INTEGRATING RAW WATER TRANSFERS INTO AN EASTERN U.S. MANAGEMENT CONTEXT: A MULTI-OBJECTIVE ANALYSIS

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ABSTRACT

David Evan Gorelick: Integrating raw water transfers into an Eastern U.S. management context: a multi-objective analysis
(Under the direction of Gregory Characklis)

In the Eastern U.S. intermittent transfers of treated water are common tool for drought management, but untreated "raw" water transfers are rare. Nonetheless, raw water transfers, free of physical and financial constraints of treating and piping water, show promise within an Eastern regulatory context and could aid in meeting future demands and delaying or avoiding expensive infrastructure. This work develops a detailed simulation model to investigate several raw water transfer schemes along a common river course, exploring tradeoffs between reliability and financial objectives in a multi-utility framework. Applied within the Research Triangle of North Carolina, modeling will inform management solutions for an Eastern U.S. region at risk of future water shortages. Raw water transfer schemes are observed to substantially improve supply reliability and reduce demand management interventions, cut inter-basin transfers by up to 90%, and reduce financial risk and long-term debt through decreased dependence on infrastructure and increased planning flexibility.

I would like to dedicate this work to my parents and my brother,
for whom I stayed in school and without whom I would not have had this opportunity.

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LIST OF ABBREVIATIONS AND SYMBOLS

AVR	Annual volumetric revenue
BAU	Business-as-usual
BP	Debt service payments on bonds
JUD	joint upstream development
MG	Million gallons
MGD	Million gallons per day
MGW	Million gallons per week
OWASA	Orange Water and Sewer Authority
RESTC	Revenue loss due to use restrictions
ROF	Risk-of-failure
RWT	Raw water transfer
RWTC	Costs due to raw water transfers
STM	Short-term mitigation costs
TWT	Treated water transfer
TWTC	Costs due to treated water transfers
USACE	United States Army Corps of Engineers

CHAPTER 1: INTRODUCTION

The United States has historically relied on dams, reservoirs and other large infrastructure projects to meet demand for water (Gleick, 2003). However, mounting environmental concerns and rising costs have made new structural solutions more difficult to implement (Postel et al., 1996). Reductions in the rate of new supply development (NRC, 2004), perennial population and economic growth, and uncertainty in climate and hydrologic patterns (NRC, 2012; GAO, 2014) suggest the US faces water scarcity challenges that are likely to be met with fewer infrastructure-oriented approaches (Gleick and Palaniappan, 2010).

As a result, water utilities have begun to consider non-structural alternatives to alleviate concerns of meeting demand (Lund, 2015). Reducing water use via demand management (Renwick and Green, 2000; Moncur, 1987; Baerenklau et al., 2014; Olmstead and Stavins, 2009) or supply augmentation via transfers and reallocation (Jenkins et al., 2004; Wilchfort and Lund, 1997) have become commonplace strategies to combat both long-term shortfalls and drought-related shortages. Water transfers, specifically, are able to compensate for supply deficits during short-term droughts and provide increased diversity in water management options (Kasprzyk et al., 2009; NRC, 2004; NRC, 1992). Transfers of untreated, "raw" water within existing water markets, typically from agriculture (low-value) to urban (high-value) activities in the Western U.S., have been shown to reduce long-term debt for utilities while maintaining supply reliability (Israel and Lund, 1995; Characklis et al., 2006; Vaux and Howitt, 1984). In the Eastern U.S., the use of treated water transfers between urban utilities has demonstrated similar ability to maintain high supply reliability while lowering costs (Palmer and Characklis, 2009; Zeff et al., 2014).

Still, transfers of raw water are rarely applied in an Eastern U.S. context (Getches, 1997), seemingly owing to uncertainty by water managers over the admissibility of raw water transfers under current institutions, reinforced by historical absence of scarcity and the corresponding lack of urgency to efficiently manage existing resources. Discrepancies in state laws on water use (Klein, 2008), restrictions on municipal impoundment of untreated water (McLawhorn and Maddux, 2009), and the lack of a water rights system may all act to limit the ability to purchase, lease, or trade raw water. As a result, existing eastern temporary transfer schemes primarily rely upon treatment and conveyance infrastructure to ferry treated water, which can be an expensive and capacity-limiting endeavor (Caldwell and Characklis, 2014). Furthermore, these schemes are often of the inter-basin variety, and transfers of water between watersheds have been sources of intense political and legal frustration (Abrams, 1982), with the associated transaction costs making them unappealing options for growing communities facing scarcity.

Nonetheless, existing institutional structures appear not to explicitly prohibit raw water transfers. For example, North Carolina law states that any entity making "financial contributions to the construction or operation of impoundments" has the right to withdraw any water attributable to the impoundment – payment toward dam operation affords a party reasonable claim over its waters (NC Gen. Stat. 143-215.44). Virginia law is more straightforward; the owner of a dam has "sole and unrestricted use" of the waters stored behind it (Va Code Ann. 62.1-115). Within these statutes, so long as natural flows are maintained, raw water transfers from an upstream impoundment to a paying downstream user do not seem to run afoul of Eastern water law, potentially providing additional resource flexibility to water-stressed regions in the East. As well, discussions with regulatory personnel appear to confirm the viability of raw water transfers between Eastern users along a common water course (Adkins et al., 2016, personal correspondence). This will be particularly important as population growth stresses existing resource management strategies. Better management of raw water within natural watershed boundaries can avoid the need for expensive treated water transfers and contentious inter-basin imports.

As it stands, there is a bevy of literature on raw water transfers in the Western U.S., under prior appropriation water law, but almost no work in the Eastern states where the riparian rights doctrine influences management strategies, meaning the potential benefit of applying Western-style transfer schemes within other geographic contexts remains largely unexplored. In addition, there is little or no evidence of previous work considering the potential for urban-to-urban raw water transfers in highly-developed Eastern regions (NRC, 1992); in fact, even studies of market-based reallocation have largely centered on transfer of water rights from agriculture to urban demands, and studies of risk-based transfer agreements between eastern U.S. urban utilities only consider piped quantities of treated water (Palmer and Characklis, 2009; Zeff et al., 2014; Zeff and Characklis, 2013).

To that end, this work explores variations of inter-utility raw water transfer schemes within an urban environment that appear allowable under existing water management institutions. Raw water transfers are modeled using an established risk-based contract structure and utility infrastructure finance concepts. Included within a “portfolio” of existing water resource management options (Zeff et al., 2014), raw water transfers are evaluated using coupled hydrologic and financial models for their ability to satisfy financial and reliability objectives simultaneously and act as an alternative to structural expansion within a multi-utility framework.

CHAPTER 2: METHODS

To reasonably judge the ability of raw water transfers to improve supply reliability and reduce long-term utility costs through decreased dependence on structural solutions, there are three requirements: a legally feasible raw water transfer agreement structure, an understanding of potential environmental and financial ramifications of raw water transfers, and a test case in which to evaluate raw water transfers through advanced computational modeling of the system.

2.1 Structuring raw water transfer agreements

For this work, we define a raw water transfer as the exchange of water for supply between two parties without the need for conveyance or treatment infrastructure, meaning raw water transfers do not require the capital to construct and maintain such systems nor are they subject to structural malfunctions and capacity limitations. This implies that transferred water must move through natural channels of a single watershed, from an upstream party to a downstream one along a river course. Such a geographic alignment influences decision-making by both parties; the upstream party may transfer water downstream only when it is comfortable with its resultant storage levels. Similarly, a downstream party is likely to request a raw water transfer when its own storage levels are low. In this modeling framework, these decision are governed by a physical definition of when the risk of future low storage rises to unacceptable levels. To do so, this work relies upon risk-based decision-making to regulate raw water transfers according to each party's perceived "risk-of-failure" (Palmer and Characklis, 2009). As described in (1), risk-of-failure (ROF) quantifies a party's water supply reliability by subjecting current storage levels to historically-observed hydrology and demands.

$$ROF_{party,year,week} = \sum_{i=1}^{T} \frac{F_{year-i}}{T} \tag{1}$$

Risk-of-failure of a given party, for the current week of the current year, is represented as a fraction of years in failure over the past T years. Each past year *y* of an ROF calculation assumes that initial storage $S_{y,week}$ is equal to current storage $S_{year,week}$ when applying the historical demands and hydrologic events over year *y*. An annual failure F_y occurs if at least one week over the range *w*, from the current week in year *y* to *t* weeks later, sees storage fall below 20% of capacity C_{party} due to the adjusted initial storage (2). For short-term mitigation strategies such as transfers or use restrictions, *t* is equal to 52 weeks. For infrastructure, *t* is 78 weeks.

$$F_y = \begin{cases} 1 \; if \; S_{y,w} < 0.2C_{party} \; for \; some \; w \in (week, week + t) \\ 0 \; otherwise \end{cases} \tag{2}$$

Risk-of-failure therefore offers a dynamic tool in decision-making that has been developed and applied for a variety of water supply planning options; additional detail on ROF calculations is given by Caldwell and Characklis (2014). With respect to this study, a downstream party to raw water transfers designates a risk-of-failure level which, if their risk-of-failure were to rise above it, would trigger an action to request raw water transfers from an upstream party. Similarly, an upstream party would only allow a transfer if their current risk-of-failure levels stood below their own set trigger level (Figure 1). In the event that a raw water transfer takes place, meaning both parties satisfy their risk-of-failure criteria, the downstream party would pay for the transferred water on a per-volume basis.

