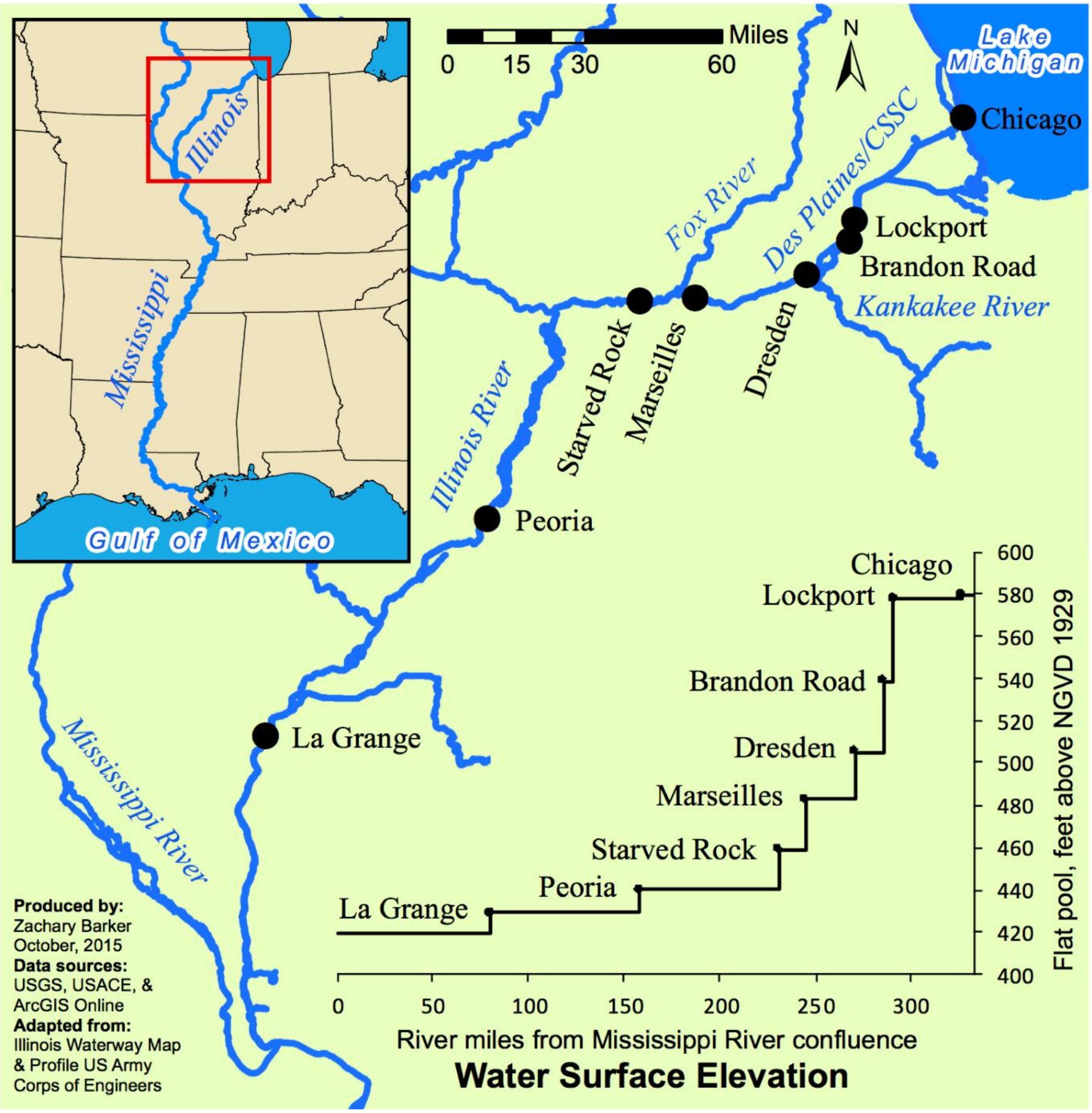

Fig. 1. *The Illinois River connects Lake Michigan with the Mississippi River and is downstream of the proposed reclaimed water consumption (adapted from Lockett (2007), using source from ESRI (2015)).*

Illinois River Case Study

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 1.

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. 2011a). Many power plants still use open-loop cooling systems, which risk 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. 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. As a combined sewer system, the hydrologic response to wet weather events is highly engineered and complicated; however, this work focuses on dry weather and low flows. 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.

Data from the Illinois Water Inventory Program and reports published by the Illinois State Water Survey and cooling data (Hlinka et al. 2011) are employed to determine the relative proportion of water withdrawal versus in-stream use. The largest user is a power plant, withdrawing 7% of the median flow, which is unlikely to be impacted by upstream reclaimed water consumption (U.S. Energy Information Administration 2018). To be impacted by adjusted streamflow, the water level would need to fall below the intake structure. In the absence of intake structure information and the withdrawals comprising a low proportion of flow, the focus of this case study is on in-stream uses rather than withdrawals.

Of the various in-stream users, barge traffic is the most susceptible to being impacted by marginally reduced flows. 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).

Illinois River: Scenario Analysis

The baseline historical conditions are compared to a range of discrete water consumption scenarios. The study uses approximately 30 water years’ worth of data, from December 30, 1986 until December 21, 2016. 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). 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 (Peer et al. 2016; Peer and Sanders 2016). 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 2. Using Equation (1), adjusted water reuse scenarios are determined by subtracting the quantity of water consumption from all data points to shift the flow duration curves.

