Impact of inter-utility agreements on cooperative regional water infrastructure investment and management pathways

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November 24, 2022

Abstract

Urban water utilities, facing rising demands and limited supply expansion options, increasingly partner with neighboring utilities to develop and operate shared infrastructure. Inter-utility agreements can reduce costs via economies of scale and help limit environmental impacts, as substitutes for independent investments in large capital projects. However, unexpected shifts in demand growth or water availability, deviating from projections underpinning cooperative agreements, can introduce both supply and financial risk to utility partners. Risks may also be compounded by asymmetric growth in demand across partners or inflexibility of the agreement structure itself to adapt to changing conditions of supply and demand. This work explores the viability of both fixed and adjustable capacity inter-utility cooperative agreements to mitigate regional water supply and financial risk for utilities that vary in size, growth expectations, and independent infrastructure expansion options. Agreements formalized for a shared regional water treatment plant with fixed or adjustable treatment capacities, coupled with structured financing for partner utilities, are found to significantly improve regional supply reliability and financial outcomes. Regional improvements in performance, however, mask tradeoffs among individual agreement partners. Adjustable treatment capacity allocations add flexibility to inter-utility agreements but can compound the financial risk of each utility as a function of the decision-making of the other partners. Often the sensitivity to partners' decision-making under an adjustable agreement degrades financial performance, relative to agreements with fixed capacities allocated to each partner. Our results demonstrate the significant benefits cooperative agreements offer, providing a template to aid decision-makers in development of water supply partnerships.

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Key Points:

1. Inter-utility agreements are useful tools to help neighboring water utilities cooperate to reduce supply risks and infrastructure costs
2. Agreements improve regional supply and financial performance vs. pathways of independent action, but introduce tradeoffs among partners
3. Agreements with adjustable financing most expose partners to decision-making by other utilities, increasing financial risks

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0 Abstract:

Urban water utilities, facing rising demands and limited supply expansion options, increasingly partner with neighboring utilities to develop and operate shared infrastructure. Inter-utility agreements can reduce costs via economies of scale and help limit environmental impacts, as substitutes for independent investments in large capital projects. However, unexpected shifts in demand growth or water availability, deviating from projections underpinning cooperative agreements, can introduce both supply and financial risk to utility partners. Risks may also be compounded by asymmetric growth in demand across partners or inflexibility of the agreement structure itself to adapt to changing conditions of supply and demand. This work explores the viability of both fixed and adjustable capacity inter-utility cooperative agreements to mitigate regional water supply and financial risk for utilities that vary in size, growth expectations, and independent infrastructure expansion options. Agreements formalized for a shared regional water treatment plant with fixed or adjustable treatment capacities, coupled with structured financing for partner utilities, are found to significantly improve regional supply reliability and financial outcomes. Regional improvements in performance, however, mask tradeoffs among individual agreement partners. Adjustable treatment capacity allocations add flexibility to inter-utility agreements but can compound the financial risk of each utility as a function of the decision-making of the other partners. Often the sensitivity to partners' decision-making under an adjustable agreement degrades financial performance, relative to agreements with fixed capacities allocated to each partner. Our results demonstrate the significant benefits cooperative agreements offer, providing a template to aid decision-makers in development of water supply partnerships.

Keywords: water utility; cooperation; demand; deep uncertainty; optimization; financial risk

1 Introduction

Water utilities anticipate a range of risks to future water supply reliability and the provision of affordable services (AWWA, 2018). Hydrologic changes, resulting from climate and land use-landcover (LULC) changes, will likely lead to increasing uncertainty in the quantity and timing of surface and groundwater availability in many regions world-wide (IPCC, 2014; USGCRP, 2018; World Bank, 2016; WUCA, 2016). Water demand growth is also expected to be a significant driver of future water scarcity (AghaKouchak et al., 2015, 2021). Spending on maintenance of aging water and wastewater infrastructure is also increasing (CBO, 2015, 2018), further straining the budgets of utilities trying to ensure reliable water supply while keeping customer rates affordable.

Increasingly, utilities are turning to 'portfolio' strategies that couple supply expansion with water use restrictions, and, increasingly, water transfers to address water supply risks (Brown et al., 2015; Loucks & van Beek, 2017; Lund, 2015). These techniques can be effective, but face challenges; as one example, supply-side capacity expansion has traditionally been the favored option for meeting long-term demand growth (AWWA, 2011; Gleick, 2003), however the rate of new dam and reservoir construction has declined in recent decades as the number cost-effective sites has dwindled and regulatory approval has become more onerous (Perry & Praskievicz, 2017). Short-term, drought mitigation measures such as water use restrictions (demand-side action) enjoy widespread use (Kenney et al., 2004; Milman & Polsky, 2016), but frequent implementation can be unpopular with customers and restrictions may not meet their desired reduction targets (Olmstead & Stavins, 2009). Similarly, water transfers have shown promise as a short-term tool to alleviate scarcity (Gupta & van der Zaag, 2008; Lund & Israel, 1995; NRC, 1992), but typically involve additional costs, sometimes in the form of expanded conveyance infrastructure, which can discourage their implementation (Characklis et al., 2006; Israel & Lund, 1995). Water transfers may also occur intermittently and at varying magnitude, adding complexity.

Water transfer purchases and water use restrictions are often motivated by drought and are thus implemented at unexpected intervals such that the cost increases and revenue reductions, respectively, can also carry unexpected financial risk (Barr & Ash, 2015; Baum & Characklis, 2020; Lund, 1993; Tiger et al., 2014). Mismatch between a utility's primarily fixed costs – debt service owed on infrastructure and fixed operating expenditures – and volumetric water sales can destabilize utility cashflow, potentially leading to budget shortfalls. Even if this does not occur, any elevated risk of non-performance with respect to debt payments can result in lower credit ratings and a higher cost-of-capital, a particular concern in the capital-intensive water utility sector, culminating in higher rates for customers (Hughes et al., 2014; Hughes & Leurig, 2013; Raftelis, 2005).

As an alternative, water utilities are more frequently considering inter-utility agreements, leveraging proximity and surplus capacity with neighboring utilities to provide additional operational and planning flexibility (EFC, 2009; Kurki et al., 2016; Reedy & Mumm, 2012; Silvestre et al., 2018; Sjöstrand et al., 2018, 2019; Tran et al., 2019). Inter-utility agreements can take a variety of forms that offer a range of benefits (EPA Office of Water, 2017): economies of scale in development and operation of regional water supply infrastructure (Apex et al., 2015); emergency or intermittent access to additional water supply (OWASA & Durham, 2009); and consistent sources of revenue from leasing of excess water supply or treatment capacity (Commissioners, 2013; Reedy & Mumm, 2012). However, despite widespread use, and long-standing institutional structures allowing inter-local agreements to facilitate cooperation in US states (e.g. NC General Statutes, 1971), quantitative assessment of their ability to mitigate both supply and financial risk is limited. In addition, differences in the legal definition of an inter-local agreement across U.S. states, as well as internationally, hamper the ability of past research to offer generalizable takeaways regarding agreement performance.

Several studies have reviewed the breadth and efficacy of regional agreements in practice (Silvestre et al., 2018; Tran et al., 2019), often via survey or data collection from utilities or resource managers engaged in existing partnerships (Bendz & Boholm, 2019; Kurki et al., 2016). A handful of studies have attempted to quantify economic costs and benefits (Arena et al., 2014; Sjöstrand et al., 2018, 2019) or financial outcomes (Gorelick et al., 2019) of agreements through scenario modeling of regional case studies, but are limited in the sources of uncertainty addressed and do not consider dynamic adaptive response by utility managers to mitigate time-evolving risks (i.e., droughts). Other studies of regional utility-scale decision-making under broad hydrologic and operational uncertainties include dynamic risk management by system actors (Gold et al., 2019; Mortazavi-Naeini et al., 2014; Tian et al., 2018; Trindade et al., 2019);

however, inter-utility agreement structures have not been the primary focus of these studies, and alternative agreement structures were not considered. Important questions therefore remain regarding the structure of inter-utility agreements, particularly as relates to their performance under uncertainty.

While inter-utility cooperation has advantages over independent utility financing and operation, agreements may also bring about unintended consequences (Bendz & Boholm, 2019; Feiock, 2013). Cooperative control of water supply systems can expose agreement partners to the risks of other partners (their counterparties) with whom they collaborate and share financial and operational ties (Hansen et al., 2020). The risk of supply failure may increase if partnerships involve consolidation of supply or treatment capacity to a single facility (Sjöstrand et al., 2018). The structure of an agreement involving commitment to fixed or variable capacity or joint financing may also limit its effectiveness if external conditions (e.g., demand growth) diverge from projections (Gorelick et al., 2019). In addition, costs and benefits of a regional partnership may not be shared equitably between individual partners (Dinar et al., 1992; Dinar & Howitt, 1997; Parrachino et al., 2006); collective action that requires compromise between utilities may be short-lived if an agreement becomes impractical for one or more participants as conditions change, even if it results in a better aggregate outcome at the regional scale (Madani & Dinar, 2012; Read et al., 2014).

Broadly, there are a number of ways in which counterparty risk may evolve under hydrologic and demand growth uncertainty. Many studies have considered the influence of endogenous (e.g., utility decision-making) and exogenous (e.g., population growth) factors may have on individual or regional utility performance (Borgomeo et al., 2018; Gold et al., 2019; Herman et al., 2015). However, little attention has been given to how increasing institutional connectivity via cooperative agreements may degrade utility (or regional) outcomes by partially exposing an individual utility to a partner's risks. Furthermore, despite recognition of demand growth as an important factor in water utility performance outcomes (Donkor et al., 2014; Herman et al., 2014; Trindade et al., 2019), projections of future growth in practice are often reduced to simplistic, linear trends (TJCOG, 2014; Walker, 2013) that exclude potential year-to-year uncertainty in growth rate. Quantifying the success of inter-utility agreement structures will require not only consideration of the flexibility of the agreement, but also contextual factors such as agreement partners, alternative supply projects, hydrologic and demand growth conditions.

This research explores the factors contributing to the benefits as well as the financial risks in inter-utility agreements through modeling cooperative regional infrastructure investment and water portfolio management that impacts six adjacent water utilities in the North Carolina Research Triangle (Triangle). Two inter-utility agreement structures are tested across a range of demand futures to assess their robustness under demand growth uncertainty. Through a comparison of supply and financial performance across agreement structures, at both a regional and individual utility scales, results respond to the questions: (1) how do differences in inter-utility agreement structure impact supply and financial risk across multiple utilities, and (2) to what degree do demand growth uncertainty and counterparty risk influence the viability of regional cooperation?

2 Methods

This work assesses the impact of different inter-utility agreement formulations on regional and individual utility performance in the Triangle through multi-utility regional modeling of decision-making, evaluating both water supply and financial outcomes under uncertainty. Multi-objective optimization is included in the modeling framework to understand the optimal tradeoffs for each agreement structure.

2.1 Region of Focus

The Triangle is a rapidly growing region with a recent history of drought that has raised concerns about water supply reliability. Home to more than two million residents, the Triangle historically refers to the three major cities of the region, Raleigh, Durham, and Chapel Hill. Growth patterns in the larger Triangle area have also spread to nearby towns of Cary, Pittsboro, and regions of Chatham County. This study broadens beyond prior published studies of the Triangle by integrating water utilities from all six areas – Town of Cary Water Resources Department, Chatham County Public Utilities, City of Durham Department of Water Management, Orange Water and Sewer Authority (OWASA; Chapel Hill), Town of Pittsboro Public Utilities, and Raleigh Water (Figure 1) – into our regional modeling framework.

Water demands in the Triangle are expected to grow considerably in the future (Table 1), however demand growth is anticipated to be asymmetric geographically. Utilities for larger population centers Raleigh, Durham, Cary, and OWASA do not expect rapid growth, while Pittsboro plans for demand increases of nearly an order of magnitude by 2060 (relative to 2015). Chatham County has three water service areas, however the County projects the vast majority of population and water demand growth to occur in its North System (Hazen and Sawyer, 2020). As a result, Chatham County North is the only water service area included in regional planning and therefore the only County system considered in this analysis.