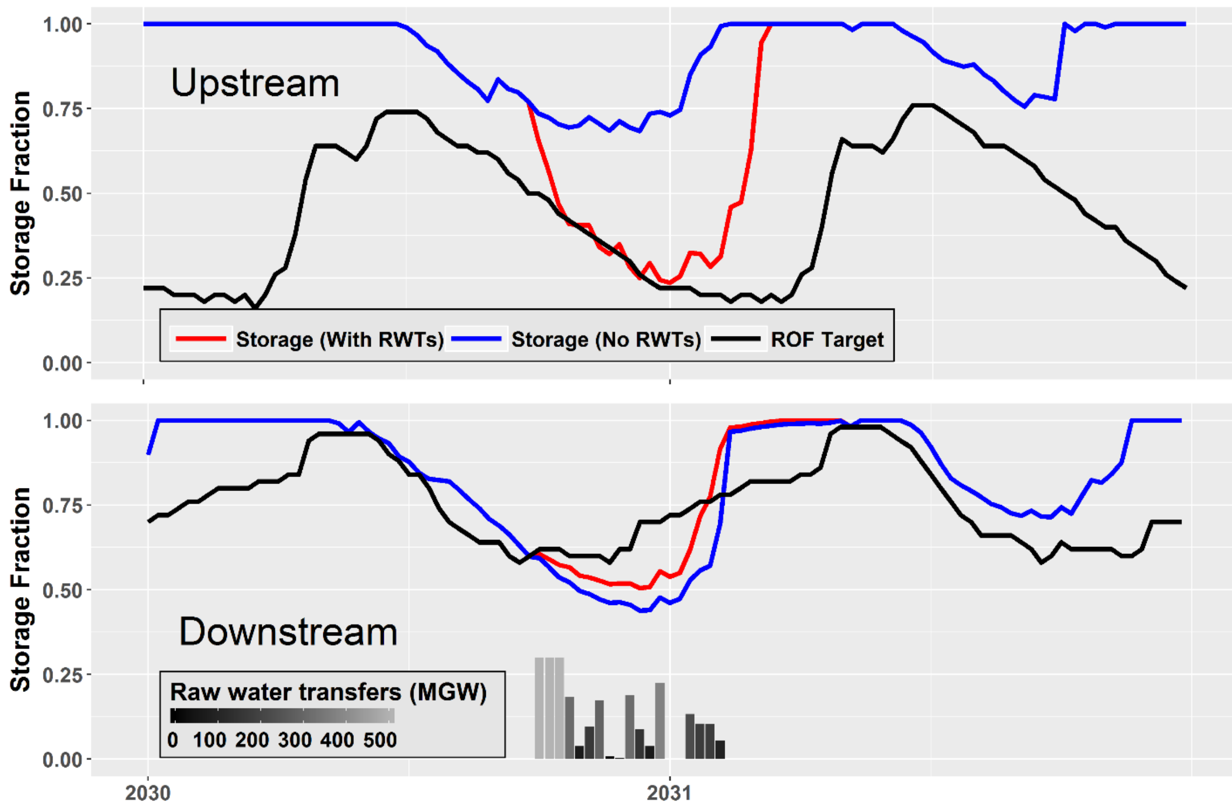

Figure 1: Example of raw water transfers at weekly intervals over a two-year period between an upstream donor (top) and downstream recipient (bottom). Raw water transfers (RWTs) are initiated if downstream storage levels fall below the downstream party risk-of-failure tolerance trigger (black, bottom) and upstream storage levels are above the upstream party risk-of-failure trigger level (black, top).

Should a raw water transfer (RWT) take place, the downstream party will initially request the full volume of water necessary to restore their reservoir storage downstream to risk-of-failure trigger storage levels (Figure 1; bottom, dotted line). This request, and all subsequent calculations, take into account the fraction of RWTs allocated for water supply downstream. This fraction, henceforth the allocation ratio, is considered to account for differences in reservoir operation – reservoirs operated by the U.S. Army Corps of Engineers (USACE), for instance, may impound or release water to maintain water quality and reduce flood risk as well as for water supply, meaning water allocated for supply is only a fraction of reservoir inflows. So, if 500 million gallons (MG) of water are required to raise supply storage levels and reduce downstream risk-of-failure to trigger levels, but only 50% of RWTs are allocated for water supply (an allocation ratio of 0.5), then a 1,000 MG RWT is requested. Reservoir releases to maintain downstream flow targets – natural flows required under environmental regulations – are not counted within RWT calculations. If downstream reservoir levels are below the failure level (20% of capacity) in any week, all RWT volume during that week is allocated for downstream water supply (allocation ratio of 1.0).

Once an initial request is made by the upstream party, the request is subject to a number of possible curtailments. The upstream party will curtail a request if the total RWT requested reduces storage levels sufficiently so as to bring risk-of-failure above the upstream risk-of-failure trigger level. In this case, the RWT request is reduced such that lower upstream storage matches the risk-of-failure trigger level (Figure 1; top, behavior of dashed line relative to dotted line). A request can be further curtailed if it is greater than an agreed-upon maximum allowable weekly RWT volume. Releasing water downstream in large quantities may pose a flooding risk and adversely affect other riparian owners or wildlife, and an upstream party may find it politically untenable to be seen releasing large quantities of water under dry hydrologic conditions. If downstream reservoirs are too full to accept the full RWT, it is curtailed accordingly – this situation may occur if downstream risk-of-failure for overall storage is high across all downstream reservoirs, but only a single reservoir is designated to receive RWTs. Due to potential allocation of RWTs for downstream water supply, water quality, and flood storage, once non-supply needs are satisfied in a RWT week, any further RWT water allocated for those sectors is diverted for water supply, or alternatively the total request is curtailed after factoring in the new temporary allocation ratio of RWT allocation. Because RWTs will temporarily increase streamflows between upstream and downstream reservoirs, a cap on the volume of water available for release in a single week will also be specified. This cap is sensitive to the historic streamflow magnitudes and shifts so as to avoid the potential of flooding.

The remaining RWT request amount is then finalized, with the agreed-upon amount released from upstream supply and added to downstream supply, according to the set downstream water supply allocation ratio. The RWT is paid for by the downstream party the amount equal to the number of gallons of water transferred multiplied by a fixed price per volume of water transferred. The upstream party is then compensated by this amount.

Raw water transfers may also take place as a result of future infrastructure development. Rather than impound and sell water downstream under defined conditions, an upstream user may choose to partner with a downstream user to jointly develop storage infrastructure, the capacity of which would be shared between parties. Cooperative utility development, shown to help water utilities meet individual objectives while decreasing overall development and long-term costs (Zeff et al., 2016), would be undertaken if either the upstream or downstream utility expected their risk-of-failure to reach unacceptably high levels in the future that could not effectively be mitigated through temporary raw water transfers or demand management options. This 'long-term risk-of-failure' is calculated annually, assuming a party's reservoirs are full at the beginning of the calendar year and that there will be some amount of future demand growth. Each party would pay toward construction and operational costs of joint upstream development (JUD) proportionately to their desired capacity stake in the project. Storage in the downstream party's

JUD capacity allocation would be available for transfer downstream at any time. The result of this storage arrangement can provide alternate futures of water management for upstream and downstream parties (Figure 2).