Lower reclaimed water consumption rates show similar shifts, but the magnitude is less detectable. At all of the streamflow gages shown in Figure 1 and for all consumption rates and patterns, the flow duration curves shift left, illustrating lower streamflow. While all of the flow duration curves in Figures S1–S5 of the Supplemental Information depict the same reductions in streamflow, gages further downstream have larger contributing drainage areas, and, therefore, the flow regime shift appears smaller.

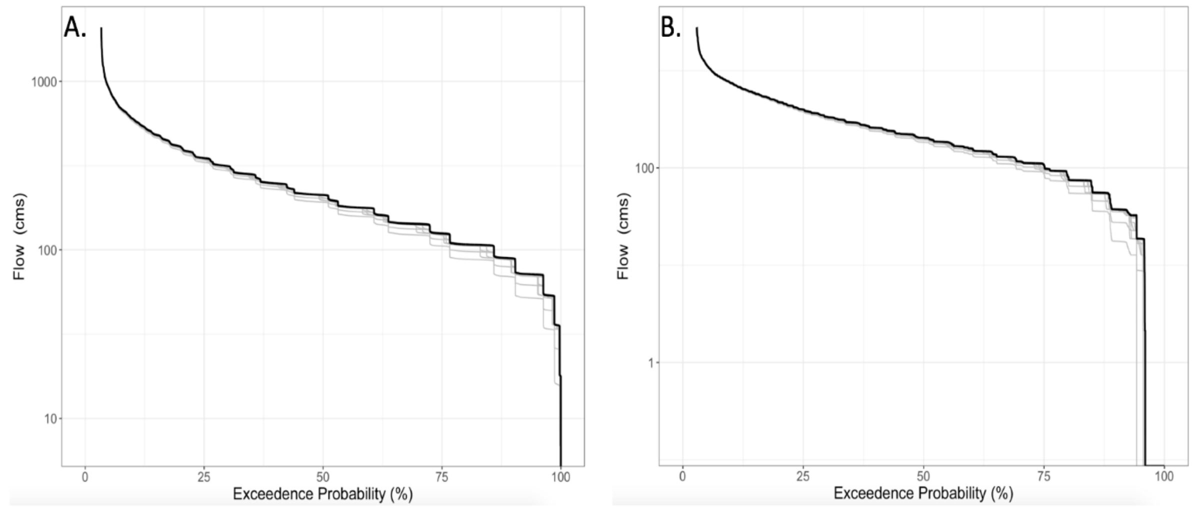

Fig. 2. *Flow duration curves at two downstream gages, Dresden (A.) and Marseilles (B.) with the original exceedance probability in bold and consumption scenarios represented in gray.*