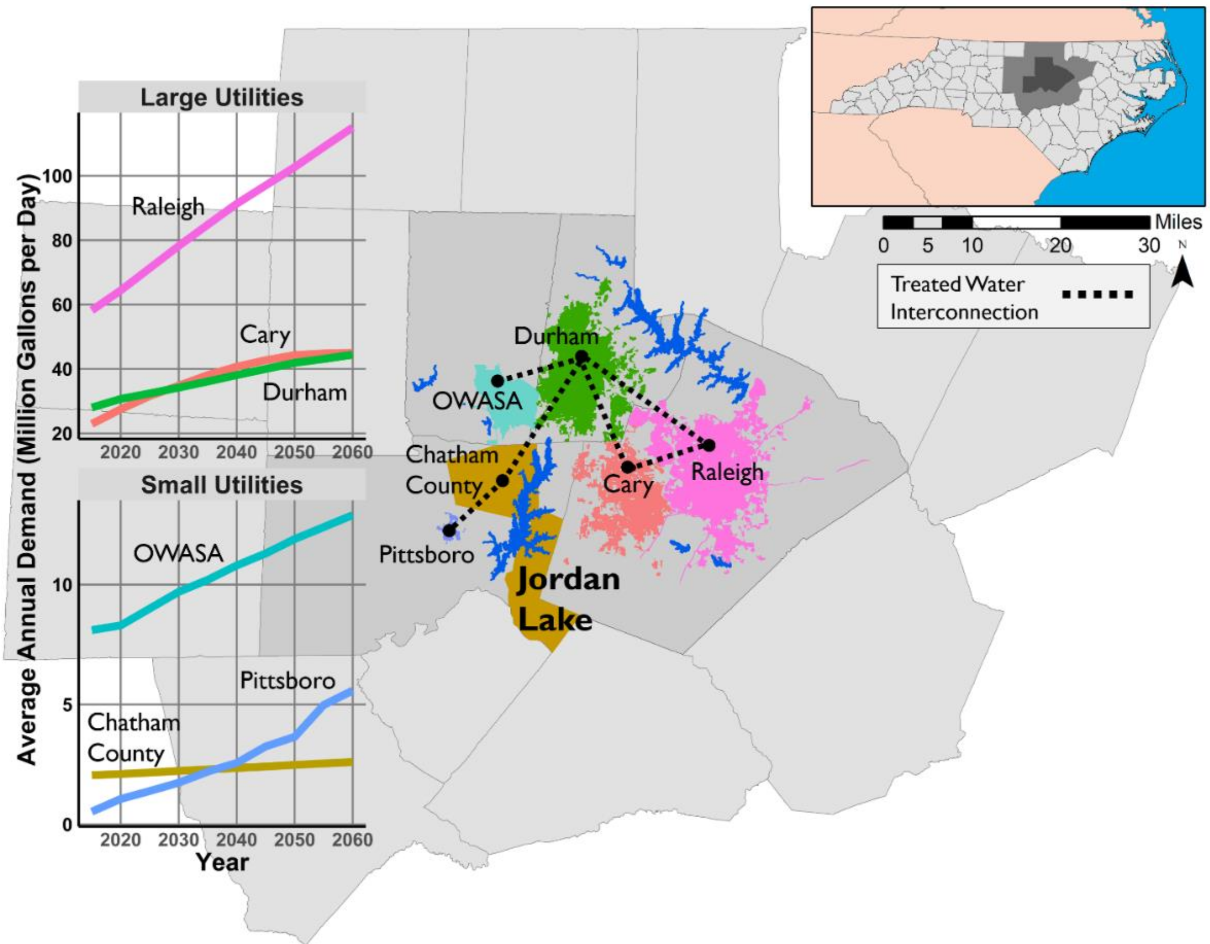

Figure 1: Six population centers (colors) of this study in the Research Triangle of North Carolina. Water demands (in annual average millions of gallons per day) are given from 2015 to 2060 on inset plots based on utility projections (TJCOG, 2014; Hazen and Sawyer, 2020).

Table 1: Projected Research Triangle water demands in millions of gallons per day (MGD).

Triangle Utility	**2020**	**2040**	**2060**
Cary**	27.5	40.7	45.0
Chatham County (North System)*	2.1	2.4	2.6
Durham	30.7	38.1	44.4
OWASA	8.3	10.8	12.9
Pittsboro*	1.1	2.6	5.6
Raleigh	64.4	91.3	115.0
Total (avg MGD)	134.1	185.9	225.5

* Pittsboro and Chatham County demands from 2019 projections by Hazen and Sawyer (2020)

** Represents sum demands of Towns of Cary, Apex, and Morrisville

Given demand growth projections, the Triangle utilities plan to expand water supply infrastructure (Table 2). A range of potential projects are under consideration by each utility or group of utilities to secure reliable water supply, differing in size (supply or treatment capacity), capital cost, earliest year construction may begin (represented here as the required permitting period for a project before it may be constructed), and whether the project is cooperative across multiple utilities.

Regional interconnections between utility water distribution systems also allow utilities to transfer quantities of treated water upon request. Durham, OWASA, and Raleigh can purchase treated water transfers from Cary's water treatment plant (WTP) that are then piped via interconnection to the purchasing utility. Durham can also sell water to Chatham County via transfer through a shared interconnection, as can Pittsboro through a separate interconnection. Transfers via these interconnections have been used in the past as alternative sources during times of high demand and/or low supply (OWASA & Durham, 2009); other interconnections in the Triangle are used to regularly supply water that meets a utility's demands. Triangle utilities also employ conservation to manage water demand, implementing both voluntary and mandatory water restrictions if necessary to reduce water use. Each Triangle utility maintains one or more reserve (contingency) funds to mitigate financial disruptions, such as cost and revenue fluctuations from restriction or water transfer use.

Table 2: Available infrastructure expansion options for Triangle utilities. Based on regional planning documents and consulting reports (TJCOG, 2014).

Project	Utility	Capacity (MG or MGD)	Capital Cost ($USD millions)	Earliest Availability (year)
Cary-Apex WTP Upgrades*	Cary	8.0, 16.0	121.5†, 243.0†	2015
Cape Fear River Intake in Harnett County	Cary	12.2	221.4	2032
Allocated Treatment Capacity in Sanford, NC WTP^	Cary / Sanford[a]	10.0	56.0	2015
Allocated Treatment Capacity in Sanford, NC WTP*^	Chatham County / Pittsboro / Sanford[a]	1.0, 2.0 / 3.0, 9.0	7.9, 11.2 / 49.6, 69.3	2022, 2028
Western Jordan Lake Regional WTP*^	Chatham County / Durham / OWASA / Pittsboro	33.0, 54.0	243.3, 316.8	2020, 2022
Reuse of Reclaimed Water*	Durham	2.2, 11.3	27.5, 104.4	2022
Teer Quarry	Durham	1315.0	22.6	2022
Lake Michie Reservoir Expansion*	Durham	2500.0, 7700.0	158.3, 203.3	2032
Cane Creek Reservoir Expansion	OWASA	3000.0	127.0	2032
Stone Quarry Expansion*	OWASA	1500.0, 2200.0	1.4, 64.6	2037
University Lake Expansion	OWASA	2550	107	2032
Haw River Intake and WTP Expansion*	Pittsboro	2.0, 4.0	18.6, 27.9	2017, 2020
Falls Lake Reallocation	Raleigh	5637	142	2022
Little River Reservoir	Raleigh	3700	263	2032
Neuse River Intake	Raleigh	16	225.5	2032
Richland Creek Quarry	Raleigh	4000	400	2055

* project that may be implemented in multiple stages, stage capacity and costs are cumulative
^ cooperative project between utilities
[a] utility not included in modeling
† costs not included in modeling (project occurs immediately after start of modeling period but is not ROF-triggered)

2.2 Problem Formulation

2.2.1 Regional Water Supply Simulation Model

To simulate water supply system planning and management through 2060 by Triangle utilities, this study develops a utility-scale computational model of the regional system using the WaterPaths stochastic simulation software. WaterPaths was developed specifically to enable computationally-efficient representation of multi-actor water systems under deep uncertainty (Trindade et al., 2020). WaterPaths offers computational flexibility to simulate the broad suite of decision-making options available for water utilities to adapt to evolving risks. The simulation framework is able to efficiently scale with high numbers of regional actors (utilities), incorporate a wide range of uncertainties (i.e. of hydrology, demand, and additional deeply uncertain factors), and facilitate simulation as well as optimization of water supply infrastructure planning policies. This study contributes an extension of a prior WaterPaths Triangle system implementation, expanding from four to six regional utilities (Gorelick et al., 2020) and exploring a wider range of uncertainties (detailed below).

2.2.2 Risk-of-Failure (ROF) Based Adaptive Management

Within WaterPaths, utility decisions to develop infrastructure, request water transfers, and implement use restrictions are made via state-aware rules, resulting in adaptive 'pathways' of action by utilities taken in response to changing risks. Decisions are triggered based on risk-of-failure ($ROF_{U,t}$), the dynamically-updating probability of supply storage falling below 20% of capacity or demands exceeding 90% of treatment capacity for a utility U at time t over the following (a) year for short-term ROF or (b) 1.5 years for long-term ROF (Zeff et al., 2016).

When short-term ROF rises above a trigger threshold $ROFT_{U,action}$, actions to implement use restrictions or purchase water transfers are taken to reduce water supply and/or treatment capacity risk. Long-term ROF is used to trigger infrastructure development of any project $IP_U \in \overrightarrow{IP}$, where $\overrightarrow{IP}$ is the set of all potential projects (Table 2 in this case). The sequencing of infrastructure project development for a utility is determined by the availability of each project (Table 2, right column) at the time a decision is triggered as well as a project's predetermined preference relative to other potential projects. WaterPaths also tracks revenues for each utility from weekly water sales, as well as utility contingency (reserve) funds that can be used to meet unexpected revenue reductions due to restrictions or increased costs arising from water transfers. All infrastructure projects, water portfolio instruments, and ROF-based rules have been specified in collaboration with the Triangle utilities. For more on WaterPaths functionality, see Trindade et al. (2020).

2.2.3 Sampling States-of-the-World for Monte Carlo Simulation

Risk-of-failure evolves based on reservoir capacity dynamics that change depending on hydroclimatic conditions, human demands, and path dependent management actions (i.e., short-term weekly portfolio management combined with long-term annual infrastructure investments).

To fully exploit the adaptive nature of ROF-based decisions, we expose candidate infrastructure investment and water portfolio policies to a broad set of plausible future states-of-the-world (SOWs). This represents an exploratory modeling centered approach for identifying infrastructure investment and water portfolio policy rules that effectively adapt to highly challenging conditions (Bankes, 1993; Moallemi et al., 2020). Uncertainties that comprise future SOWs can be categorized as being either a “well-characterized” uncertainty (WCU), with a known probability distribution or large amounts of historical data, or a deep uncertainty (DU), without a known probability and limited historical data (Kwakkel et al., 2016; Marchau et al., 2019). In this study, hydro-climatic internal variability is treated as a stationary WCU (i.e. synthetic stochastic hydrology, described in section 2.2.3.1 below). DUs included in this study include water demands, economic factors, climate change along with deeply uncertain management and policy factors, within our modeling framework. For this work, five hundred SOWs, each representing one set of future conditions, were generated using a Latin Hypercube Sampling (LHS) approach (Figure 2).

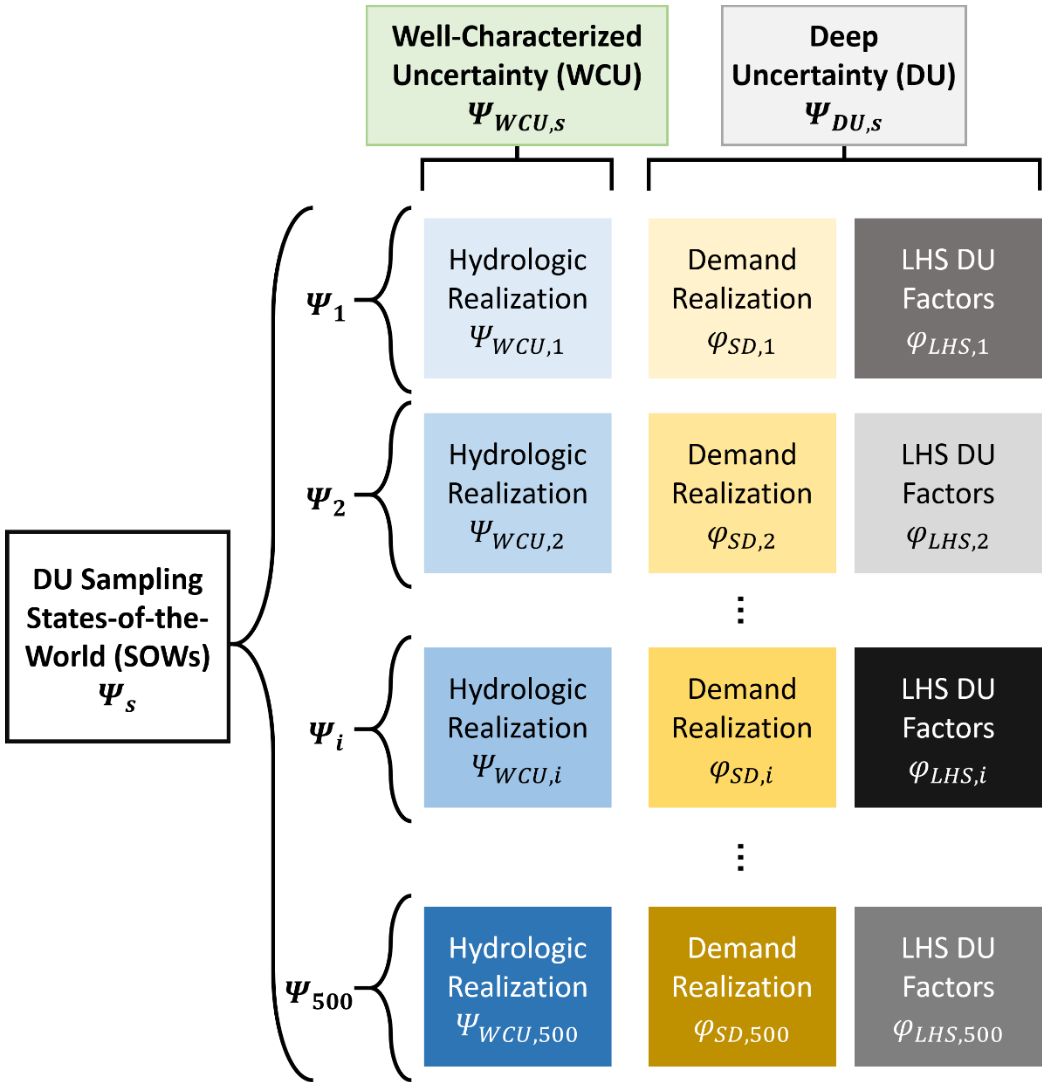

Figure 2: Visualization of DU sampling of SOWs, including timeseries realizations of hydrologic (reservoir inflow) and utility water demand along with DU factors sampled via LHS. Timeseries samples of hydrologic and demand WCUs are coupled with DU factor samples to form the set of SOWs.