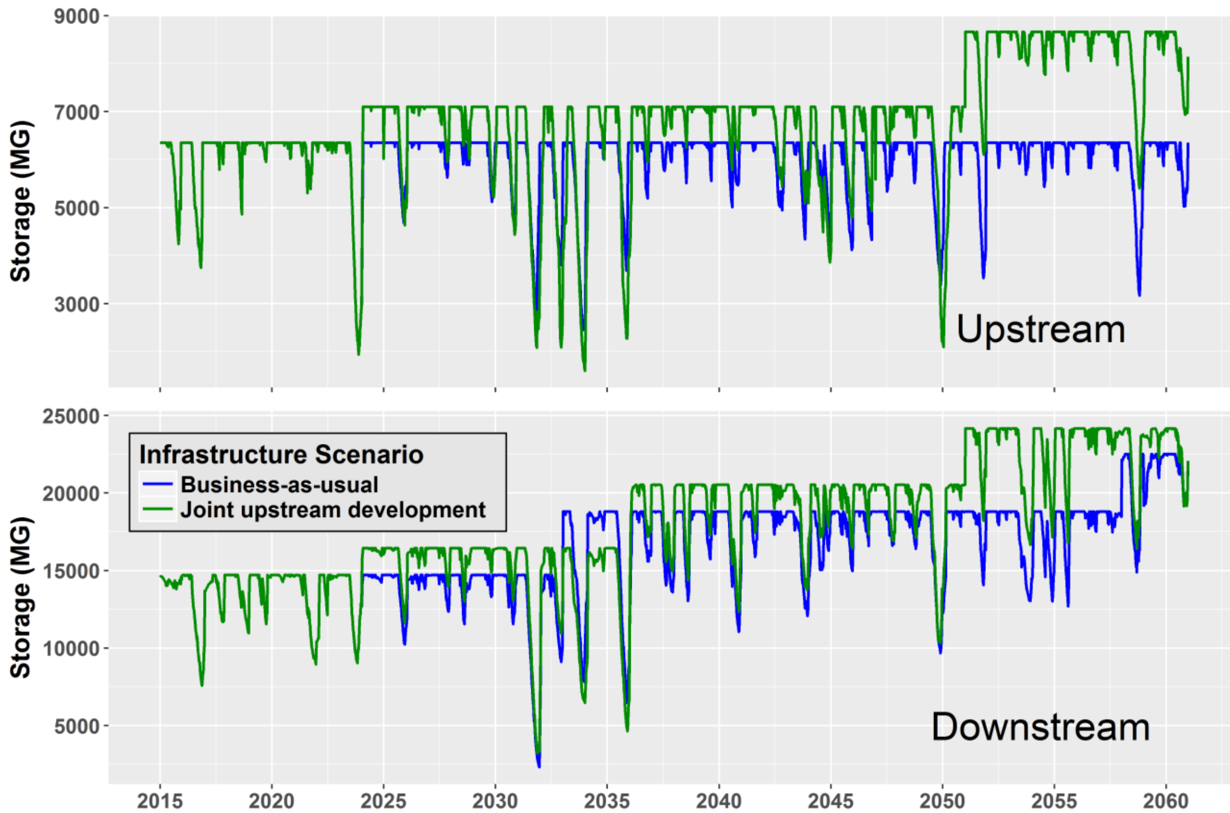

Figure 2: Example of potential upstream and downstream differences in storage capacity between scenarios with (green) and without (blue) joint upstream infrastructure development. In this joint development case, upstream and downstream parties cooperate to expand capacity by 2025 and again in 2052.

2.2 Study area and modeling framework

To demonstrate the potential impact of raw water transfers within existing Eastern U.S. water management practices, transfer schemes are applied to the Research Triangle region of North Carolina (Triangle; Figure 3). A rapidly growing urban region with four major water utilities – Raleigh, Durham, Cary, and Orange Water and Sewer Authority (OWASA) – facing water scarcity challenges in the near future, the Triangle is a suitable test bed as a reflection of the similarly at-risk and densely-populated Eastern U.S. (GAO, 2014). Raleigh, the largest and fastest-growing city in the Triangle, is directly downstream from the City of Durham within the Neuse River Basin; these cities will act as the upstream (Durham) and downstream (Raleigh) parties to raw water transfers originating from Durham's Lake Michie water supply reservoir and moving downstream into Falls Lake, Raleigh's primary water supply source. Falls Lake, operated by USACE, maintains supply, water quality, and flood storage to the degree that only 42.3% of all inflows are allocated for water supply. This allocation ratio may be adjustable for raw water transfers, though this appears unlikely and is not directly addressed in this work. The Flat River, which transports water from Lake Michie to Falls Lake, routinely experiences streamflows between 100 and 1,000 cubic feet per second (380 - 3,800 MGW) with a mean weekly discharge of 919 MGW (USGS gage no. 02085500 at Bahama, NC). For this analysis, caps on weekly RWT volume were designated with sensitivity to the past observed record of regularly-occurring events along the Flat River so as to avoid flooding via RWTs. In addition, because RWTs generally occur during dry hydrologic conditions - when flows into Falls Lake are low – including additional streamflow through RWT is unlikely to cause flooding.

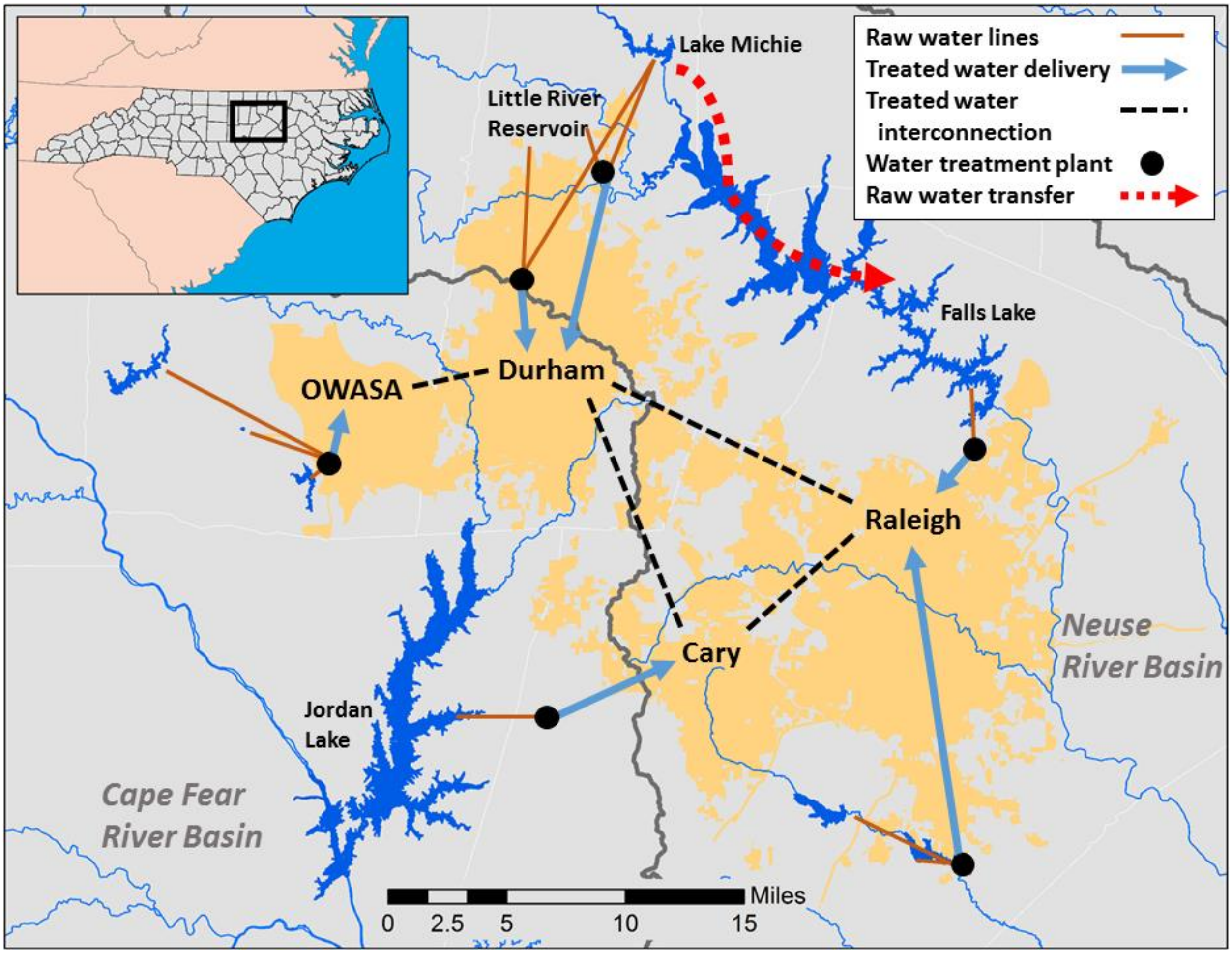

Figure 3: The Research Triangle region of North Carolina in the eastern United States. Existing treated water infrastructure and potential raw water transfer activities highlighted.