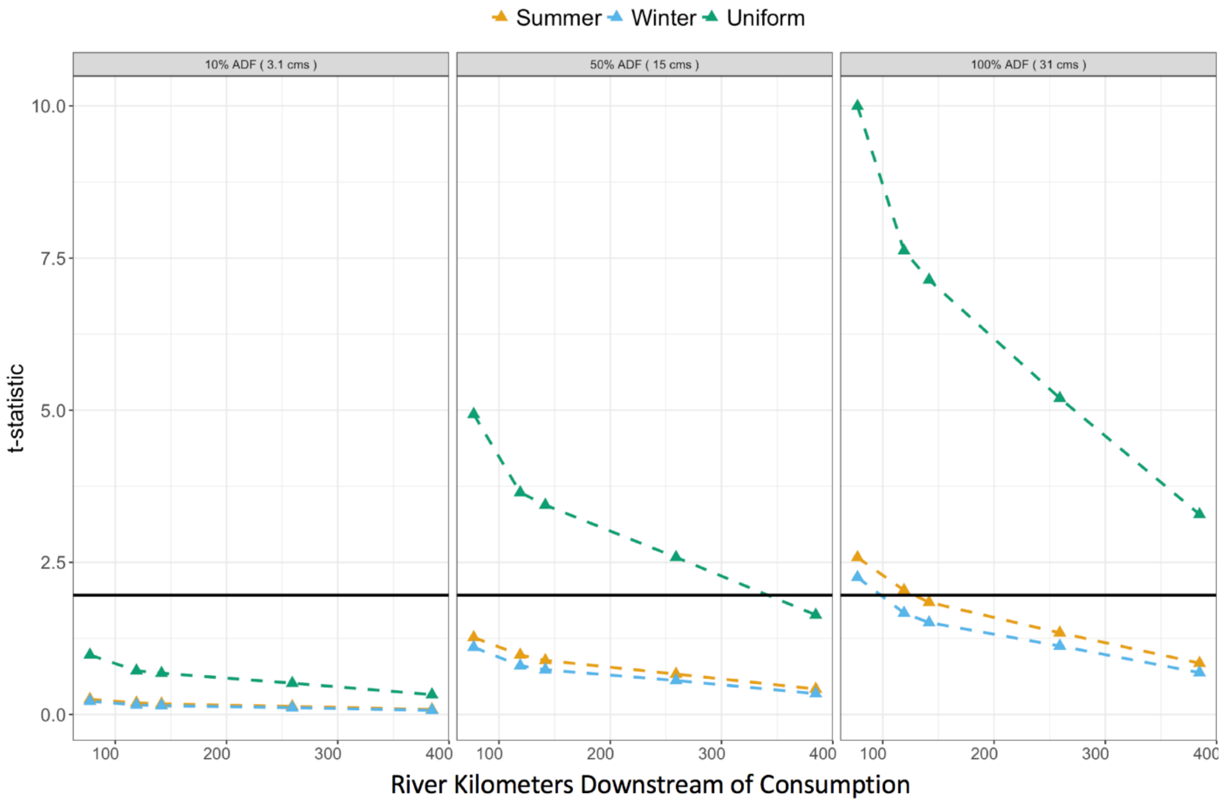

Fig. 3. *Uniform consumption of 50% of the Average Daily Flow (ADF) would lead to statistically significant decreases in streamflow at most stream gages downstream of Stickney Water Reclamation*

Plant, shown above the line representing a significance level of 0.05. Statistical significance decreases with distance downstream of the site of consumption due to larger contributing areas.

Illinois River: Statistical Significance

To quantify the difference in flow regimes illustrated in Figure 2, 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 3.

The significance in mean streamflow reductions due to reclaimed water consumption increases with additional effluent consumption for each consumption scenario. These impacts diminish with distance downstream and are below the significance level ($\alpha = 0.05$) 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. Overall, consuming reclaimed water in only the winter and spring generates consistently lower differences in mean streamflow compared to consuming reclaimed water in the summer and fall.

Illinois River: Stakeholder Metrics

As previously mentioned, barge traffic is an important stakeholder on the Illinois River. The analysis requires setting thresholds based on river stage 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. The current probability that the minimum stage is not met is found using the reported stage and streamflow data (see the Supporting Information for a discussion on rating curves) 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 4.

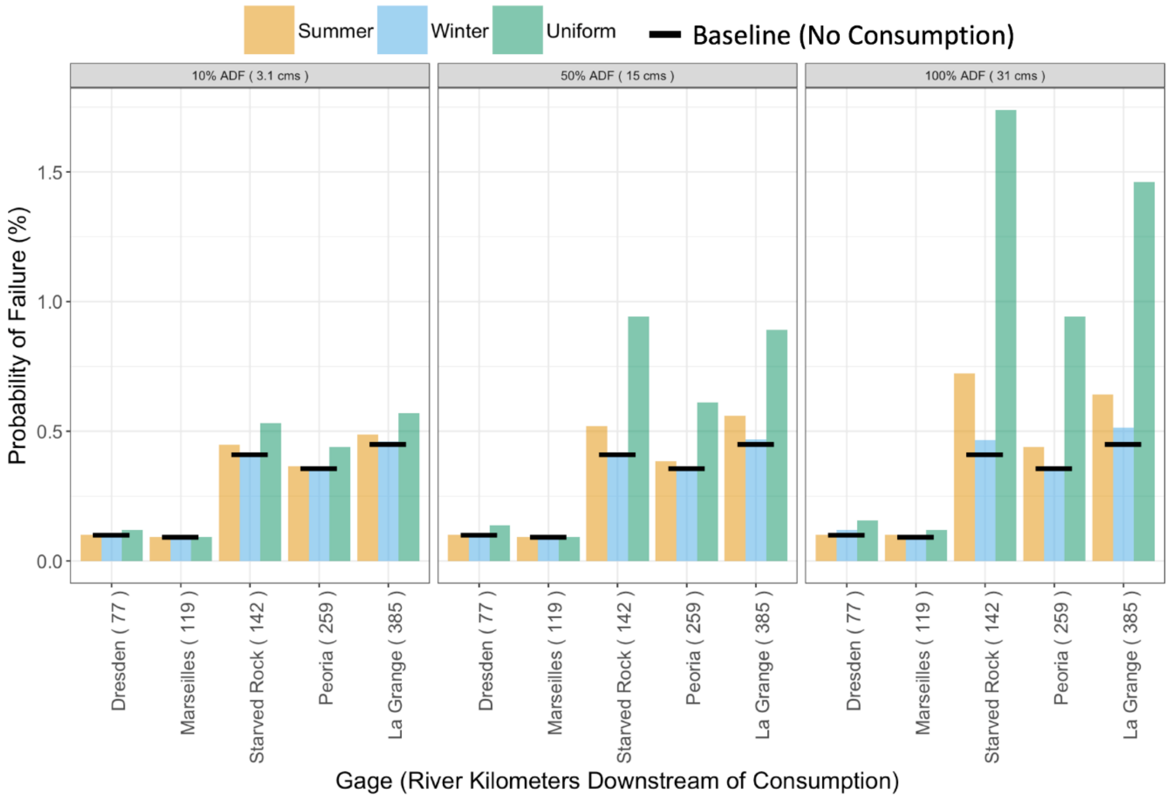

Fig. 4. *The probability that the stage at each gage falls below the 9-ft minimum channel depth is small under current conditions (no reclaimed water consumption; black bars) and increases marginally with increases to the proposed consumption scenario.*

Figure 4 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 upstream from the Mississippi River confluence, as would be expected by the trend of the *t*-statistic. This disagreement between the *t*-statistic and probability of failure can be partially explained by the use of stage in the probability of failure calculations rather than only streamflow. Stage can be affected by the river depth and width, causing enhanced changes in stage relative to streamflow alone.