Table 3: Description and ranges of deeply uncertain factors

Factor	**Description**	**Range (multiplier factor)**
Bond Term (B_{term})	affects number of years over which infrastructure capital costs are repaid as debt service	0.8-1.2
Bond Interest Rate (B_{rate})	factor adjusts fixed interest rate on bonds for infrastructure	0.6-1.2
Discount Rate (D_{rate})	applied to the discount rate, affecting how future infrastructure investment is discounted to 2015	0.6-1.4
Restriction Efficacy (RE_U: 6 factors, 1 per utility)	impacts how effective use restrictions are at reducing water demand	0.8-1.2
Lake Evaporation (E)	controls the rate water is evaporated from regional reservoirs	0.9-1.1
WJLWTP Permitting Period (PP)	brings forward or delays the year after which the WJLWTP can be constructed	0.75-1.5
WJLWTP Construction Time (CT)	lengthens the construction time that would be needed to build WJLWTP	1.0-1.2
Sinusoidal Demand Variables		
α	controls amplitude of sinusoidal function	0.000001-0.13
β	affects shape and periodicity of sinusoidal function	3000-6000
ρ	shifts sinusoidal function period	600-1200

Each row of panels in Fig. 2 denotes a single SOW, Ψ_i, in the set of all sampled SOWs, $\boldsymbol{\Psi_s}$, generated through the combined sampling of both well-characterized and deeply uncertain factors. WCU in hydrology ($\boldsymbol{\Psi_{WCU}}$) is sampled from synthetic records of hydroclimatic conditions, generated from patterns in historical observations (described in the following sub-sections). Additionally, Table 3 lists the DU factors included in our analysis, their relevance, and testing ranges, which were based on values used in previous Triangle research by Trindade et al.

(2017; 2019). Each SOW contains one set $\Psi_{DU,i}$ of sampled DU factors $\boldsymbol{\Psi_{DU}} \ni [\boldsymbol{\varphi_{SD}}, \boldsymbol{\varphi_{LHS}}]$, containing demand growth realizations $\boldsymbol{\varphi_{SD}}$ (development described in section 2.2.3.2) and multiplicative factors $\boldsymbol{\varphi_{LHS}} \ni \left[\vec{B}_{term}, \vec{B}_{rate}, \vec{D}_{rate}, \boldsymbol{RE}, \vec{E}, \overrightarrow{PP}, \overrightarrow{CT}, \vec{\alpha}, \vec{\beta}, \vec{\rho}\right]$ applied to perturb financial parameters of utility debt financing – bond term length B_{term}, bond flat interest rates B_{rate}, and discount rate D_{rate} – along with use restriction efficacy for each utility RE_U, rate of lake evaporation E, permitting period PP and construction time CT, and sinusoidal effects on demand growth α, β, and ρ (detailed in 2.2.3.2).

2.2.3.1 Hydrologic Realization Development

The WCU samples of hydrology account for the internal variability of the hydrological record by generating synthetic timeseries of regional reservoir inflows. The full ensemble of synthetic inflows are developed through statistical resampling of the historical record (represented as full natural inflows, developed by HydroLogics, 2011) that preserves autocorrelation and spatial correlation patterns of the past through Cholesky decomposition while producing a wider range of extreme events than what is present in the historical record (Kirsch et al., 2013); this expanded evaluation of extreme conditions holds value as evaluation based on historical data alone can miss extreme events and overestimate the robustness of a potential development pathway or policy (Herman et al., 2016; Quinn et al., 2017; Vogel & Stedinger, 1988). For additional detail on water supply modeling in the Triangle, risk-of-failure policy, or synthetic generation of streamflows, see Gorelick et al. (2018) and Herman et al. (2016).

2.2.3.2 Demand Realization Development

Future water demand is based on projections of population and per-capita water use (TJCOG, 2014; Hazen and Sawyer, 2020), and week-to-week fluctuations are modeled through a joint probability distribution with inflows (as a proxy for the relationship between weather conditions and water demand; hot, dry days see higher outdoor water use, as an example) (Zeff & Characklis, 2013). Though per-capita water use has been in decline, Triangle utilities anticipate that population growth increases will more than offset this effect leading to overall increased future water demand for the region. Consistent with the ensemble of hydrologic realizations used, 500 realizations of demand ($\boldsymbol{\varphi_D}$) with seasonal variation and response to hydrologic conditions are generated to match, using a joint probability distribution between historical water demand and reservoir inflows as a proxy for hydrologic conditions (as described by Zeff et al., 2013, 2014).

Demand growth is also infamously difficult to accurately forecast at decadal time-scales (Walker, 2013). Previous studies that treat demand growth rate as deeply uncertain have been limited to examination of ranges of constant, linear growth projections (Herman et al., 2015; Trindade et al., 2019). However, water demand growth rate is often non-constant and non-monotonic, and the assumption of constant linear growth may lead water managers to mischaracterize risks associated with demand growth. In this study, we account for potential non-monotonic demand growth through a sinusoidal factor approach. This sinusoidal scaling approach has previously been applied by Quinn et al. (2018) and Trindade et al. (2020) to emulate hydrologic variability in synthetic streamflow projections. Deeply uncertain sinusoidal factors are repurposed here to stress utilities under temporally varying demand growth rate changes. Equation (12) below describes how DU factors α, β, ρ control demand growth. These sampled sinusoidal factors $m_{s,t}$ are mapped to individual demand realization, impacting the shape and rate of water demand growth in each SOW.

$$m_{s,t}(\alpha, \beta, \rho) = 1 + \alpha \sin\left(\frac{2\pi t}{\beta + \rho}\right) - \alpha \sin(\rho) \tag{1}$$

Trindade et al. (2020) calibrated α, β and ρ to increase or decrease streamflow means no more than 20% compared to historical conditions. Similarly, in this study, we chose sinusoidal factor ranges of α, β and ρ to ensure future annual average demands could not be more than 25% different than utility demand projections. Our approach for synthetic demand realization generation is demonstrated in Figure 3. Panel A shows a demand growth projection without the sinusoidal factor multiplier applied. Panel B demonstrates how the factor may be used to generate two very different demand projections and the bottom panel shows the time-varying sinusoidal factors used to generate the records in panel B. By applying sinusoidal factors to demand realizations that follow existing utility projections of demand growth, this study can explore the impacts of both long-term and shorter-term changes in how demand projections on utility planning. Mathematically, the generation of sinusoidal demand timeseries $\boldsymbol{\varphi_{SD,s}}$ of each SOW can be written as

$$\boldsymbol{\varphi_{SD,s,t}} = m_{s,t}(\alpha, \beta, \rho) * \varphi_{D,s,t} \tag{2}$$

for all weeks t in each SOW s.

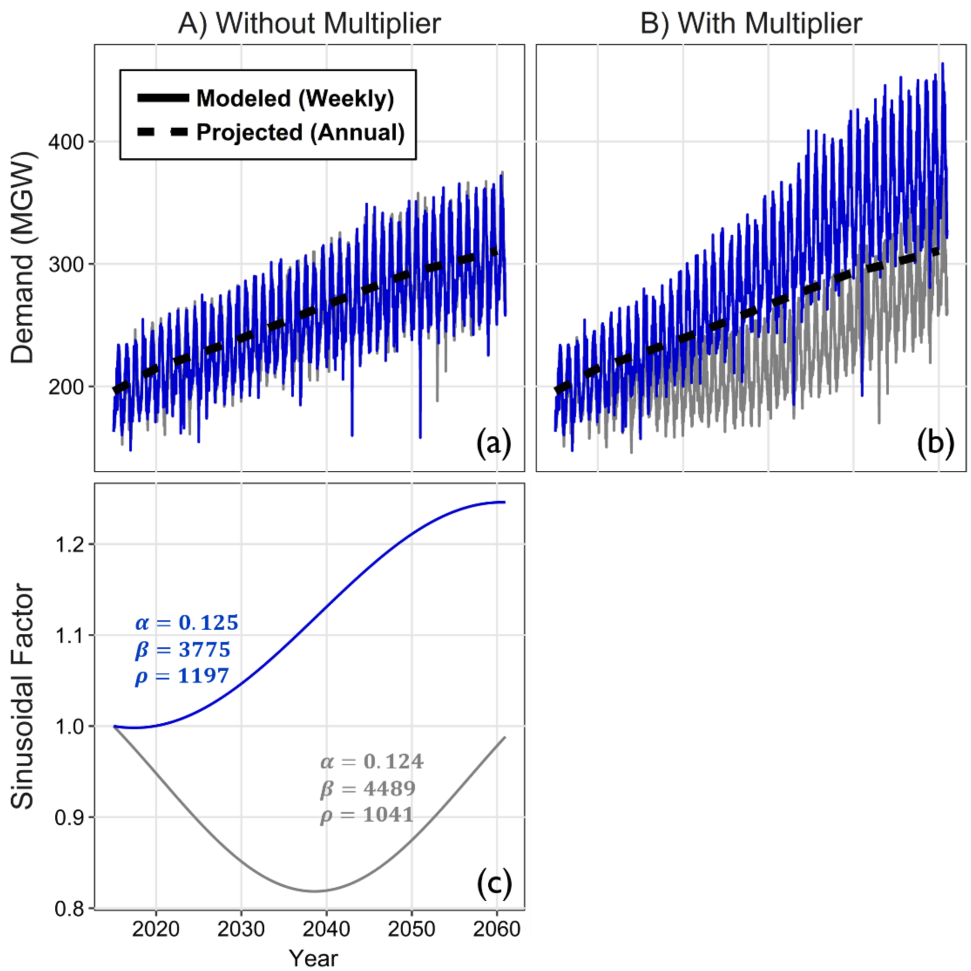

Figure 3: Deeply uncertain sinusoidal factors used to generate diversity between two example demand realizations. Demand timeseries (a) are multiplied in each timestep with (c) the factor timeseries plotted using Equation (1), with t changing across time to create the (b) outcome sinusoidal demand realizations described in Equation (2).

2.2.4 Deeply Uncertain Optimization Framework

Many-objective optimization is performed to search for model parameters (decision variables) that provide the best possible outcomes across utility objectives. Recent work has found that including deep uncertainty in the many-objective search can improve the robustness of candidate alternatives (Bartholomew & Kwakkel, 2020; Eker & Kwakkel, 2018; Trindade et al., 2017; Watson & Kasprzyk, 2017). Our research employs a DU Optimization framework (Trindade et al., 2017) to search for Pareto approximate regional agreements that are robust to a wide range of plausible future scenarios. In DU optimization, each candidate regional agreement is evaluated across 500 DU SOWs, generated using the sampling strategy shown in Figure 2. The terminology Pareto approximate refers to high quality approximation representations of tradeoffs where improvements in performance in any single objective comes at the cost of performance in one or more of the remaining objectives. The optimization problem can be mathematically described as a search for a set of Pareto-optimal policies $\boldsymbol{\theta}^*$ which minimize the objective function vector $\vec{F}$ such that

$$\boldsymbol{\theta}^* = \min_{\boldsymbol{\theta}} \vec{F} \tag{3}$$

where

$$\vec{F}(\boldsymbol{\theta}, \boldsymbol{X}, \boldsymbol{\Psi_s}, a) = [-f_{Rel}, f_{RF}, f_{NPC}, f_{PFC}, f_{WCC}, f_{UC}] \tag{4}$$

In Equation (2), the objective function vector $\vec{F}$ contains six regional supply and financial objectives: f_{Rel} is the objective of supply reliability (negated above, as maximizing reliability is equivalent to minimizing failure in this problem); f_{RF} is the restriction use frequency objective; f_{NPC} represents the net present cost of infrastructure investment; f_{PFC} is the peak financial cost objective; f_{WCC} gives the objective of worst-case cost; f_{UC} describes the unit cost of service objective. Each objective is described in further detail below. Objective values in Equation (4) are conditioned based on

$$\boldsymbol{\theta} = \left[\overrightarrow{ROFT}_{action}, \overrightarrow{IP}_{rank}, \overrightarrow{CFC}, \overrightarrow{JLA}, \overrightarrow{DP}, \overrightarrow{\overrightarrow{TCA}_{\tau}}\right] \tag{5}$$

$$\boldsymbol{X} = [\vec{x}_{LTROF}, \vec{x}_{STROF}] \tag{6}$$

$$\boldsymbol{\Psi_s} = \begin{cases} \boldsymbol{\Psi_{WCU}} \\ \boldsymbol{\Psi_{DU}} \ni [\,\boldsymbol{\varphi_{SD}}, \boldsymbol{\varphi_{LHS}}] \end{cases} \tag{7}$$

where $\boldsymbol{\theta}$ is a candidate set of decision variables, $\boldsymbol{X}$ represents the time-varied state of both short- and long-term ROF ($\vec{x}_{LTROF}, \vec{x}_{STROF}$), $\boldsymbol{\Psi_s}$ contains vectorized sampled sets (s) of both (a) well characterized uncertainties (WCU; Ψ_{WCU}) and (b) deeply uncertain (DU) variables (Ψ_{DU}), and $a \in [a_{fixed}, a_{adjustable}, a_{none}]$ indicates the tested inter-utility cooperative formulation (described in detail in section 2.2.5).