Both utilities currently use risk-of-failure to trigger short-term interventions – water use restrictions and treated water transfers from Jordan Lake in the Cape Fear River Basin – as well as long-term infrastructure projects. While Durham has the ability to return wastewater effluent to the Cape Fear River Basin in substantial quantities, Raleigh does not, meaning any treated water transferred to Raleigh from Jordan Lake is considered an inter-basin transfer.

Previous modeling of the Triangle system (Palmer and Characklis, 2009; Caldwell and Characklis, 2014; Zeff et al., 2016) has provided a validated foundation to support the testing of raw water transfer schemes. Designed using the C++ programming language, the overall

Triangle framework operates at several temporal scales (Figure 4). A model run, or simulation, is subject to a fixed set of decision parameters; these include risk-of-failure triggers for water transfers, use restrictions, and infrastructure as well as the raw water transfer allocation ratio and maximum weekly cap. Each simulation computes 1,000 realizations of the Triangle system from 2015 to 2060, evaluating utility decision-making and performance under unique, synthetic hydrologic "states-of-the-world" (Herman et al., 2013). Doing so allows a determination of the robustness of formulations and decision parameters across a wide range of potential future hydrologic and water demand scenarios (Kasprzyk et al., 2012; Reed et al., 2013). The synthetic hydrologic projections are based on inflows to Triangle reservoirs, generated through a re-creation of statistical moments and seasonal patterns in the historic record at several streamflow gages within the region using an auto-correlated bootstrapping technique (Kirsch et al., 2013). Projections of future demand growth are based on utility-provided estimations of annual growth and historical records of seasonal trends. Weekly demand is varied using a joint probability density function with observed inflow to develop a distribution of possible deviations from the weekly mean for each utility, which is then randomly sampled and the value is applied to adjust week-to-week demand.

As simulation results accrue in each week of each realization, they are stored for eventual calculation of objective values for the entire simulation. Risk-of-failure for use restrictions and water transfers is calculated weekly based on the current storage levels for each utility, while long-term infrastructure risk-of-failure is calculated annually and assumes reservoirs begin each year at capacity to capture the total drought resilience potential of existing systems. Action to expand infrastructure capacity or implement transfers and use restrictions is taken should risk-of-failure rise to specified decision trigger levels. For additional detail on risk-of-failure and streamflow and demand projections in the Triangle system, see Zeff et al. 2016.

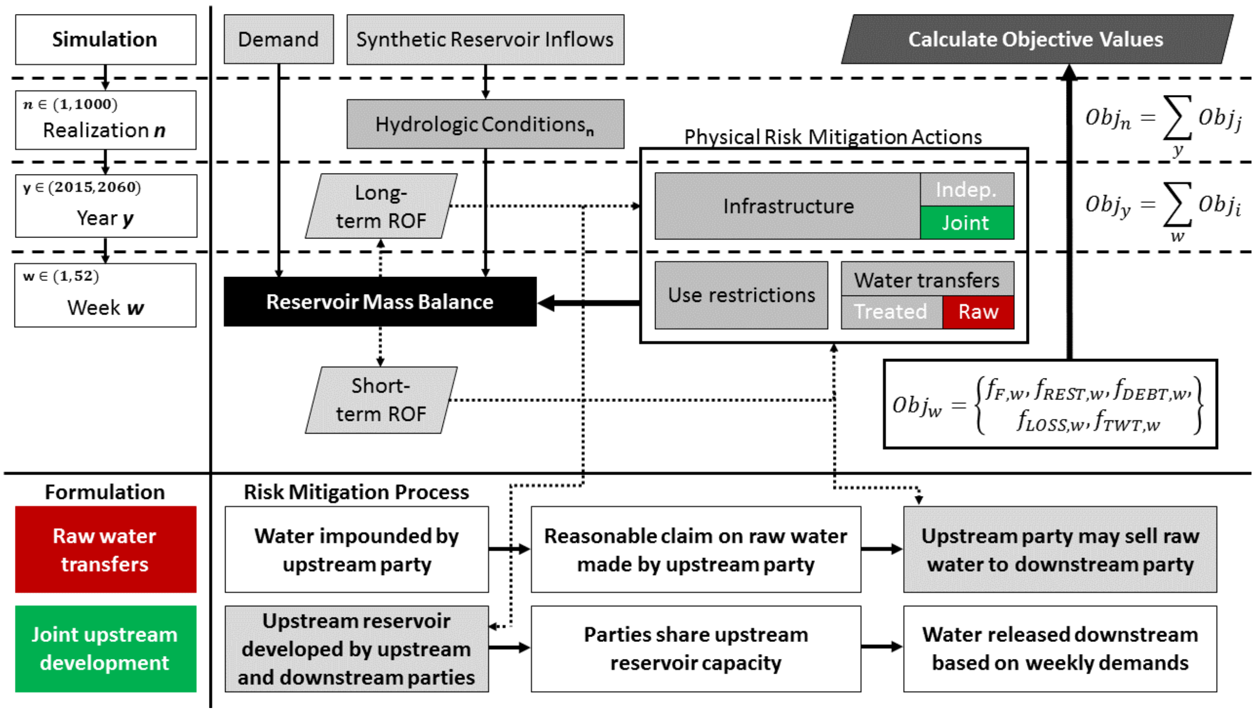

Figure 4: Triangle water supply model. Processes detailed based on temporal resolution (left of vertical solid line, separated by horizontal dashed lines) and formulation (colors, bottom rows). The business-as-usual simulation formulation involves all processes in grey, the raw water transfer formulation adds mitigation actions in red, and the joint upstream development formulation includes both red and green risk mitigation actions.

Joint, or cooperative, upstream development of infrastructure between the upstream and downstream parties to raw water transfers is controlled similarly to other infrastructure options. For all infrastructure available for future development (Table 1), long-term risk-of-failure must rise above a set trigger level for each utility before the infrastructure option is implemented – for cooperative development, infrastructure is triggered when any of the participating utilities' risk-of-failure is sufficiently high. Any chosen project will also not be constructed until after its permitting period, an amount of time during which it is assumed that a project has not been approved by all involved regulatory bodies, has ended; permitting period lengths were determined based on conversations with and reports by regional water utilities. Once a project is implemented, it takes 3-5 years to be completed at which point the storage or production of that project is added to the participating utilities' water supply budget. The cost of each option is spread over 25 years as debt service payment on bonds with 4% interest rates, parameters which are set based on consultation with Triangle water utility officials. For jointly-developed projects between two utilities, the fraction of project cost covered by a utility is exactly proportionate to that utility's stake in production or capacity of the infrastructure option.

Table 1: Infrastructure projects available for Triangle utilities across all modeled simulations.

Infrastructure option	**Utility**	**Cost ($MM)**	**Storage / Production**	**Permitting period end date**
Stone Quarry deep exp.	OWASA	64.6	2200 MG	2032
Lake Michie expansion (low)	Durham/Raleigh	158.3	2500 MG	2022
Lake Michie expansion (high)	Durham/Raleigh	203.3	7700 MG	2037
Little River Reservoir	Raleigh	263	3700 MG	2027
Falls Lake WQ Pool Reallocation	Raleigh	68.2	4100 MG	2017
Neuse River Intake	Raleigh	225.5	16 MGD	2017
Western Jordan WTP (initial)	Durham/OWASA	243.3	33 MGD	2022
Western Jordan WTP (expansion)	Durham/OWASA	73.5	54 MGD	2037

Raw water transfer schemes between Durham and Raleigh are evaluated through the comparison of three model formulations: (0) business-as-usual (BAU), where each utility acts independently of the others to manage its water supply; (1) BAU with raw water transfers (Figure 4, red), a formulation allowing Durham to sell impounded water downstream to Raleigh from week-to-week; (2) BAU with raw water transfers and joint upstream development (Figure 4, green), meaning Durham may sell portions of its own Lake Michie capacity to Raleigh and that the two utilities concurrently have the ability to partner and jointly expand the Lake Michie reservoir with Raleigh paying for and owning a share of the increased capacity. Each formulation will be tested over a number of model simulations, with every simulation having different values selected for decision parameters such as risk-of-failure trigger levels, the maximum raw water transfer allowed in a given week, and the downstream allocation ratio.