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 5), 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.

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 6) 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).

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 likely 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.

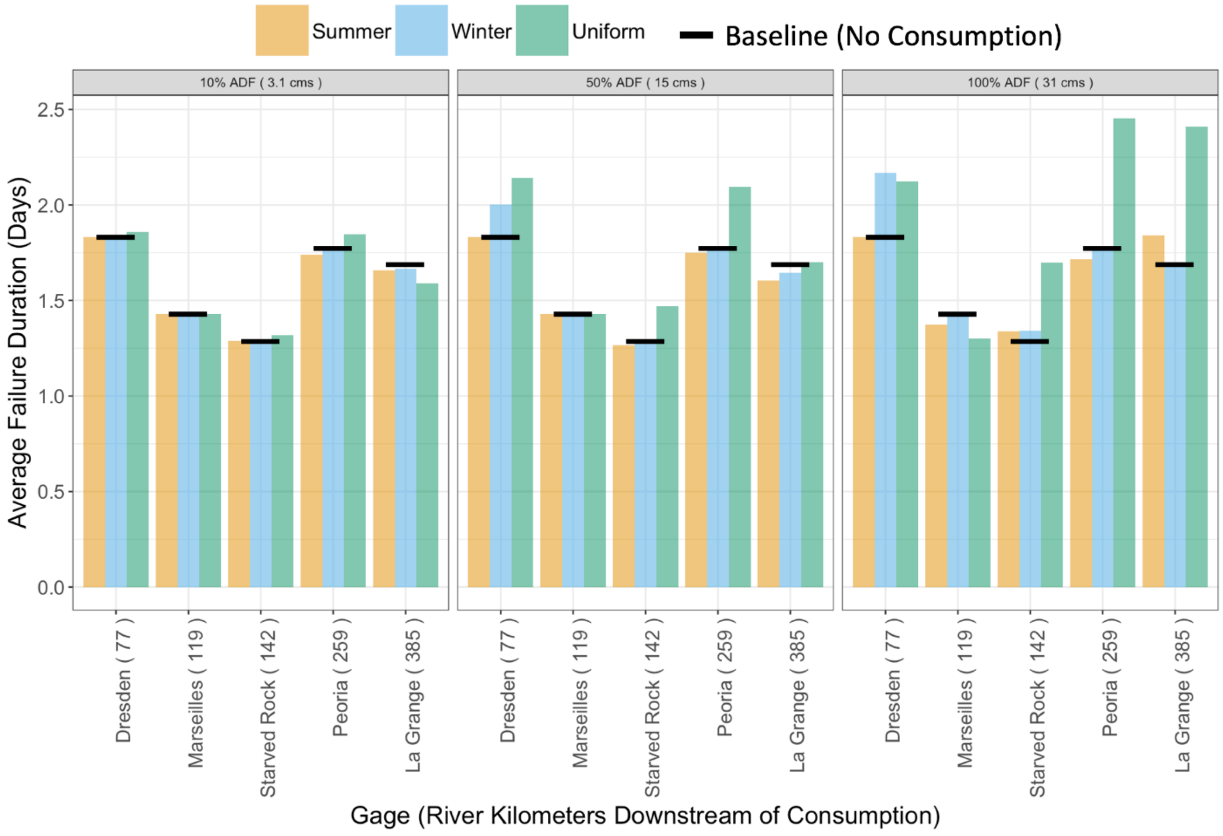

Fig. 5. *The average period in which river stage is below the 2.74-m threshold varies at each downstream gage for each consumption scenario, compared to existing conditions (black bars).*