In Equation (5), $\overrightarrow{ROFT}_{action}$ is the vector of all risk-of-failure triggers for each regional utility for potential $action \in [water\ transfers, restrictions, infrastructure]$, $\overrightarrow{IP}_{rank}$ is a vector of ranking variables for each potential infrastructure project IP, $\overrightarrow{CFC}$ is a vector of annual utility contingency fund contributions (specifically the fraction of annual revenues contributed), $\overrightarrow{JLA}$ is a vector containing each regional utility's Jordan Lake water supply allocation, $\overrightarrow{DP} = [r_{proj}, l_{proj}, \vec{b}]$ is the vector holding regional demand projection variables where $\vec{b}$ is the vector of demand buffers for all utilities, and $\overrightarrow{TCA}_{\tau}$ is the vector of initial WJLWTP treatment allocations for each partner utility.

Equation (7) above details the set of deeply uncertain factors $\boldsymbol{\Psi_s}$, containing both (a) WCU from sampling hydrologic realizations, as well as (b) realizations of water demand and vectors of key DU factors.

2.2.4.1 Regional Performance Metrics

Assessment of utility performance from each model evaluation is based on values generated across six regional objectives:

1. Water supply reliability (f_{Rel}); frequency of annual supply failure ($F_{r,U,y} = 1$ if any week during a calendar year $y \in \boldsymbol{Y} = [2015{,}2060]$ in which storage drops below 20% of supply capacity or demand exceeds 90% of treatment capacity, 0 otherwise) across $N_r =$

500 states-of-the-world (r) is quantified to measure the ability of a utility (U) to maintain reliable water service. To determine a regional objective value, the maximum objective value across the set of all utilities ($\vec{U}$) is taken.

$$f_{Rel} = \max_{\overrightarrow{U \in U}} \left[\frac{\max_{Y} \left(\sum_r F_{r,U,y} \right)}{N_r} \right] \tag{8}$$

2. Restriction use frequency (f_{RF}); utilities have incentive to limit the amount of time restrictions are implemented, as it can be politically unpopular and reduce utility revenues (Hughes et al., 2014); the fraction of years ($N_y = 46$) with at least one week of use restrictions in place over a model evaluation is therefore another important performance metric. Restriction use indicator $R_{r,U,y} = 1$ when year y of realization r has at least 1 week of restrictions implemented by utility U, and is 0 otherwise.

$$f_{RF} = \max_{U \in U} \left[\frac{\sum_r \sum_y R_{r,U,y}}{N_r N_y} \right] \tag{9}$$

3. Infrastructure net present cost (f_{NPC}); large infrastructure investments often force water utilities to increase water rates, a step they would prefer to defer or avoid altogether. When population and water demand growth are projected to exceed existing capacity, however, supply infrastructure expansion may become necessary. Quantifying net present infrastructure investment – present-valued debt service $DS_{r,u,y}$ based on a discount rate d, summed across SOWs r and years y for each utility U – can be compare with and without inter-utility agreements to demonstrate their ability to reduce overall infrastructure investment.

$$f_{NPC} = \max_{\overrightarrow{U \in U}} \left[\frac{\sum_r \sum_y \frac{DS_{r,U,y}}{(1+d)^{y-1}}}{N_r} \right] \tag{10}$$

4. Peak annual costs (f_{PFC}); tracking the peak annual sum of drought mitigation costs and debt service paid across each realization offers more detail on the financial health of a utility in each model evaluation, where a utility's goal is to minimize peak costs relative to revenue streams. This objective returns the average of each realization's worst year, in terms of the fraction of utility annual volumetric revenue (AVR) required to cover annual debt service DS, contingency fund contribution CFC, revenue losses to restriction use RC, and costs of purchasing water transfers TC.

$$f_{PFC} = \max_{\overrightarrow{U \in U}} \left[\frac{\sum_r \max_{y \in [2015,2060]} \left(\frac{DS_{r,U,y} + CFC_{r,U,y} + RC_{r,U,y} + TC_{r,U,y}}{AVR_{r,U,y}} \right)}{N_r} \right] \quad (11)$$

5. Worst-case cost (WCC); while infrastructure spending over the full planning period is important, financial volatility due to drought mitigation in any given year is also a key utility concern. Specifically, water utilities are concerned with years where revenue losses from restrictions and costs of water transfers cannot be met with existing contingency funds (CF). To identify the worst-case costs a utility could face, this objective quantifies the 99$^{\text{th}}$ percentile highest annual cost across all SOWs (r).

$$f_{WCC} = \max_{\overrightarrow{U \in U}} \left[P_{99} \left(\max_{y \in [2015,2060]} \left(\frac{RC_{r,U,y} + TC_{r,U,y} - CF_{r,U,y}}{AVR_{r,U,y}} \right) \right) \right] \quad (12)$$

6. Unit cost of infrastructure expansion (UC); similar to objective 3, this objective quantifies present-valued debt service paid relative to water demand growth over the planning period, offering an assessment of how financially-efficient a utility is able to be when mitigating supply risk.

$$f_{UC} = \max_{\overline{U \in U}} \left[\frac{\sum_r \sum_y \frac{\frac{DS_{r,U,y}}{(1+d)^{y-1}}}{\left(D_{r,Y,y} - D_{r,Y,2015}\right)}}{N_r} \right] \tag{13}$$

2.2.5 Cooperative Formulations of Inter-Utility Agreement

Five of the six Triangle utilities (Raleigh excluded) have water supply allocations from Jordan Lake, the region's largest water source. Only Cary and Chatham County have direct access to their Jordan Lake allocations through independent WTPs, necessitating that other regional utilities access their own allocations through purchases of treated Jordan Lake water from either Cary or Chatham County. In 2018, partially in response to this bottleneck of Jordan Lake water supply access, regional utilities formed the Triangle Water Supply Partnership to determine how shared infrastructure on Jordan Lake could have regional water supply benefits. As a result, the development of a shared WTP on Jordan Lake is being considered by Chatham County, Durham, OWASA, and Pittsboro (Table 2, Western Jordan Lake Regional WTP, or WJLWTP). These four partnering utilities in the development would be allocated treatment capacity in the WJLWTP, from which they may pipe treated water directly to their respective distribution systems (TJCOG, 2014; JLP, 2014). As a part of such an infrastructure project, an agreement between Triangle water utilities to finance and operate the WJLWTP would be required. Inter-utility and capacity-sharing agreements are common across the U.S. and globally (Silvestre et al., 2018; Tran et al., 2019). Differences in how an agreement is structured, however, can have significant impacts on the water supply and financial outcomes for participating partners (Gorelick et al., 2019; Sjöstrand et al., 2018).

Assessment of inter-utility agreement formulations within our water supply modeling framework requires each formulation be evaluated under identical conditions for comparison of performance, as well as against a formulation without agreement that contains only independent infrastructure planning by utilities. Therefore, this paper tests three model formulations:

1. Regional utilities have the option to develop the WJLWTP with fixed treatment capacity and financing allocations (2.2.5.1)
2. The WJLWTP may be developed with adjustable treatment capacity and financial allocations (2.2.5.2)
3. No cooperative agreement is reached, and Triangle utilities do not develop a joint WJLWTP (2.2.5.3).

2.2.5.1 Fixed Capacity Treatment Allocations

Fixed allocation inter-utility agreements are common. For example, the Cary-Apex WTP serves the towns of Cary, Apex, and Morrisville where each hold a fixed capacity allocation while Cary operates the plant (Cary-Apex WTP Agreement, 2015). Under such an agreement, treatment capacity allocations (in terms of maximum quantity of water treated per day) for each partner utility are fixed when the WTP comes online after construction. Each partner's share of the capital costs of construction are set based on the fraction of capacity allocated to each. Conveyance and other variable costs of water treatment or transfer, which are relatively small in comparison to capital costs, are not considered within the agreement structures evaluated in this research. The allocation of treatment capacity and debt service on capital expenditures for the WJLWTP under a fixed allocation agreement is described by (14) and (15) below:

$$TCA_{U,y} = TCA_{U,\tau} \tag{14}$$

$$DS_{WJLWTP,U,y} = \frac{TCA_{U,\tau}}{\sum_{u \in \vec{U}} TCA_{u,\tau}} * DS_{WJLWTP,y} \tag{15}$$

Here, τ is the year in which the WJLWTP begins operating, $TCA_{U,y}$ is the treatment capacity allocation for utility U in year $y \geq \tau$, $\vec{U}$ is the set of WJLWTP partner utilities, $DS_{WJLWTP,y}$ is the total debt service owed for capital costs and interest on the WJLWTP in year y to be disbursed among agreement partner utilities. Debt service is modeled for this work for each utility such that $DS_{p,U,y}$ for any future infrastructure project p (Table 2) is equal in all repayment years $y \in Y_p$ where Y_p is the set of years from project p beginning operation (and debt repayment begins) to the year of debt maturity for that project.

2.2.5.2 Adjustable Treatment Allocations

Alternatively, an inter-utility agreement with flexibility in allocations may be beneficial to partner utilities. An adjustable capacity agreement is designed to ensure that the unit cost of treating water in a given year is equal between partners, no matter how much use occurs in aggregate; as an example, this type of accounting is used to cover costs of development by Tampa Bay Water Authority, which charges a uniform rate for supply to its six wholesale customers by scaling water supply production for each customer to match their respective levels of demand each year (Asefa, 2015). This work abstracts an adjustable capacity agreement structure, in which the rate of water can be set annually based on water use by all partners and costs – debt service, in this case – to be recovered over the year. Capacity allocations for WJLWTP partners are adjusted based on expected near-term water demand, allowing allocations to be adjustable year-to-year. The treatment capacity allocation under this agreement structure is described by (16) and (17):

$$TCA_{U,y} = \begin{cases} TCA_{U,\tau} & when\ y = \tau \\ TCA_{U,y-1} + \left(WSF_{JL,U,y} * DGR_{U,y}\right) & when\ y > \tau \end{cases} \tag{16}$$

$$DGR_{U,y} = f\left(r_{proj}, l_{proj}, b_U\right) \tag{17}$$

Under an adjustable agreement, capacity allocations in each year $y > \tau$ are based on the previous year allocation for utility $U \in \vec{U}$, adjusted based on estimated annual demand growth rate $DGR_{U,y}$ and the fraction of water supply drawn from Jordan Lake $WSF_{JL,U,y}$. Each utility's reliance on Jordan Lake is, in part, governed by the water supply allocation JLA_U awarded to the each utility in Jordan Lake by the US Army Corps of Engineers that operates the reservoir. Demand growth estimates for a utility are a function of how often re-projections of demand are done (r_{proj}), the length of the recent historical record (l_{proj}) used to estimate future demand, and any buffer (safety factor hedge against high growth) a utility may add (b_U). Debt service allocations are, like in a fixed agreement, proportionate to treatment capacity allocations.

2.2.5.3 No Cooperative Agreement

Though Triangle utilities intend to develop the WJLWTP, it remains possible that no agreement is reached and the facility is not constructed or financed. This potential alternative is also tested as a cooperative formulation in our work.

2.2.6 Computational Experiment and Multi-Objective Optimization Search

In this study, we employed the Borg multi-objective evolutionary algorithm (MOEA), which has demonstrated as an effective tools for identifying high-quality Pareto approximate solutions to non-linear, complex problems such as those in water supply management (Hadka & Reed, 2013). Optimization runs for each formulation were run on The Cube Cluster of the Cornell University Center for Advanced Computing and the Stampede2 and Comet Clusters of the Texas Advanced Computing Center (TACC) Extreme Science and Engineering Discovery Environment (XSEDE) (Towns et al., 2014). Borg MOEA optimization seeds were allowed to progress for a maximum of 150,000 function evaluations. A single reference set of solutions was identified after combining individual reference sets from each seed across all inter-utility agreement formulations. Runtime diagnostics were performed using hypervolume and visual analytics to confirm convergence; more detailed discussion of the Borg MOEA optimization diagnostics and validation of reference set performance using an-out-of-sample set of SOWs is shown in Supplement A.

2.2.6.1 Defining Satisfactory Regional Performance

To identify management portfolios that produce satisfactory utility water supply and financial performance under uncertainty, reference set solutions identified in DU optimization are screened based on three key management criteria. The criteria of satisfaction are based on feedback from Triangle utilities' personnel, previously used to screen results from similar past research in the region (Herman et al., 2015; Zeff et al., 2014):

1. Reliability ≥ 99%: to meet demands, utility water supply storage cannot fall below 20% of capacity more than once in 100 years.
2. Restriction Use Frequency ≤ 20%: to maintain their efficacy and avoid public frustration, regional utilities hope to implement use restrictions less than 1-in-5 years on average.
3. Worst-Case Cost ≤ 5% AVR: unplanned financial disruptions of more than 5% AVR in a given year would be ruinous for regional utilities' budgets – only states-of-the-world that can minimize worst-case cost below this threshold, a function of hydrologic, demand, and utility decision-making factors, are acceptable.