Consistent through all formulations will be the independent infrastructure projects available to each utility, based on regional reports on future water supply planning (Table 1; TJCOG, 2014) and past modeling of optimal infrastructure pathways for regional sustainability (Zeff et al., 2016). To emphasize the potential benefits of raw water transfers and joint upstream development within the Triangle system, the following infrastructure options are made available: OWASA may choose to expand the smallest of its three reservoirs (Stone Quarry), while Raleigh may implement up to three primary supply enhancement options (reallocation of the Falls Lake water quality pool for water supply storage, construction of an intake to draw water from the Neuse River, or creation of a reservoir along Little River) and Durham, not including potential joint upstream development in model formulation (2), can opt along with OWASA to access an allocation of Jordan Lake by financing a water treatment plant to divert and treat the water and distribution mains to transport it to the utility.

2.3 Impacts of raw water transfers

As with other short-term water management options, raw water releases may have unintended consequences to both upstream and downstream parties. Though water transfers can reduce long-term utility costs, they also subject purchasing utilities to financial risk through unpredictable, short-term cost spikes (Zeff and Characklis, 2013) and may leave the seller more vulnerable to drought. Consequently, water use restrictions, for example, may be implemented to hedge against low storage levels upstream by temporarily reducing water demands, typically by restricting outdoor water usage, in order to maintain supply reliability. Conversely, if a downstream party were to request raw water transfers, but was denied, it is likely to seek water from another source, perhaps outside its watershed (an inter-basin transfer), potentially raising legal and environmental opposition. And, if short-term mitigation options are limited, ineffective, or unavailable, a utility may be forced to expand its infrastructure in order to ensure reliable supply to cover infrequent and short-lived drought events, increasing their debt burden and likely raising water rates for customers. It is essential, therefore, to monitor the impact of raw water transfers across a number of objectives for both the upstream and downstream utilities. Assessment of raw water transfers based on their ability to satisfy objectives of

1. reliability f_F
2. use restriction frequency f_{REST}
3. peak infrastructure debt burden f_{DEBT}
4. risk of financial losses f_{LOSS}
5. inter-basin treated water transfer use f_{TWT}

will evaluate the merit of raw water transfers in physical, economic, and financial terms, as well as illuminate any trade-offs between objectives that may arise as a result.

Each of the above objective values will represent regional worst-case results; evaluation of results in this way captures the benefit of each model formulation without ignoring potential tradeoffs between individual actors. For example, from each of 1,000 realizations, reliability is calculated for each utility as the percentage of weeks in failure in the year of most weekly failures. The utility with the greatest average worst-year weekly failure rate, or lowest reliability, will represent the region as the objective value f_F for the entire simulation (3). Each objective is mathematically described below:

The reliability (failure rate) objective is determined for a simulation by maximizing the worst-case failure rate among realizations *r* and utilities *U* and across years *y*. F is either 0 or 1 depending on the existence of weekly storage failure in year *y* as described in (2). As with each objective, reliability is calculated separately for each utility *U* and the worst-performing utility represents the objective value (3).

$$\min f_F = \max_U \left[\sum_{r=1}^{n} \frac{\max_y (F_{r,U,y})}{n} \right] \tag{3}$$

Restriction use frequency is quantified as the average percentage of weeks under restriction by the worst-performing utility in the worst year of each realization of a simulation. *R* represents the percentage of weeks under restriction in year *y* for utility *U* in realization *r* (4). Water utilities are often under political and public pressure to avoid implementing restrictions, making reduced restriction frequency a priority.

$$\min f_{REST} = \max_U \left[\sum_{r=1}^{n} \frac{\max_y (R_{r,U,y})}{n} \right] \tag{4}$$

Utilities also consistently hold debt in order to maintain their system infrastructure, and the debt burden relative to expected revenues is an important indicator of the financial health of a water utility (Leurig, 2010). The worst-case debt for a utility is measured based on the ratio of annual debt service payments on bonds BP to the utility's expected annual volumetric revenue

AVR. The peak debt objective represents the average worst year debt ratio over all realizations (5). Bond payments are subject to the length of bond financing and interest rates for a utility.

$$\min f_{DEBT} = max_U \left[\sum_{r=1}^{n} \frac{max_y \left(\frac{BP_{r,U,y}}{AVR_{r,U,y}} \right)}{n} \right] \quad (5)$$

The potential for short-term supply shortfall mitigation strategies to destabilize utility revenues – use restrictions, for example, temporarily reduce revenues – means that minimizing transfers and use restrictions is crucial (Hughes and Leurig, 2013). To measure potential financial risk due to revenue losses, the financial losses objective represents the costs of short-term mitigation STM, as a fraction of annual volumetric revenue, not expected to be exceeded in 99% of years through a simulation (6). Though the financial loss objective calculates value-at-risk for each utility that results from implementing short-term mitigation actions, this study did not include any measures the utility might take to mitigate those financial losses (i.e. reserve funds, financial insurance).

$$\min f_{LOSS} = max_U [(STM_r : P\{STM_r > STM\} = 0.01)_U] \quad (6)$$

Short-term mitigation, for any realization include costs or revenue losses, in the worst realization year, due to use restrictions $RESTC$ and both raw $RWTC$ and treated $TWTC$ water transfers (7).

$$STM_{r,U} = \max_y \frac{\left(\max(RESTC_{r,U,y} + TWTC_{r,U,y} + RWTC_{r,U,y}, 0\right)}{AVR_{r,U,y}} \qquad (7)$$

For any utility purchasing on treated, inter-basin water transfers, there are both financial and political incentives to reduce reliance on this exchange. To quantify use of treated water transfers by the downstream party of raw water transfers, the treated water transfers objective represents average treated transfers TWT to the downstream utility in the worst year of each realization over a simulation (8).

$$\min f_{TWT} = \max_U \left[\sum_{r=1}^{n} \frac{\max_y\left(TWT_{r,U,y}\right)}{n}\right] \qquad (8)$$

CHAPTER 3: RESULTS

3.1 Objective performance across formulations

One-hundred and thirty-five model simulations across 3 formulations were run, each with a different set of parameter combinations (Table 2) and available infrastructure options. Figure 5A details the objective performance of each simulation to allow for visual comparison; each simulation is represented by a line across all five objectives with the ideal solution being a flat line across the bottom of the figure. Objective results for all 405 simulations are averaged by formulation in Table 3, Set A.

While patterns between formulations are difficult to visually discern in the entire objective set, trends in results are more apparent when downstream development by Raleigh is limited to one infrastructure option (Neuse River Intake) in Figure 5B (Table 3, Set B). These simulations are henceforth referred to as “low-development” simulations. In low-development simulations on average, formulations with temporary raw water transfers added, but no joint upstream development (Figure 5B, red), reduce the regional failure rate objective from 4.5% to 3.4%, cut use restriction frequency from 43% to 38% of weeks and marginally decrease downstream treated transfer use in the worst simulation year relative to the business-as-usual (BAU) formulation (Figure 5B, blue) while maintaining the peak debt burden objective. However, the financial loss objective, measuring the fraction of AVR at-risk in the worst 1% of simulation years, rises from 15.4% to 16.0% due to the introduction of payments by Raleigh to Durham for raw water transfers that places Raleigh in a situation of greater financial risk during years with many transfer requests. Objective improvements persisted for the joint upstream development formulation (Figure 5B, green); relative to BAU, JUD formulations with limited downstream development lowered failure rate from 4.5% to 1.7%, worst-year restriction frequency from 43% to 18% of weeks, and worst year downstream treated transfer use by 85%. Furthermore, peak debt burden decreased from 252% of AVR in the worst year to 238% AVR, while financial risk only rose by 0.2% of AVR. It should be noted that neither OWASA nor Cary utilities were drivers of the objective results, meaning objective values for either Durham or Raleigh – the two parties involved in raw water transfers – were reported as the worst regional result in all cases.