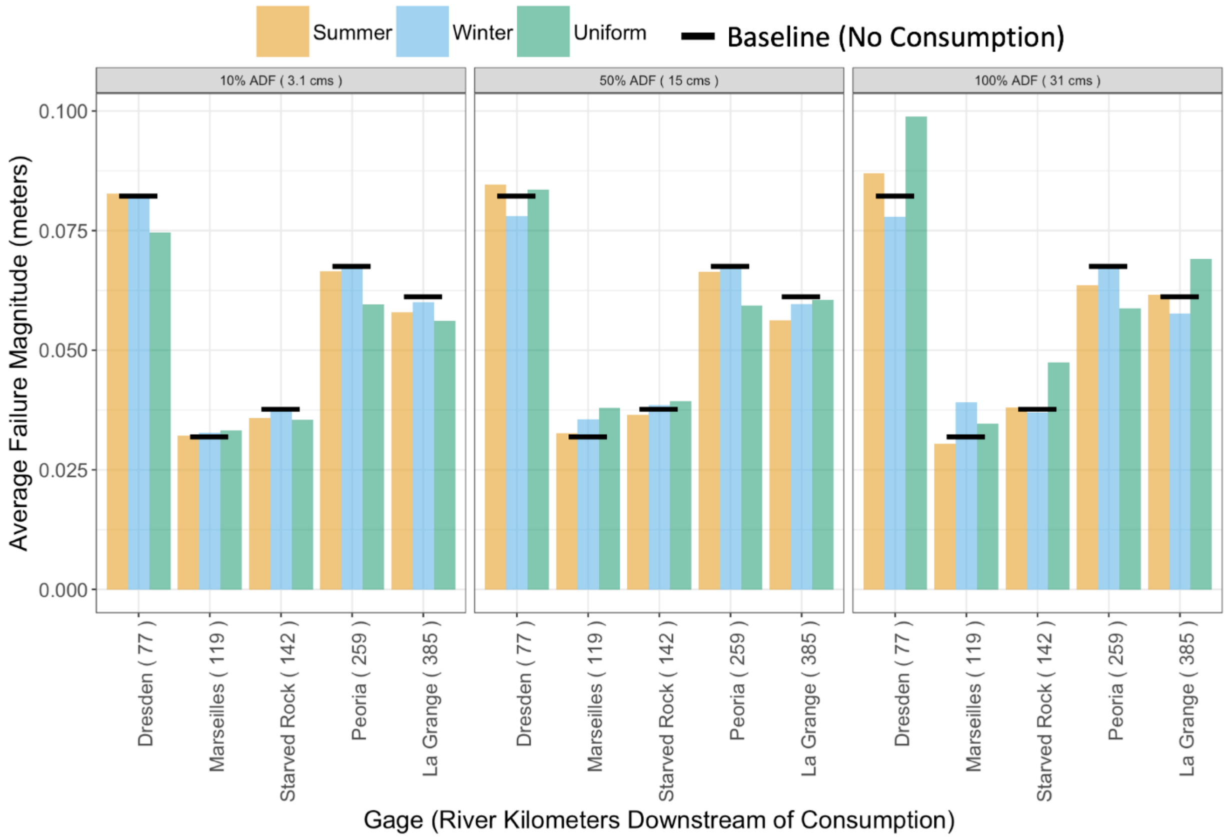

Fig. 6. *The average magnitude of a failure decreases for most consumption scenarios because of the occurrence of more single-day failures, which is corroborated by the increase in probability of failure at these downstream gages compared to existing conditions (black bars).*

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 their 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.

Fig. 7. *The Middle Rio Grande stretches from Albuquerque, New Mexico to the Elephant Butte Reservoir. This stretch of river contains multiple large diversion dams used for irrigation (map utilizing ESRI (2015)).*

Rio Grande Case Study

Impacts from reclaimed water consumption are assessed along the Middle Rio Grande downstream of Albuquerque, New Mexico (Figure 7). 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.

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 New Mexico and Texas, as well as an international agreement between the United States and Mexico. In accordance with 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 due to 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).

Rio Grande: Scenario Analysis

Similar to the Illinois Case Study, an adjusted 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). Consumption magnitudes of 1.28 cms (50% ADF) and 0.255 cms (10% 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). 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. 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 5), located along the Rio Grande between the Southside Water Reclamation Plant and Elephant Butte reservoir. The study uses 30 water years' worth of data, from October 1, 1986 until September 30, 2016. Days in which data were unavailable, which accounted for 15.9% of the total days in this time range, are excluded.