3 Results

Results from DU optimization of three potential inter-utility cooperative formulations – where a shared WTP on Western Jordan Lake (WJLWTP) is (1) developed with fixed treatment allocations for each utility; (2) with adjustable capacity allocations; (3) not built, and no agreement is made – are presented below. Beginning with outcomes at a regional objective level, results span both regional and individual utility objective performance for Pareto-approximate solutions under all formulations. Key relationships between decision variables and objective outcomes, as well as characteristics of representative solutions, are further explored to quantify differences in utility behavior and performance between cooperation formulations.

3.1 Regional Objective Outcomes

Figure 4 is a parallel axis plot of the Pareto-approximate reference set of solutions across all cooperative formulations. Each line across the six vertical axes represents regional objective results for a single solution of the reference set. The lower a solution crosses an objective's vertical axis, the better its performance in that objective. Solutions of the Pareto-approximate reference set (Fig. 4, light grey, $n = 29{,}654$) include non-dominated solutions across all optimizations performed (one for each formulation). Objective values represented for a solution are the “minimax” objective value across all utilities – the worst-performing utility, in terms of each objective, represents the regional objective value for that solution. These results are shown in two panels on Figure 4: Figure 4a visualizes the objective outcomes of the 588 solutions that meet utilities’ performance criteria; Figure 4b identifies one well-performing representative solution under each cooperative formulation – meeting stricter performance criteria of greater than 99.2% reliability, less than 5% restriction use frequency, and less than 1% AVR worst-case cost – for subsequent exploration in this section.

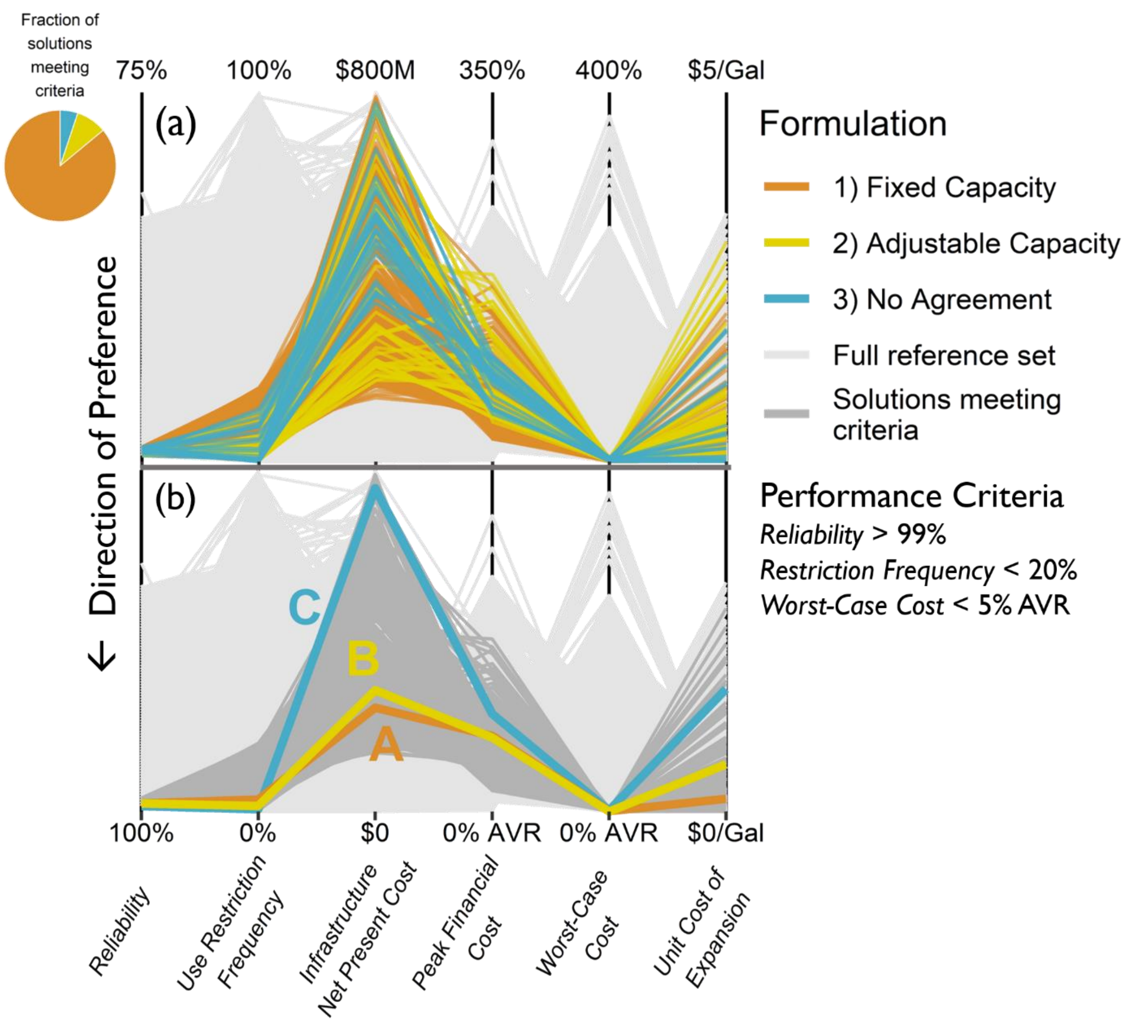

Figure 1: Parallel axis plot of the Pareto-approximate reference set of solutions (light grey), with solutions meeting utility performance criteria in color. Solution performance is shown across management objectives (from left to right). Each colored line represents objective results for a single solution. Solution performance is better if its line is closer to the bottom of the plot across each objective. Panel (a) compares the full reference set of solutions to those meeting criteria; panel (b) identifies three representative high-performance solutions meeting utility criteria, used for detailed comparison in subsequent results.

Imposing the utilities' performance criteria on the reference set yields a smaller suite of tradeoff solutions with high reliability, limited restriction use, and low worst-case costs, shown on Fig. 4a in color. Of the 588 solutions that meet the utilities' criteria, 506 include a fixed capacity agreement for development of the WJLWTP (Fig. 4a, orange), 52 use an adjustable capacity WJLWTP agreement (Fig. 4a, yellow), and only 30 had no cooperative agreement and no development of the WJLWTP (Fig. 4a, blue). The relatively limited number of solutions able to meet utility performance criteria without an inter-utility agreement indicates that inter-utility agreements contribute planning flexibility and regional performance benefits through both the fixed and adjustable capacity variants. This is especially apparent in terms of net present cost of infrastructure (Fig. 4, third vertical axis), where the highlighted solutions meeting the utilities' performance criteria without an inter-utility agreement required relatively high investment in infrastructure expansion; solutions with an agreement could meet performance criteria at lower levels of infrastructure investment.

3.2 Individual Utility Objective Outcomes

Objective performance of Pareto-approximate solutions in Fig. 4 show only regional outcomes; however, identifying differences in individual utility performance is key to understanding how inter-utility agreements may benefit utilities asymmetrically. Figure 5 shows for which solutions of Fig. 4 that an individual utility was the 'driver' of that solution's objective value, answering the question: how often, for a particular objective, was each utility the worst-performing?

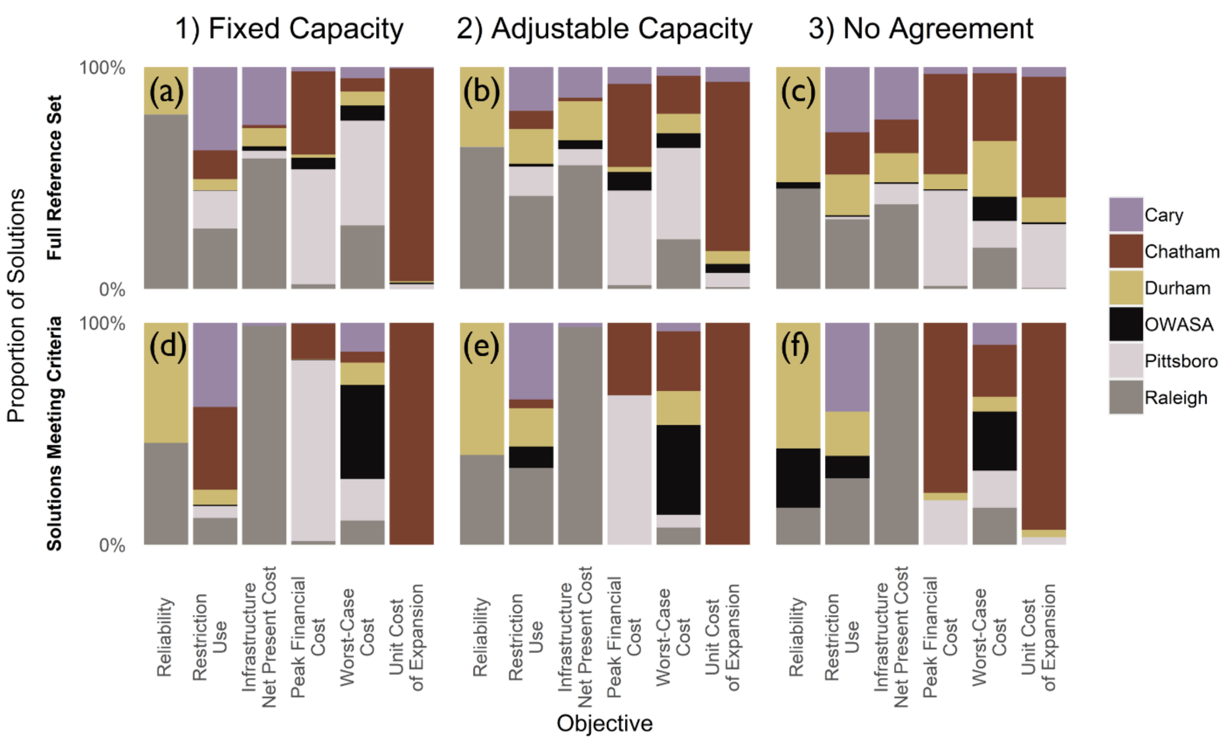

Figure 2: Fraction of solutions – in the (abc) Pareto-approximate reference set and (def) solutions meeting utility criteria – for which an individual utility (color) represents the worst-performing of the region for a particular objective (x-axis), by formulation (columns of panels).

Across the full reference set of solution (Fig. 5abc), a handful of differences between solutions with an inter-utility agreement (Fig. 5ab) and those without (Fig. 5c) emerge. When an inter-utility agreement is available across all solutions, allowing Triangle partnering utilities to develop the WJLWTP, Durham (yellow) is less-frequently the utility of lowest reliability (Fig. 5ab), with Raleigh (dark grey) becoming the most frequent utility to attain the lowest reliability. Only in solutions without any inter-utility agreement does OWASA (black) appear as the worst-performing utility in terms of reliability.

Financially, a larger share of solutions with inter-utility agreement show Pittsboro (light grey) as the worst-performing utility for both peak financial and worst-case cost objectives (Fig. 5, fourth and fifth columns of each panel), compared to solutions without an agreement. Whether or not cooperation via the WJLWTP is possible, Chatham County is the worst-performing utility in terms of unit cost of infrastructure expansion (Fig. 5, sixth column of each panel) across almost all solutions.

Between the full set of solutions and solutions meeting utilities' performance criteria (Fig. 5def; corresponding with solutions of Fig. 4a in color), other shifts in distribution of worst-performing regional utilities are apparent. These differences indicate which utilities may act as a "limiting factor" for regional performance as criteria for satisfactory performance become increasingly strict. For example, Raleigh was the utility of greatest infrastructure net present cost (Fig. 5, third column in each panel) across all solutions meeting utility performance criteria under fixed and adjustable cooperative formulations (Fig. 5de). Similarly, OWASA (black) became the worst-performing utility most frequently as measured by worst-case cost in solutions meeting performance criteria, and Pittsboro or Chatham County were almost exclusively responsible for the regional peak financial cost objective value in the same solutions.

3.3 Cooperative Formulation Differences on Jordan Lake

When evaluating the benefits of the cooperative inter-utility agreement formulations, it is important to distinguish the impacts across the partnering utilities for a WJLWTP – Chatham County, Durham, OWASA, and Pittsboro. Figure 6 shows the ranges of the utilities' objective outcomes for solutions meeting the regional performance criteria under each agreement formulation.