Table 2: Raw water transfer model parameters of relevance

Parameter	**Range of simulation values**
Risk-of-failure triggers	
Use restrictions	
All utilities	10%
Treated water transfers	
Raleigh	2 - 10%
Durham	2 - 10%
OWASA	2%
Raw water transfers	
Raleigh	4 - 10%
Durham	4 - 10%
Infrastructure	
All utilities	5%
Raw water transfer weekly cap	100 - 5,000 MGW
Raw water transfer downstream water supply allocation ratio	0.423 - 1.0
Cost of treated water transfers	$3,500/MG
Cost of raw water transfers	$3,500/MG
Fraction of Lake Michie expansion capacity for Durham water supply	0.1 - 1

Table 3: Comparison table for subsets of simulation objective results, averaged by formulation

Objective	Simulation Set (Figure 5 facet)	Formulation		
		BAU	RWT added	JUD added
Failure Rate (worst-year avg. % weeks)	All (A)	2.9%	2.9%	1.7%
	Low-development (B)	4.5%	3.4%	1.7%
	Low-dev. subset (D)	4.5%	3.0%	1.2%
Use Restrictions (worst-year avg. weeks)	All (A)	25%	24%	18%
	Low-development (B)	43%	38%	18%
	Low-dev. subset (D)	43%	39%	16%
Peak Debt Burden (worst-year % of AVR)	All (A)	191%	191%	238%
	Low-development (B)	252%	252%	238%
	Low-dev. subset (D)	252%	252%	231%
Financial Losses (99% VaR, % of AVR)	All (A)	15.4%	15.4%	15.4%
	Low-development (B)	15.4%	16.0%	15.6%
	Low-dev. subset (D)	15.4%	14.6%	15.2%
Downstream TWTs (worst-year avg. MGD)	All (A)	0.054	0.052	0.008
	Low-development (B)	0.054	0.052	0.008
	Low-dev. subset (D)	0.060	0.059	0.006

One indicator of particular importance to water utilities is their ability to maintain high levels of reliability. When considering only simulations from this study that experience failure in less than 1.5% of weeks in the worst average year, joint upstream development formulation simulations greatly outnumbered, 95 to 4, simulations of the business-as-usual formulation (Figure 5C). Though all joint upstream development formulations had greater average worst-year peak debt compared to business-as-usual formulations, due to cooperative Lake Michie expansion occurring early in the modeled time frame, these formulations also averaged nearly ten times fewer worst-year treated water transfers to Raleigh (Figure 5C, right column). The only business-as-usual formulations able to sustain this level of reliability developed at least two of the three available downstream infrastructure options at Raleigh's disposal, but many simulations of the joint upstream development formulation were able to meet this reliability level with only one downstream infrastructure option used. Overall low-development scenarios with joint upstream development can reasonably match the reliability, restriction use, and financial risk objective goals of a more developed future under business-as-usual practices.

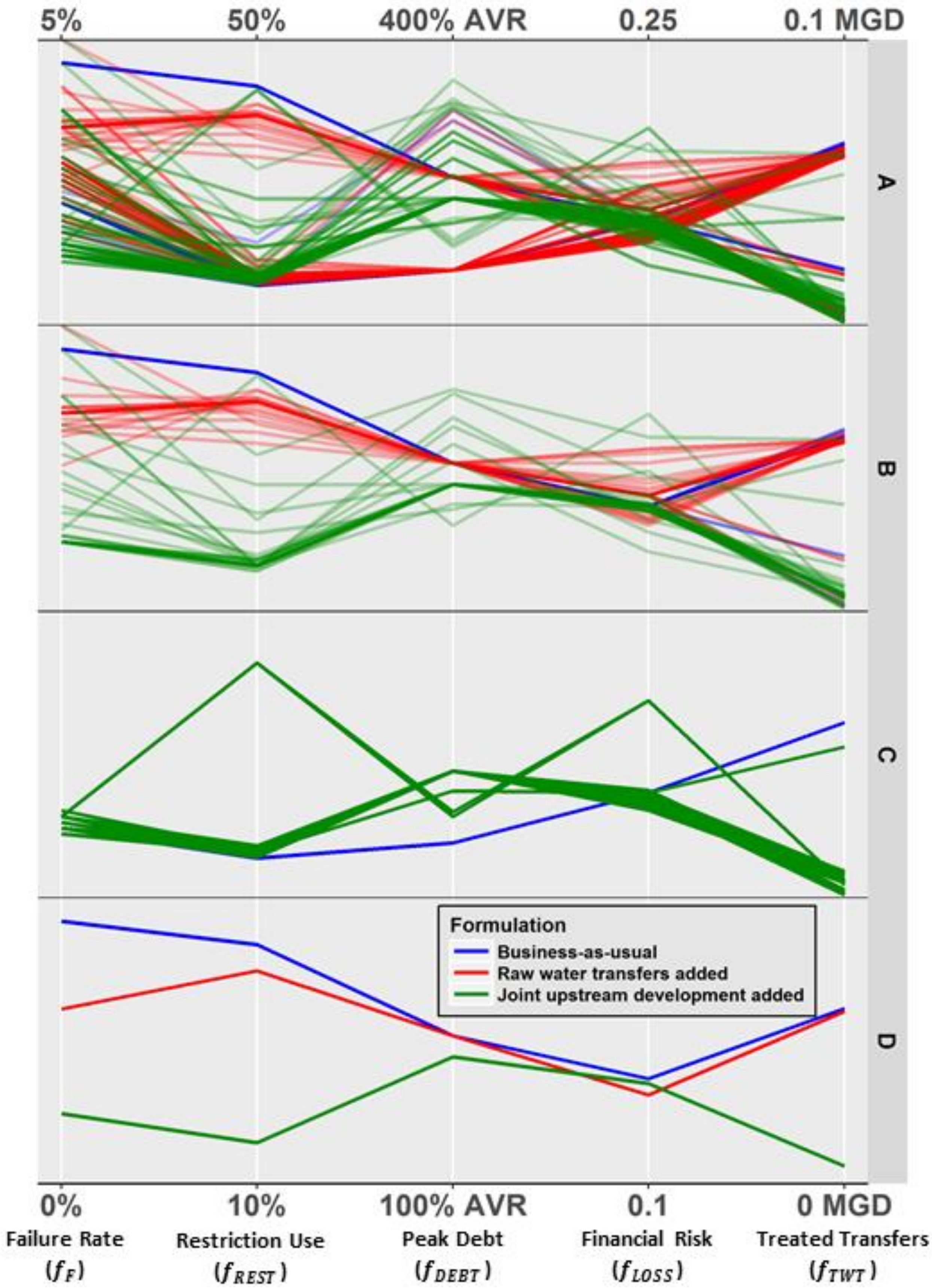
5%
50%
400% AVR
0.25
0.1 MGD
A
B
C
D
Formulation
Business-as-usual
Raw water transfers added
Joint upstream development added
0%
10%
100% AVR
0.1
0 MGD
Failure Rate
(f_F)
Restriction Use
(f_{REST})
Peak Debt
(f_{DEBT})
Financial Risk
(f_{LOSS})
Treated Transfers
(f_{TWT})

Figure 5: Parallel axis plots of objective performance across business-as-usual (blue), temporary raw water transfer (red) and joint upstream development (green) in sets of: (A) all computed simulations (B) low-development simulations only (C) all simulations with under 1.5% of worst realization years in failure (D) select low-development simulations. Objectives of failure rate (far left column), use restriction frequency (first column from left), peak annual infrastructure debt (middle column), financial risk (first from right), and treated water transfers to Raleigh (far right column) are determined from the worst-case year results over a model simulation. Ideal objective performance would be marked by a straight line across the bottom of the plot.

For further analysis, Figure 5B was distilled to three simulations representative of the distribution of low-development results in Figure 5D (Table 3, Set D). Each simulation in (D) has the same decision parameters and infrastructure options, the only difference being the formulation. Improvement across all objectives, by both the RWT and JUD formulations relative to BAU, demarcate the possible benefits of raw water transfer use. Though not all simulations tested had such clear trends between formulations, this subset of results displays the potential of raw water transfer schemes when implemented effectively; both RWT and JUD formulations objectively dominate the business-as-usual formulation. With regard to utility supply reliability, raw water transfer and joint infrastructure development formulations improve upon the business-as-usual formulation (Figure 5D, left column) by reducing failure rate from 4.5% to 3.0% and 1.2% respectively. Under business-as-usual conditions this high rate of failure would be unacceptable; however joint upstream development is able to reduce failures considerably across the worst model simulation year. meaning future scenarios with limited regional infrastructure development not possible under business-as-usual practices become feasible through raw water transfers and joint upstream development. Furthermore, the percent of weeks under restriction in the worst average simulation year fell from 43% in the BAU formulation to 16% with JUD, constituting an enormous improvement for the regional water utilities, who aim to provide reliable service without needing to implement restrictions often and upset their customers. In this low-development simulation subset, both peak debt and financial risk objectives were either maintained or improved by RWT and JUD formulations relative to BAU; regional worst-year peak debt is reduced by 21% of AVR by the JUD formulation relative to BAU, while both RWT and JUD formulations reduce financial risk from the 15.4% AVR levels of the BAU formulation.