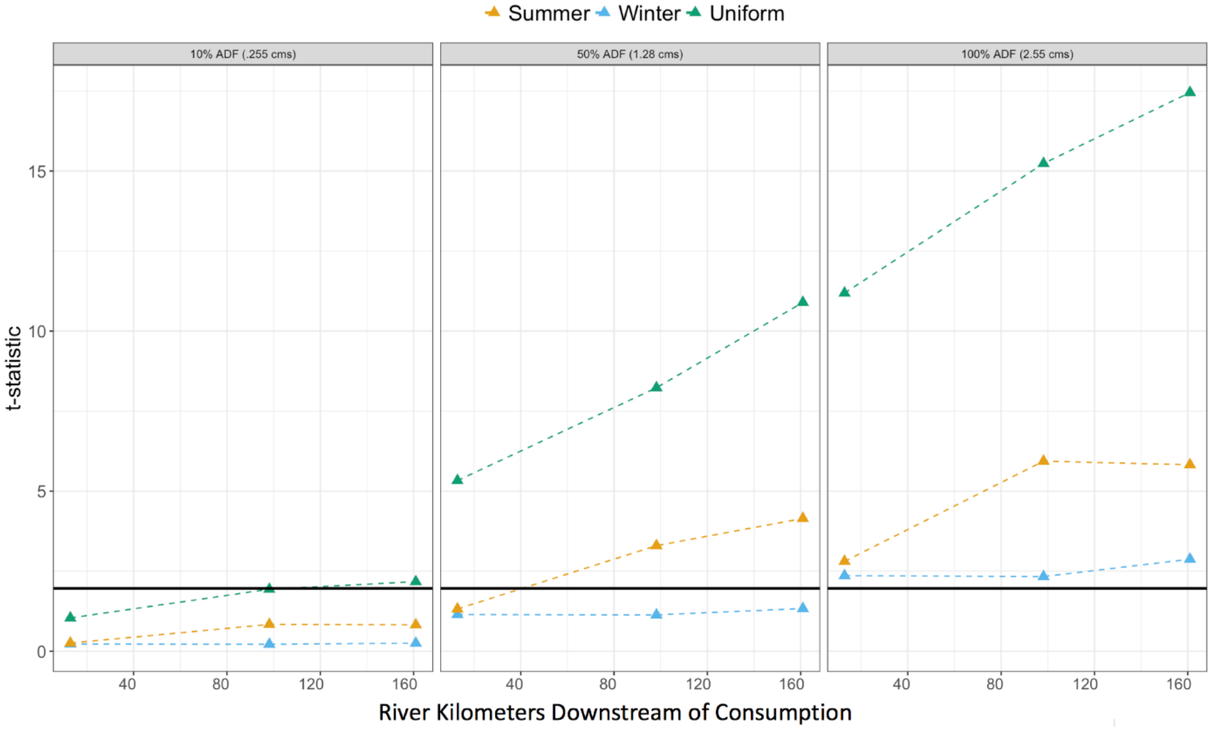

Fig. 8. *Statistical significance of reductions to mean streamflow along the Middle Rio Grande generally increase with distance downstream of the proposed reclaimed water consumption, shown above the line representing a significance level of 0.05, due to large instream diversions for irrigation.*

Rio Grande: Statistical Significance

The statistical significance to reduction in mean streamflow is determined, shown in Figure 8. Unlike the Illinois Case Study, reduction in mean streamflow generally increases with distance downstream from Albuquerque. This reduction is likely due to the large diversions of water downstream from the wastewater treatment plant. 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. The lower value indicates impacts to stakeholders may be mitigated with consumption only in the winter months.

Rio Grande: Stakeholder Metrics

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 threshold varies each year depending on streamflow at the Otowi gage. Because both the threshold and the metric are determined yearly, a one-year time step is used for the determination of probability of failure. The failure threshold is only exceeded for the uniform consumption of 100% ADF. 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). A time series representation of the ability to adhere to the Rio Grande Compact and additional discussion on the topic can be found in the supplemental information (Text S3 and Figure S14).

As previously mentioned, 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 9. This baseline probability of failure is then compared with each of the consumption scenarios (Figure 9).

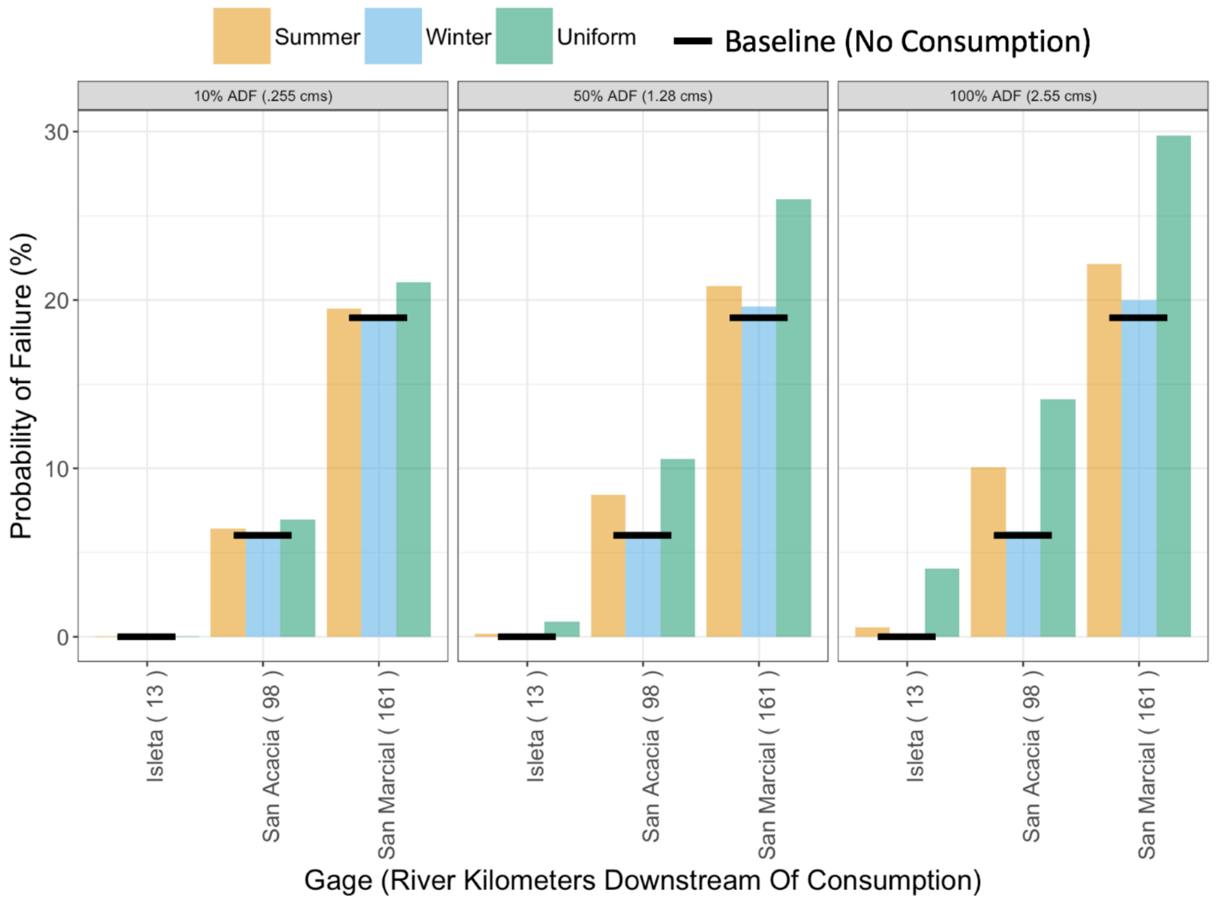

Fig. 9. *The probability that a given day in the Middle Rio Grande will experience streamflow below 1.42 cms (50 CFS) increases with an increase in reclaimed water consumption, compared to existing conditions (black bars). Consumption in the summer months leads to greater probability of failure than in the winter.*