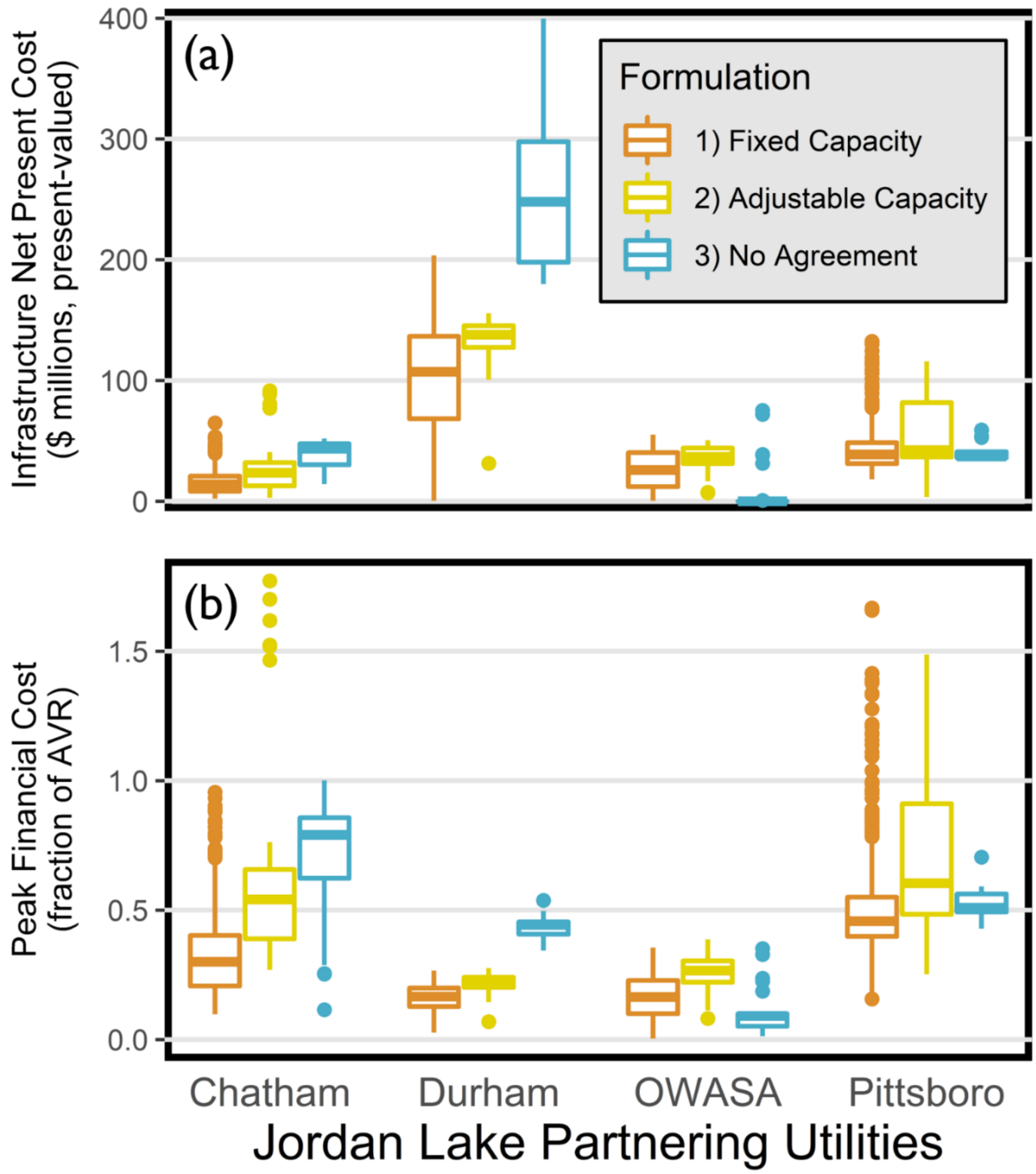

Figure 3: Range of (a) infrastructure net present cost and (b) peak financial cost objective values across Pareto-approximate reference set solutions meeting utility performance criteria, for utility partners to a WJLWTP agreement (x-axis) under each cooperative formulation (color).

Broadly, infrastructure net present cost (Fig. 6a) and peak financial cost objective values (Fig. 6b) improve for Chatham County and Durham under inter-utility cooperation formulations with the WJLWTP included (Fig. 6, orange and yellow), versus solutions without a WJLWTP agreement made (Fig. 6, blue). By contrast, OWASA and Pittsboro generally experience the worst financial objective outcomes when a WJLWTP is constructed. As the largest utility partner to the WJLWTP, Durham invests more than other partners in infrastructure net present costs regardless of formulation. Chatham County and Pittsboro are relatively small utilities, so they experience larger variability in peak financial cost than OWASA and Durham. On average, a fixed allocation WJLWTP agreement (Fig. 6, orange) formulation resulted in lower objective values than under an adjustable capacity agreement (Fig. 6, yellow), but solutions with adjustable capacity agreements could out-perform fixed capacity allocation agreements in some cases. Also, fixed capacity allocation agreements more frequently resulted in poor-performance (i.e., high objective values), in comparison to adjustable capacity agreements (Fig. 6, longer tails and outliers on upper bounds of boxplots).

The effects of inter-utility agreements on an individual utility's objective performance are not only tied to the agreement formulations but also to differences in a utility's exposure to the decisions of its counterparties (other WJLWTP partner utilities). Figure 7 explores the statistical relationships observed between initial treatment capacity allocations for each utility partnering on the WJLWTP and utility financial objective outcomes. Under a fixed capacity allocation agreement (Fig. 7abcd), each utility's WJLWTP initial treatment capacity allocation is strongly positively correlated (green) to that utility's financial objective outcomes, with the exception of Chatham County who maintain a minimal initial allocation across most solutions. When allocations are fixed, the objective outcomes for a single utility are not strongly correlated with the initial allocations of other utilities.

Under an adjustable capacity agreement (Fig. 7efgh), however, a utility's objective performance is more substantially correlated to the treatment allocations of other utilities – OWASA offers a particularly clear example (Fig. 7g), where OWASA objective outcomes are strongly positively correlated to its own WJLWTP allocation size, but also strongly negatively correlated (purple) with Chatham and Pittsboro treatment allocations. Increased sensitivity to other utilities' adjustable allocations appears for Durham and Chatham as well; in fact, Durham's financial objective outcomes (Fig. 7f) become more correlated to Chatham County and Pittsboro allocations than to the City's own allocation. Though the utilities do have statistically significant impacts on the objective outcomes of their partners through fixed agreements (i.e., Durham and Pittsboro), the correlations are positive and relatively weak, indicating that initial fixed allocations of one partner may impact another adversely, but only to a small degree.

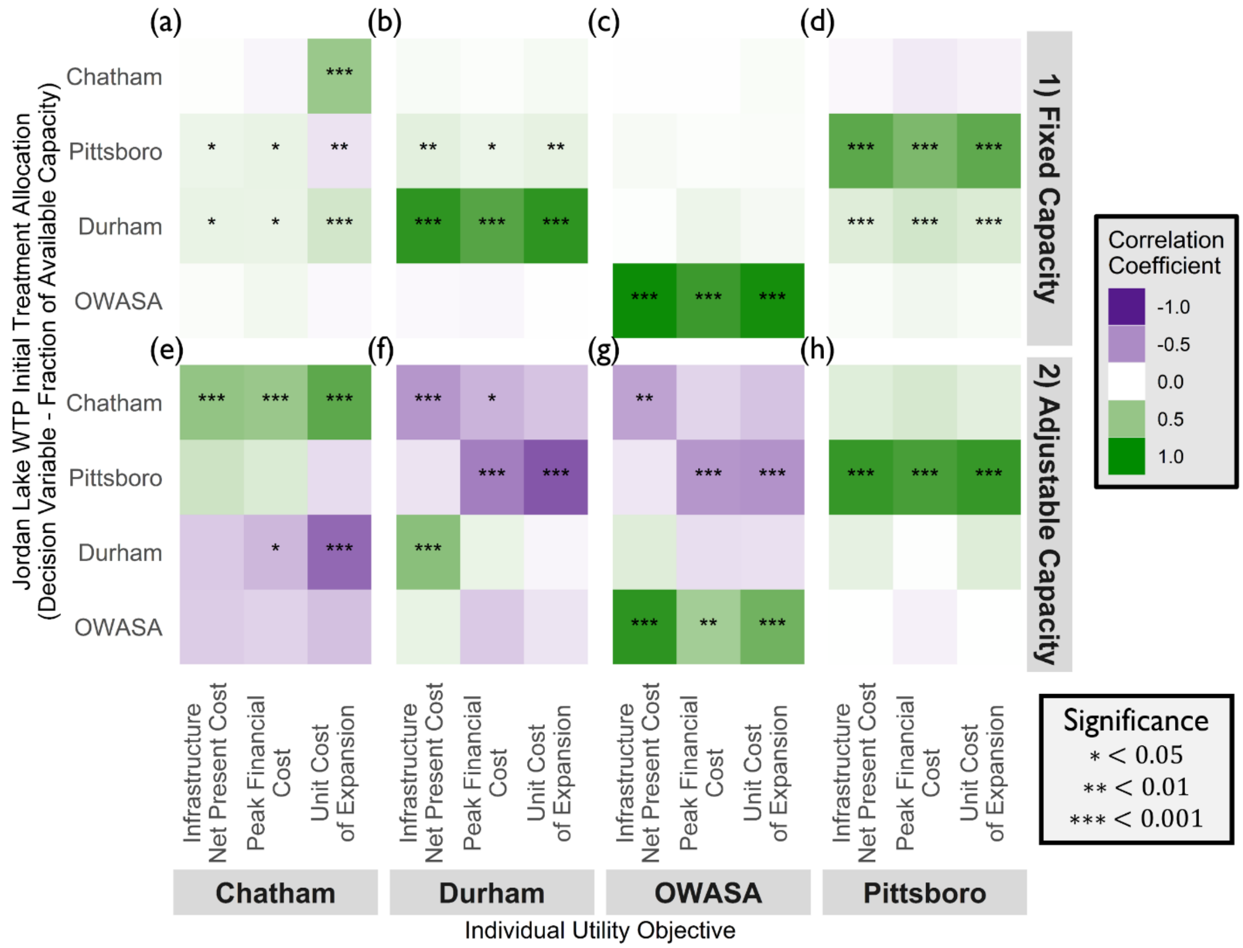

Figure 4: Spearman correlation coefficients (color) and p-value statistical significance (asterisks) between (rows) individual utility financial objective values and (columns) initial treatment capacity allocations in the WJLWTP for Pareto-approximate solutions meeting utility performance criteria under each cooperative formulation (rows of panels).

3.4 Demand Growth Influences on Infrastructure Pathways

Cooperation on the WJLWTP has significant influence on regional performance despite being just one potential infrastructure project within a larger set of investment options for the utilities to develop. Fig. 8 details how infrastructure pathways evolve across SOWs of three high-performance example solutions that meet utility performance criteria (Fig. 4b), chosen for their similar initial treatment allocations in the WJLWTP.

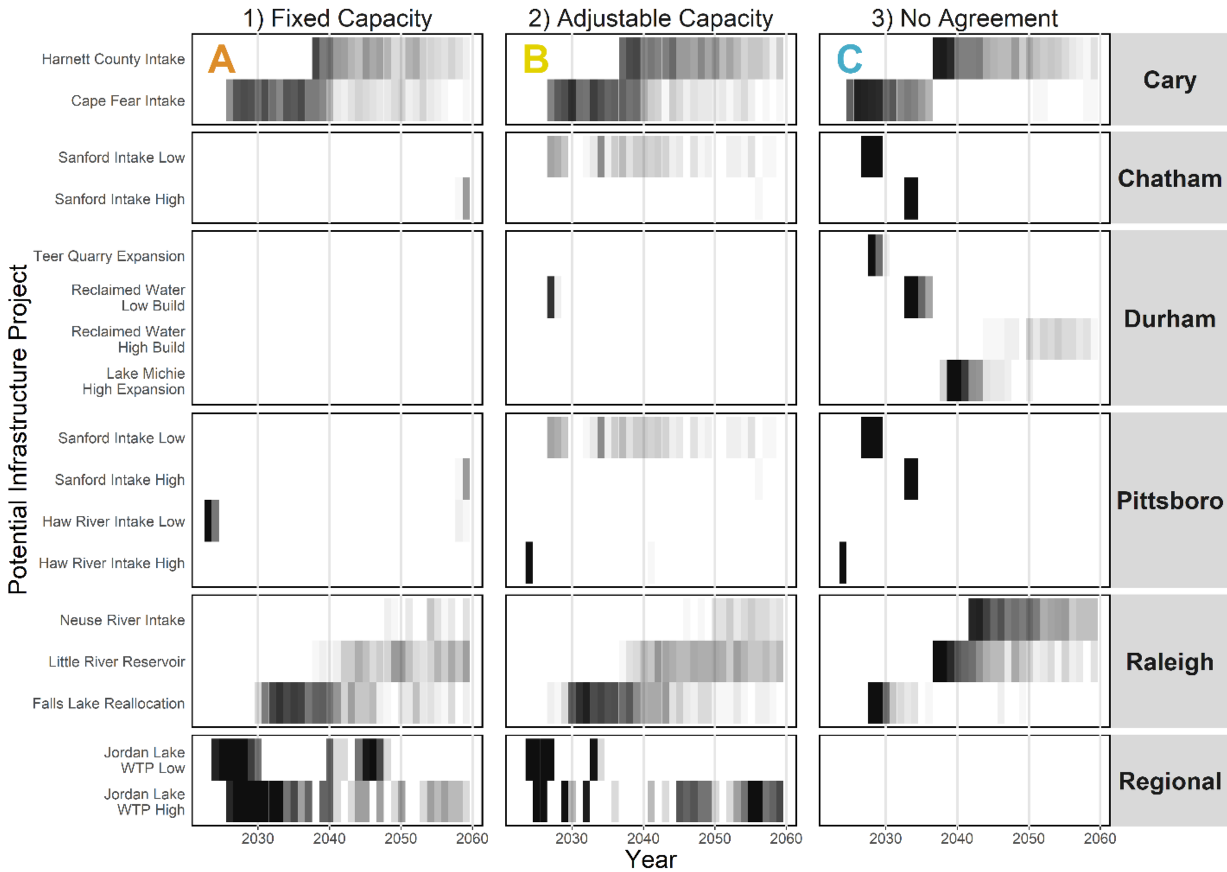

Figure 5: Infrastructure development pathways from 2015-2060 (x-axis) by utility across example solutions (shown in Fig. 4(II)) in each cooperative formulation (columns). Darker shading indicates a higher fraction of SOWs where an infrastructure option (y-axis) is constructed.