3.2 Tradeoffs between upstream and downstream parties

When the objective results of Figure 5D are dis-aggregated to show realization results within each simulation, it is evident that notable tradeoffs exist across objective performance between upstream (Durham) and downstream (Raleigh) parties to raw water transfers (Figure 6). Comparison of model formulations using distributions of restriction frequency and treated water transfers for each utility in a simulation, representing the worst year in each of the 1,000 realizations, demonstrated shifts across objectives. The upstream party to raw water transfers saw increases in restriction frequency and treated water transfer volume relative to the business-as-usual, no raw water transfer formulation, while the downstream party saw a decrease in use restriction frequency (Figure 6, differences between red and blue distributions). This is directly attributable to the exchange of raw water from Durham to Raleigh; raw water transfers reduce storage capacity in upstream reservoirs, more use restrictions are put in place and more treated water transfers are requested in response to this increased risk-of-failure. The downstream effects are opposite, where lower risk-of-failure levels as a result of increased reservoir inflows from raw water transfers mean fewer use restrictions are enacted. Though raw water transfer and joint upstream development formulations clearly shift risk from the downstream to the upstream party, regional objective performance improves (Figure 5D) relative to business-as-usual. This indicates that, though Durham is taking on risk by releasing water to Raleigh and sharing upstream reservoir capacity, Durham (the upstream party) does not suffer objectively while providing downstream objective improvement due to more efficient use of available resources.

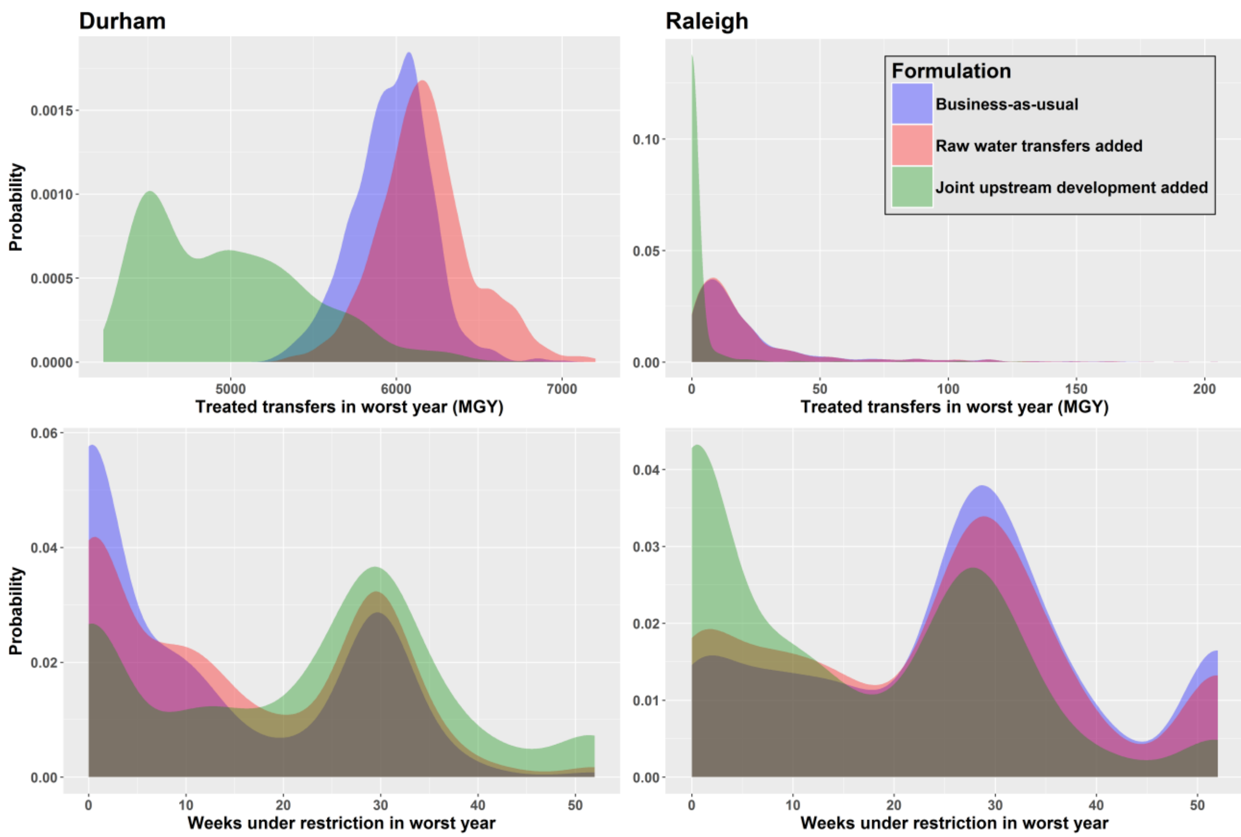

Figure 6: Comparison of model formulations through distributions of treated transfer volume (top) and use restriction frequency (bottom) in the worst year of each of 1,000 realizations within a single simulation for the upstream (Durham, left) and downstream (Raleigh, right) parties to raw water transfers. Raw water transfer formulation results (red) show increased treated water transfers to and use restrictions by Durham but fewer use restrictions for Raleigh relative to business-as-usual (blue). Formulations also including joint upstream Lake Michie development (green) demonstrate increases in Durham and decreases in Raleigh use restriction frequency relative to business-as-usual and temporary raw water transfer formulations. Joint upstream development resulted in decreased treated water transfer use for both utilities relative to other formulations. Distributions of treated water transfers to Raleigh under business-as-usual and raw water transfer formulations were nearly identical, hence the appearance of a single, discolored distribution.

The ability for Durham and Raleigh to jointly develop additional upstream reservoir capacity through expansion of Lake Michie (JUD formulation) illuminated further tradeoffs between utilities. Changes in Figure 6 between joint development (green) and alternative formulations show that upstream use restriction frequency in the worst year was greatest with joint upstream development relative to either business-as-usual or temporary raw water transfer formulations, while the opposite was true for downstream restriction frequency. While this is logical for downstream Raleigh – more storage capacity means lower risk-of-failure – Durham sees increasing restriction use even with added reservoir capacity. This has two causes: differences in Durham's necessity in the joint development formulation to expand Lake Michie should Raleigh come under risk-of-failure as well (in the business-as-usual formulation, Durham does not cooperate with Raleigh), and Durham's capacity stake in Lake Michie expansion. These results show Lake Michie, able to expand to either a low or high level, being expanded to a small extent before 2025 when joint development is allowed. This means that Durham's preferred independent expansion option, accessing an allocation of Jordan Lake, is pushed into the future relative to the business-as-usual scenario. This change in development is further strained depending on the size of Durham's stake in the capacity of an expanded Lake Michie. For these results, Durham purchases only 30% of Lake Michie expansion capacity. The combined push to expand Lake Michie by Raleigh, driven by Raleigh's large future demands, with Durham waiting longer to tap a larger, independent supply means Durham must enact more use restrictions to deal with worst-case hydrologic conditions.

3.3 Implications for inter-basin transfer

Joint upstream development of Lake Michie, however, drastically reduces treated transfer needs for both Durham and Raleigh relative to business-as-usual and temporary raw water transfer formulations (Figure 6, top). Durham does not need to rely as heavily on treated transfers from Jordan Lake with additional firm capacity in Lake Michie, and similarly Raleigh avoids the need to purchase emergency treated water transfers from Jordan Lake (diverted and treated by Cary before being piped through existing interconnections) in worst cases. Joint upstream development showed the ability to reduce treated water transfers to Raleigh by at least 85% on average relative to BAU, and by 90% in the low-development simulation subset (Figure 5D).

The resultant impact of this intra-basin cooperation is that Raleigh has reduced its need for inter-basin treated water transfers to mitigate dangerously low storage levels. In North Carolina, a municipality must apply for the right to transfer water between watersheds if the transfer exceeds a one-time limit of 3 MGD or 2 MGD on average. To assess the ability of raw water transfers and joint upstream development to remove the need for inter-basin transfers to Raleigh, the week of most transfers to Raleigh in every realization was identified for the low-development subset simulations (Table 3, Set D; Figure 5D). Relative to business-as-usual, temporary raw water transfers alone do not reduce inter-basin treated transfers to Raleigh enough to fall under the legal threshold (Figure 7). Of the 1,000 realizations in each simulation, 16% (157 realizations) of the BAU and 15% (148) of the RWT formulations experienced a week in which greater than 21 MG of inter-basin transfers were purchased. This is largely due to correlated hydrologic conditions between Raleigh and Durham, meaning that many times Durham does not have enough water to allow raw water transfers in the weeks when Raleigh storage is low. However, joint upstream development of Lake Michie, allowing Raleigh to develop additional capacity, results in enough supply during drought scenarios for Raleigh to almost completely avoid the need to purchase inter-basin transfers in almost all future states of the world (Figure 7, green), with only 1% (13) of 1,000 realizations violating the 21 MG worst-week inter-basin transfer threshold.