Probability of streamflow being below the 1.42 cms threshold increases with additional consumption at each gage, but there are seasonal and spatial differences. The summer consumption scenario consistently causes a larger probability of failure than the winter scenario. Also, the probability of streamflow being below the threshold increases with downstream distance from the wastewater treatment plant.

Average failure duration (Figure 10) is calculated to determine how long negative impacts to the stakeholder persist. Longer failure durations are generally harder for a stakeholder to overcome and may require augmentation of water supplies from other sources such as reservoir storage. If the average failure duration in the Rio Grande increases, the resilience of the silvery minnow becomes pertinent.

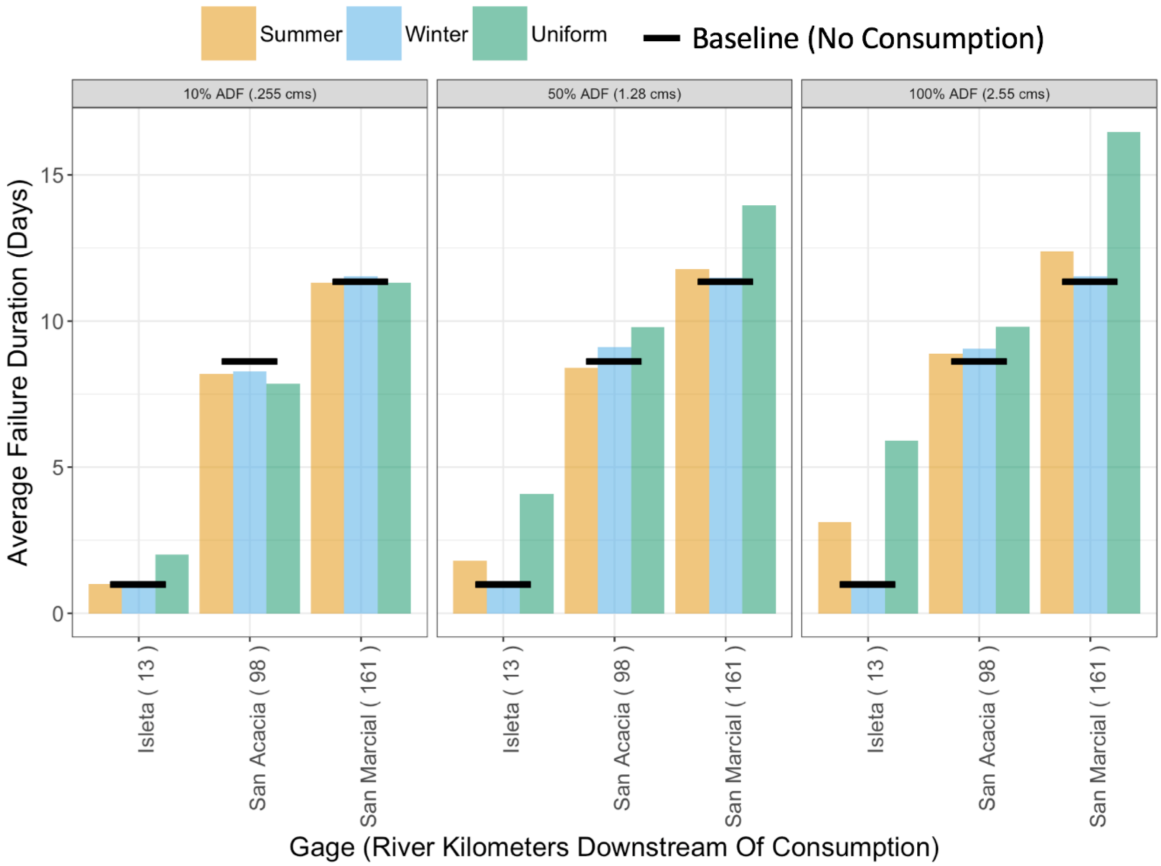

Fig. 10. *The average failure duration in the Middle Rio Grande remains relatively constant for lower consumptions but increases with larger consumptions compared to existing conditions (black bars).*

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 11). 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).