When the WJLWTP (Fig. 8, Regional) is utilized under a fixed or adjustable capacity allocation formulation, it is constructed and/or expanded before 2035 in the majority of SOWs. Implementation of the WJLWTP has consequences for agreement partners, especially Durham who avoids constructing up to four independent infrastructure options (Fig. 8, Durham). Pittsboro is able to avoid a large/high expansion of its Haw River Intake project with a fixed WJLWTP agreement. The Haw River Intake is built in almost all SOWs when no WJLWTP agreement is made. When the WJLWTP is constructed, Pittsboro instead blends the use of a small/low expansion of the regional WJLWTP with deferred construction of a Sanford intake. Chatham County, when the WJLWTP is available, can similarly defer construction of a Sanford intake (a shared project with Pittsboro) and/or reduce the scale of Sanford intake required. OWASA, the fourth partner utility on the WJLWTP, has no representation in Fig. 8, indicating no other infrastructure is built by OWASA other than the WJLWTP.

Differences in pathways between cooperative formulations can be attributed, in part, to how each WJLWTP agreement formulation responds to demand growth and allocates treatment capacity and debt service among partners. Fig. 9 visualizes how treatment allocations are set year-to-year for the WJLWTP under two example SOWs of high and low demand under each WJLWTP cooperative formulation (A and B from Fig. 4b).

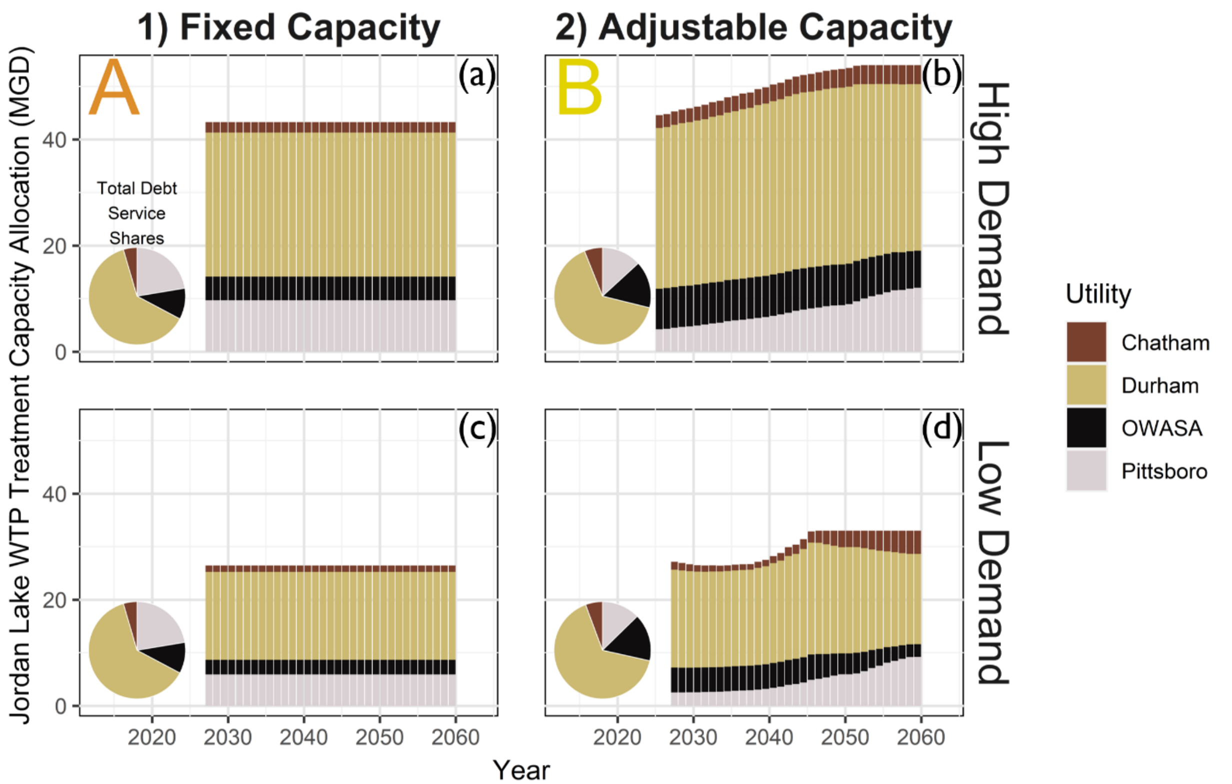

Figure 6: Year-to-year treatment allocations in the WJLWTP for each utility (color), under (a,c) fixed and (b,d) adjustable capacity allocation agreement formulations, under two example SOWs of high (a,b) and low (c,d) demand growth. Relative shares of debt service paid by each utility over the course of capital repayment for each utility is shown by inset pie charts for each realization.

Aspects of Fig. 9 demonstrate the relative benefits and drawbacks of each cooperative agreement formulation, in terms of treatment capacity availability and financial responsibility. Under a fixed capacity agreement (Fig. 9ac), utility treatment capacity and debt service (pie charts) are steady over time, though differences in demand growth impacts the initial sizing of WJLWTP construction. When an adjustable capacity agreement is used (Fig. 9bd), annual treatment capacity allocations increase as water demands grow, which results in reduced overall debt service paid by smaller partner Pittsboro (light grey), primarily at the expense of larger partners Durham (yellow) and OWASA (black). When capacity is available, an adjustable agreement also allows Chatham County (brown) to accumulate a larger share of treatment capacity as it grows, compared to the fixed allocation agreements. If initial treatment capacity allocations sum to less than the total available capacity, and no additional partners join the project, an adjustable agreement can adapt to make use of that excess capacity as demands shift, while a fixed agreement cannot.

4 Discussion

Contextualizing results of this study within the two primary research aims – (1) how may differences in inter-utility agreement structure impact utility supply and financial risk, and (2) to what degree do demand growth uncertainty and counterparty risk influence the viability of regional cooperation – requires interpretation of regional (4.1) and individual (4.2) utility performance, as well as what effects counterparty risk (4.3) and demand growth uncertainty (4.4) may have to influence performance under cooperative agreement formulations.

4.1 Regional performance with inter-utility agreements

Inter-utility cooperative agreements for the WJLWTP offer the Research Triangle region substantially more planning flexibility to meet utility performance criteria of high reliability, low restriction use frequency, and low worst-case costs compared to futures without any cooperation to develop a shared WTP on Jordan Lake. That flexibility specifically offers partner utilities (Chatham County, Durham, OWASA, Pittsboro) the ability to defer or avoid other infrastructure projects they might have had to build otherwise.

While it is possible for the Triangle to meet regional performance criteria without a cooperative agreement, such solutions exhibited significantly higher infrastructure investment (indicated by high infrastructure net present cost objective values) and peak financial costs. The behavior of non-agreement solutions indicates a strong tradeoff between reliability, restriction use, worst-case costs, and infrastructure investment; substantially increasing supply and treatment capacity through infrastructure expansion, increasing infrastructure net present cost, which can then increase reliability and decrease restriction frequency. Worst-case costs are similarly reduced, as the frequency of water transfer purchases and restriction implementation is reduced due to higher levels of treatment or supply capacity available to a utility. Use of an inter-utility agreement, in comparison, can reduce the severity of this tradeoff through economies-of-scale, offering the region the potential to reduce infrastructure investment without compromising water supply or financial performance.

4.2 Individual utility tradeoffs to meet regional performance criteria

Inter-utility cooperative formulations offer clear water supply and financial objective performance benefits regionally, relative to solutions without an agreement, but differences in performance between fixed and adjustable capacity allocation agreement formulations were not as obvious at a regional scale. To identify the diverse impacts that inter-utility agreements can have across the multi-actor Triangle system, individual utility outcomes across water supply and financial objectives in solutions that meet utility performance criteria are most informative.

This analysis finds that the worst-performing utility in terms of each performance objective, which drives the regional objective value, varied by objective. For some objectives an individual utility is the worst-performing for all solutions meeting utility criteria, such as Raleigh driving regional outcomes of infrastructure net present cost. Related to infrastructure spending, Raleigh also shows to be the worst-performing utility in cooperative solutions meeting utility performance criteria in terms of water supply reliability, with Durham being the only other utility exhibiting worst regional reliability outcomes; Raleigh, not being a partner to Jordan Lake WTP development, is forced to respond to low reliability levels through substantial independent investment in its own infrastructure projects. However, when no agreement is used, Durham is most frequently the worst-performing utility in terms of reliability. This discrepancy between cooperative formulation is due to inter-utility agreement on the WJLWTP, allowing Durham a lower-cost pathway to expanding water supply and treatment capacity earlier. Cooperation via the WJLWTP also reduces Durham exposure to drought and demand growth that later result in reduced reliability, a pathway that does not exist without Jordan Lake cooperation.

Chatham County and Pittsboro almost exclusively represent the region's worst-performing utilities for peak financial cost in solutions meeting regional utility performance criteria. Because both Chatham County and Pittsboro have the smallest demands – and projected demands – of Triangle utilities, financial fluctuations of debt service paid on infrastructure expansion have an outsized impact on them compared to other utilities. While about 15% of solutions meeting utility criteria under a fixed allocation agreement show Chatham County to be the worst-performing utility in terms of peak financial cost, this percentage rises to more than 25% of solutions under an adjustable capacity agreement. Pittsboro, the faster-growing of the two smallest partners, has an incentive to reserve an allocation in the WJLWTP much larger than its projected demands would suggest if allocations are fixed and cannot be revised later as demands grow. However, reservation of a large fixed allocation results in Pittsboro more often being the worst-performing utility, paying debt service on the WJLWTP as a higher percentage of their annual revenues in early years before demands have grown. Chatham County, being small and projected to grow slowly, reserves very small fixed WJLWTP allocations and (mostly) avoids the financial risk outcomes seen by Pittsboro. Under an adjustable agreement where treatment allocations can grow in time with demand, Chatham County still has incentive to request a small initial allocation in a WJLWTP; however, Pittsboro now does as well, which means that the same treatment allocation between agreement formulations for Chatham County can result in a larger share of debt service owed under an adjustable agreement.

4.3 Counterparty effects of cooperative infrastructure development

Regional supply and financial outcomes may improve as a result of inter-utility cooperation but impacts to individual utilities may go unnoticed, due to the asymmetric size and growth trends of each partner utility. One example of this is that inter-utility cooperation offers clear financial benefits to Durham and Chatham County relative to futures without cooperation, reducing infrastructure investment and peak financial costs, while cooperation simultaneously has negative effects on OWASA and (to a lesser degree) Pittsboro. Because Chatham County, OWASA, and Pittsboro are relatively small utilities in the Triangle, their increased financial risk or levels of infrastructure investment as a result of cooperation may not negatively impact regional financial objective outcomes; instead, larger utilities Cary, Durham, or Raleigh can, conversely, have an outsized impact on regional objectives.

When comparing fixed and adjustable cooperative formulations, generally better performance for solutions was attained under a fixed allocation agreement formulation. In part, adjustable agreement solutions resulted in less-effective cooperation because of the counterparty exposure each partner utility faces as result of decisions made by other partners, as demonstrated by the increased strength of correlation between partner utility objective outcomes and other utilities' initial treatment allocations when allocations are adjustable. When allocations are fixed each utility can more effectively control its own objective outcomes. With adjustable allocations, a tradeoff in financial performance appears between larger (Durham and OWASA) and smaller (Chatham County and Pittsboro) WJLWTP partners – with smaller initial treatment allocations for Durham and OWASA comes increased financial costs for Chatham County and Pittsboro, and vice versa. While adjustable capacity agreements can offer financial benefits to smaller partners 'growing into' their treatment allocations as demands rise, the counterparty effects can constrain the overall value of an adjustable inter-utility agreement.

4.4 Infrastructure pathway adaptation via inter-utility agreement

Cooperation between partner utilities on Jordan Lake could not only impact the decision-making and infrastructure pathways of partners but also those of other regional utilities like Cary and Raleigh. When a WJLWTP is constructed, Cary less frequently chooses to build a Harnett County Intake, or defers doing so until after 2035, compared to SOWs where no regional agreement is reached. The changes to Cary infrastructure pathways are due to (a) more frequent requests of water transfers from Cary to Durham, OWASA, and Pittsboro during periods of water scarcity when no Jordan Lake agreement is available; (b) the capacity of Cary's water supply allocation in Jordan Lake, which can be susceptible to lower levels in the 2050s as demands grow and raise Cary's risk of supply failure. Regional cooperation on a shared WTP is able to relieve pressure from Cary to reduce its effective treatment and supply capacity to meet regional transfer requests, giving Cary more flexibility to defer or avoid medium-to-long-term infrastructure expansion – as a result, regional cooperation does not only offer benefits to partner utilities, but other actors in the region as well.

Raleigh also appears to benefit from the existence of a WJLWTP agreement, despite not being a partner, as the agreement often keeps it from investing in the Neuse River Intake after 2040 when Jordan Lake cooperation is ongoing. However, Raleigh is the utility with the greatest infrastructure net present cost in all solutions meeting regional performance criteria, but not all of those cooperative formulation solutions saw less infrastructure investment than solutions without cooperation. With the WJLWTP built, Durham and other partners can more easily achieve the performance criteria of 99% supply reliability, putting the onus of regional improvement on Raleigh; as a result, maintaining a regional reliability of at least 99% requires Raleigh to balance (over)investment in infrastructure against increased risk-of-failure. In some states of the world, Raleigh can do so without expanding infrastructure to the extent necessary when no WJLWTP exists, but that is not always the case.