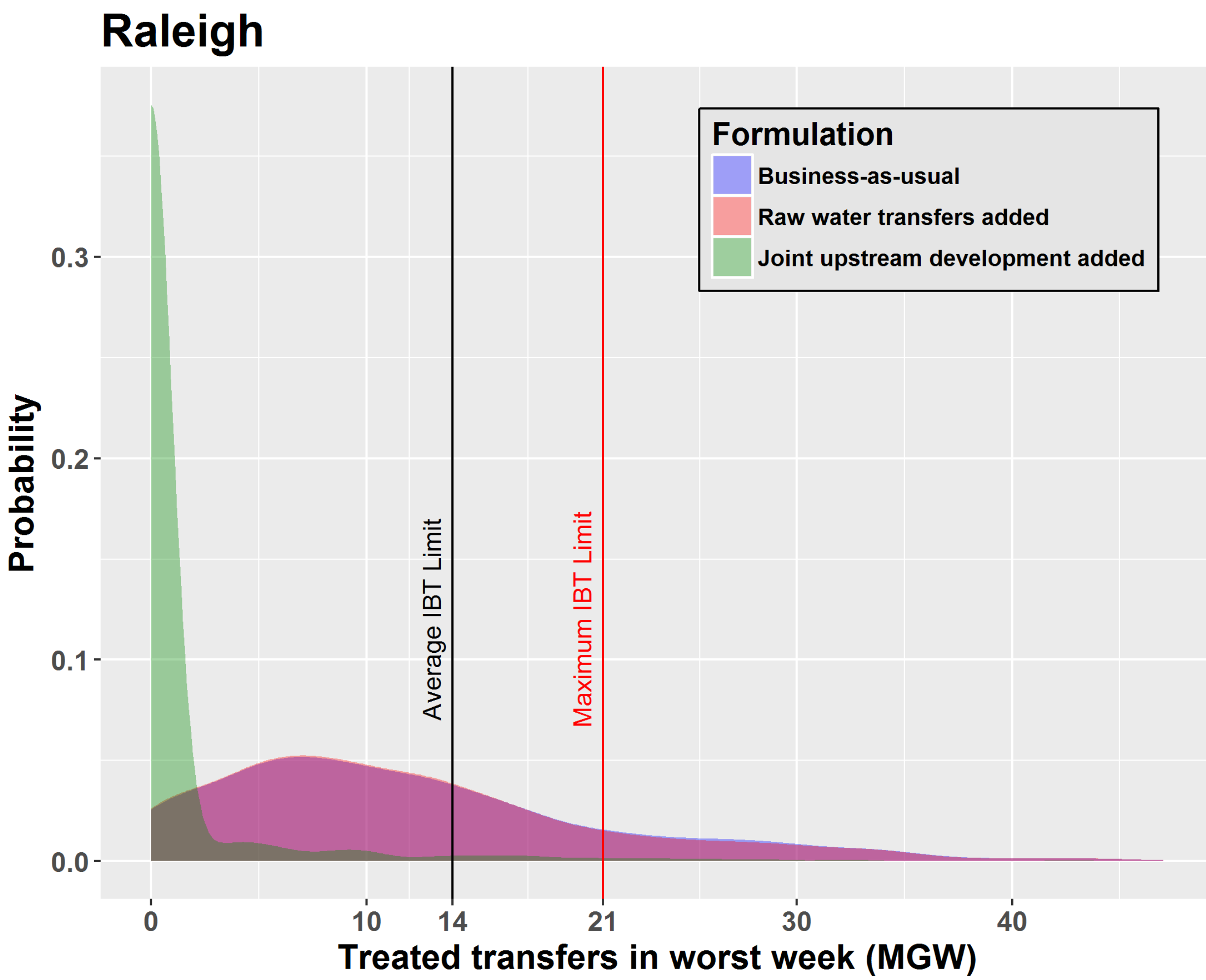

Figure 7: Comparison of model formulations treated inter-basin transfer in the worst week of each of 1,000 realizations within a single simulation for the downstream (Raleigh) party to raw water transfers. NC municipalities are required to receive governmental approval for inter-basin transfers of over 3 MGD (red line) or 2 MGD (black line) on average. Joint upstream development of Lake Michie essentially absolves Raleigh of the need for inter-basin transfers above the legal threshold. Distributions of treated water transfers to Raleigh under business-as-usual and raw water transfer formulations were nearly identical, hence the appearance of a single, discolored distribution.

CHAPTER 4: DISCUSSION

The potential for raw water transfer schemes to improve the flexibility of eastern U.S. water management flexibility is not solely limited to the NC Research Triangle. Though this type of raw water exchange, to the authors' knowledge, has not been extensively used outside of the Western U.S., we find evidence that it can be applied within existing Eastern institutions, largely because many state laws regarding water use are old and purposefully vague. So long as upstream impoundments do not reduce downstream river flows so as to deprive riparian users of their right to the resource – something that would not occur as a result of increased flows from raw water transfers – the financial and reliability benefits afforded by raw water transfers, creating an additional supply augmentation strategy while reducing regional infrastructure use, appear to demonstrate considerable potential.

Should raw water transfers schemes be put in place, clearly it will be imperative to also understand the objectives and tradeoffs for each party within a region, as well as the full impact of any considerations that would factor into an agreement between upstream and downstream utilities. For instance, this analysis was able to identify several factors surrounding raw water transfers that substantially altered their effectiveness, including the maximum allowable quantity of water transferred per week, the fraction of transferred water allocated for downstream water supply, and the relative capacity shares of each utility in cooperative upstream development. The authors cannot foresee any raw water transfer agreement in which these three aforementioned factors are not negotiated; to identify each crucial tradeoff between agreement parameters and their implications would require a comprehensive sensitivity analysis. Furthermore, it should be noted that this analysis was not an optimization of decision variables surrounding raw water transfers, and the results portrayed demonstrate the potential of raw water transfers and joint upstream development to improve regional objectives, but do not fully characterize the Triangle system. Future efforts will couple large-scale optimization of raw water transfer decision-making with sensitivity analysis of relevant parameters to confidently scope the potential for raw water transfers and joint development to positively influence water management.

A major finding of this work is the potential of raw water transfers to remove the need for inter-basin transfers to downstream communities. Inter-basin transfers, in the Triangle (Gargan, 2017) and elsewhere (Abrams, 1982), often carry significant legal, environmental, and financial burdens that act as strong disincentives for building new infrastructure. Relying upon inter-basin transfers for water supply can be the path of greatest resistance for water utilities. A primary motivation for this work, therefore, was to identify opportunities for more efficient within-basin resource management to avoid inter-basin transfer dependence. To that point, raw water transfers appear to provide a reasonable alternative.

CHAPTER 5: CONCLUSIONS

The ability to combine raw water transfer schemes with existing water management policy in the eastern U.S. may be valuable for regions with rising populations seeking to meet water demands. Reduced reliance upon traditional, structural solutions to limit water supply shortfalls through more flexible use of existing capacity and regional cooperation will be important in the face of uncertain demand and hydrologic futures. The introduction of raw water reallocation schemes, free from the physical and financial constraints of treating and piping water, would allow urban centers of the eastern U.S. meet future demands and avoid or delay expensive structural alternatives without necessitating difficult institutional change. This work proposed and evaluated several variations of inter-utility raw water transfer scheme, involving transfers along a common river course, using a regional, multi-utility framework. Application within the Research Triangle of North Carolina demonstrated that, relative to business-as-usual management strategies, raw water transfers and joint upstream development are in some cases able to improve reliability by reducing the rate of supply failure from 4.5% to under 2%, avoiding months of water use restrictions in drought years, cutting inter-basin treated water transfers by nearly 90%, maintaining or slightly lowering financial risk, and significantly decreasing peak and long-term debt burden through decreased dependence on infrastructure and increased flexibility in planning options. It can be inferred from these observations that raw water transfers have the potential to diversify and improve water supply management strategies, and can be generalized to other parts of the Eastern United States within existing state water law.

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