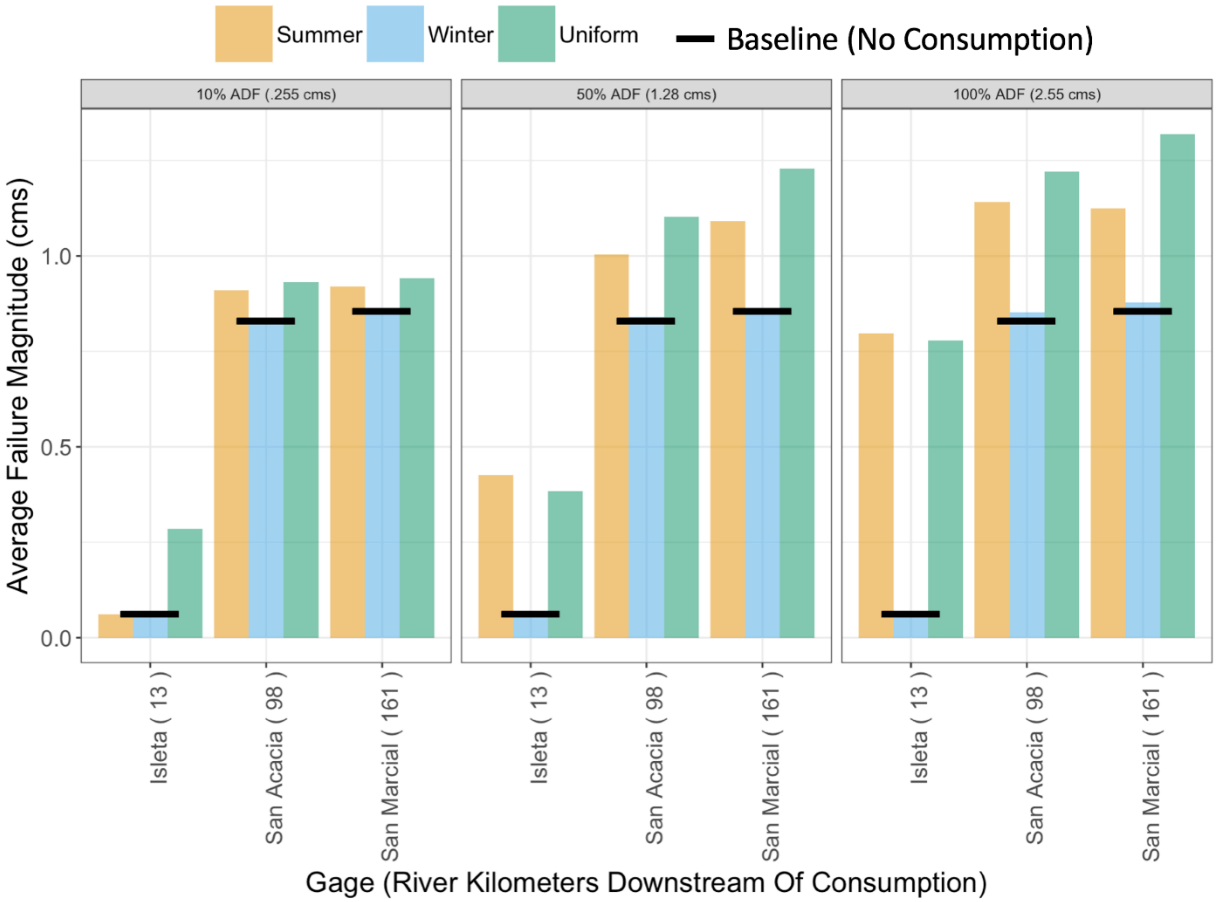

Fig. 11. *The average failure magnitude in the Middle Rio Grande increases with distance downstream of the proposed consumption compared to existing conditions (black bars). Consumption in the winter months has negligible impact on the likely magnitude of failures.*

The average failure magnitude follows the same pattern as the probability of failure and average 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.

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 determined 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 on 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 Bernanlillo 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.

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 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, 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. However, due to the overall lower amount of streamflow in the Rio Grande, some limited applications of water reuse may be warranted to augment the stressed water supply.

For informed decision making, each downstream metric must be assessed with consideration to each other and with consideration to the requirements of the stakeholder. 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.

Limitations

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 or the Illinois River Basin, it is possible that upstream water could be released to supplement streamflow during low flow periods. Future extensions to the work could incorporate probabilistic forecasts and changes to operation policy in lieu of historical streamflow data.

When using this framework to study water reuse, care must be taken in properly defining the “consumptive” use of water. Some consumptive uses may eventually return to the basin of origin (Liu et al. 2009), so future users of this framework should be careful to calculate a hydrologic water balance to ensure that consumption is defined properly. Reclaimed water use could also aid in aquifer recharge via increased groundwater flow, which could also improve soil and water quality depending on baseline conditions (Miller 2006). The framework outlined could be integrated with hydrologic models to capture complex interactions with groundwater and evapotranspiration. Additional integration with water quality or temperature models could expand the capabilities of the framework (Miara and Vörösmarty 2013; Stewart et al. 2013). Implicit in the analysis is the assumption that all reclaimed water diversions occur upstream of the study area. When planning for multiple diversions, from separate sources, the flow dynamics that occur between the sources should be considered.

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 decision makers 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 policies to predict the local, regional, and probable future impacts. Results from these types of analyses can be applied to assess the relative merits of individual reclaimed water projects, or more broadly, to design water resources policies that are more sustainable to all stakeholders.

Data Availability Statement

All data, models, or code generated or used during the study are available in the following GitHub repository: https://github.com/BrendanCUBoulder/Downstream-Effects-of-Reclaimed-Water-Consumption.

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Supplemental Materials

Figs. S1–S14 and Table S1 are available online in the ASCE Library (www.ascelibrary.org).

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