While cooperation is regionally beneficial, this study documented how individual utilities may simultaneously experience unintended financial consequences. This may be most apparent for OWASA, who do not opt to invest in independent infrastructure options in almost all solutions meeting regional performance criteria. This implies that OWASA is unlikely to be the WJLWTP partner to trigger construction of the project and doesn't experience elevated risk-of-failure levels that would necessitate infrastructure expansion of any project before 2060.

4.5 Additional considerations

Just as infrastructure expansion was not limited to cooperative development on Jordan Lake, other aspects of the Research Triangle management and planning system could impact the results of this work. One example could be how satisfactory regional performance is quantified. Regional water managers were polled to determine the performance criteria, used to screen our Pareto-approximate set for management policies that were robust under uncertainty, with a preference for risk-averse solutions. Should performance criteria be relaxed (or tightened), different conclusions could be drawn about the ability of management policies or cooperative agreements to meet utility goals. However, the regional benefits of cooperation compared to scenarios without cooperation under the selected reliability, restriction use, and cost performance criteria are a strong indicator that inter-utility agreements are a broadly useful technique to reduce water supply and financial risk.

Similarly, the minimax approach for objective calculation used here can well identify solutions that improve overall regional outcomes in a multi-actor system but does not always explicitly reveal conflict and tradeoffs among the objectives of the individual participating actors. Future work to improve or locate shortcomings of a minimax approach in the Triangle system should include re-analysis of solutions identified here, re-optimized for individual utility objectives.

Though this work applied a sinusoidal factor method to subject water utilities to greater uncertainty in demand growth than in past studies of this nature, our research still falls short of quantifying system dynamics under two important uncertainties: (a) spatial asymmetry of demand growth; and (b) management response to realized vs. projected demand. Sinusoidal factors were applied to all utility demand projections uniformly, meaning changes to demand growth rate were regionally correlated. Even within a single region, however, demand growth can react differently spatially (i.e. in suburbs where growth is planned vs. already urbanized areas, an economic recession having different impacts based on development type and zoning, etc.). By anchoring sinusoidal factor perturbations to long-term demand projections of each individual utility, our work is partially able to account for spatial disparities in growth rate, but future work to better assess spatial asymmetry in growth among regional actors would be valuable to the water systems management literature. Secondly, this study was able to test utility performance under realized demand growth changes, but not changes in how utilities project long-term growth; because utilities generally make decisions on infrastructure development at a decadal scale, based on projections, this work has only addressed one "side of the coin" in terms of decision-making under demand growth uncertainty. The authors hope future work into demand growth uncertainty will investigate not only the impacts of changes in demand growth over time, but also of changes to how utilities dynamically project demands and choose to develop infrastructure as a result.

5 Conclusions

Cooperation between urban water utilities is increasingly common. Partnerships can offer lower costs via economies of scale through shared ownership or use of a supply, water treatment plant, or other facility. However, cooperation may also expose partners to counterparty risk. Under agreements made based on highly uncertain long-term projections of demand growth and water availability, unexpected changes can introduce both supply and financial risk. Risks may also be compounded by the structure of the agreement itself. This work demonstrates both the benefits that inter-utility cooperative agreements can provide, as well as the added counterparty risk that may jeopardize the effectiveness of cooperation. To identify key differences in cooperative strategy, both individual and regional utility objectives must be considered under a broad range of conditions. Results of this work can inform regional decision-makers considering cooperative partnerships to manage risk and provide general guidance for the development of robust regional water supply management strategies under uncertainty.

6 Acknowledgements and data availability statement

The authors would like to thank and acknowledge the Triangle Water Supply Partnership, especially Ruth Rouse (OWASA), Syd Miller (Durham), and Ed Buchan (Raleigh) for their feedback and support of this work. All WaterPaths modeling code used to simulate Triangle water supply decision-making can be found at https://github.com/bernardoct/WaterPaths/tree/JLWTPAgreementsModel. Additional code for input data preparation and results visualization is being prepared for sharing now and will be made available before acceptance of this manuscript.

The authors declare no conflicts of interest related to this work. The authors would like to mention and to thank the National Science Foundation for funding this work (Water Sustainability and Climate Program, Award 1360442). This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1548562. This work used the Extreme Science and Engineering Discovery Environment (XSEDE) Stampede2 and Comet at the Texas Advanced Computing Center through allocation TG-EAR090013.

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8 Supplement A: Multi-objective optimization details

Runtime diagnostics on Borg optimization seeds were performed using hypervolume and visual analytics to confirm convergence (Fig. A1). Six random seeds for each formulation were run for 150,000 function evaluations (NFE). An additional test run of 50,000 NFE was also included in the reference set, as runtime diagnostics using the Hypervolume indicator (Zitzler et al., 2003) confirmed that the algorithm converged before 50,000 NFE.

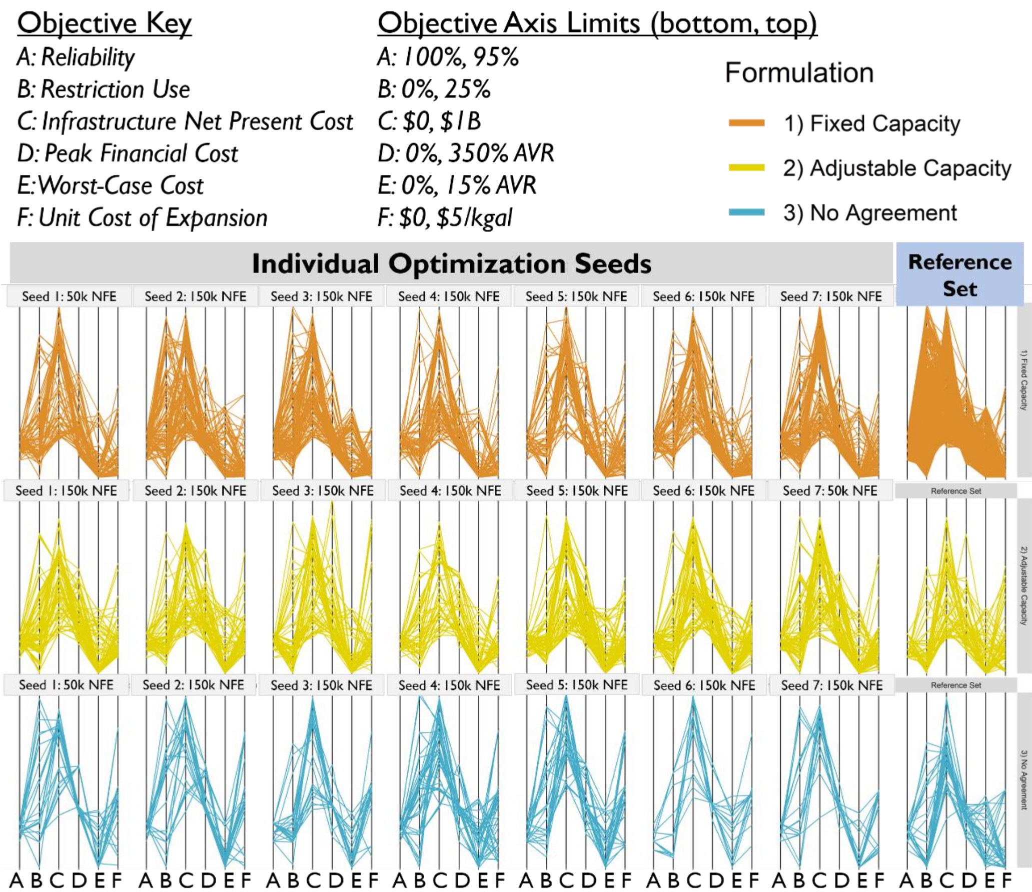

Figure A1: Visual analysis of Borg optimization seed convergence. Individual seed (panels) reference sets were screened for solutions satisfying utility reliability, restriction use, and worst case cost performance criteria for each formulation (rows) and compared to the full reference set of solutions across all seeds (right column of panels). Seeds with a maximum of both 50,000 and 150,000 function evaluations were able to successfully identify solutions meeting criteria.

Following DU optimization, Pareto approximate reference set solutions that meet utilities' performance criteria were re-evaluated under a separate set of 500 SOWs to validate robustness of solutions identified by the DU optimization and ensure representative solutions presented in results did not represent outlier solutions (i.e. satisfactory in initial DU optimization but not in re-evaluation. Fig. A2 shows the ability of solutions identified as satisfactory under both (a) the SOW set used in DU optimization, and (b) the re-evaluation SOW set to perform similarly, demonstrating the ability of DU optimization to successfully identify robust policy pathways.

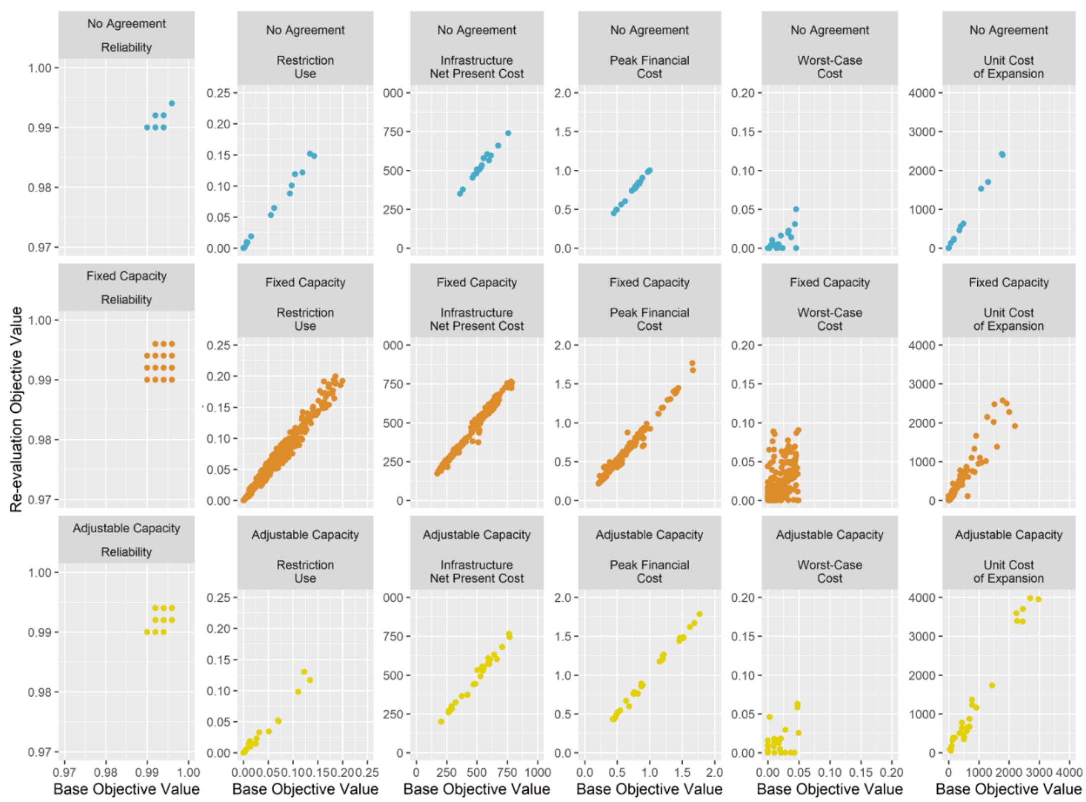

Figure A2: Comparison of regional objective performance by solutions identified by DU optimization as meeting utilities' performance criteria under base SOWs (x-axis) to performance of the same solutions under the re-evaluation SOWs set (y-axis). Colors and rows of panels separate inter-utility agreement formulations, columns separate the six regional objectives. Dots represent solutions that met performance criteria under both base and re-evaluation SOW sets.

Table A1 provides further detail on the ability of DU optimization satisfactory solutions to remain so under re-evaluation with different SOWs. Of 588 satisfactory solutions identified by

DU optimization, 434 were also satisfactory in re-evaluation. When re-evaluation criteria of reliability satisfaction was loosened by 0.04%, the number of satisfactory solutions rises to 546. In all sets, the relative percentages of satisfactory solutions found under each inter-utility agreement formulation were consistent (parentheticals in Table A1), providing confidence that DU optimization correctly identified inter-utility cooperative agreements as robust options for improving regional performance. Furthermore, our re-analysis confirmed that representative solutions, used for example analysis in Fig. 4 of the main text, satisfied utility criteria in both SOW sets.

Table A1: Summary statistics comparing the number of solutions under both (a) the initial reference set identified by DU optimization, and (b) the re-evaluation of satisfactory solutions under new SOWs that meet utility performance criteria.

	Number of solutions meeting utility performance criteria by formulation (and percent of all solutions):			
States-of-the-World	**0: No Agreement**	**1: Fixed Capacity**	**2: Adjustable Capacity**	**Total**
Reference (with Reliability performance criteria of 99%)	30 (5%)	506 (86%)	52 (9%)	588 (100%)
Re-evaluation (with Reliability performance criteria of 99%)	19 (4%)	385 (89%)	30 (7%)	434 (74%)
Re-evaluation (with Reliability performance criteria of 98.6%)	26 (5%)	473 (86%)	47 (9%)	546 (93%)