AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2013WR015126

Key Points:
- Adaptive measures increase supply reliability but also add financial risk
- Financial mitigation helps to achieve reliability and financial objectives
- Index insurance can reduce the cost of mitigation when used with self-insurance

Supporting Information:
- Readme
- Figure S1

Correspondence to:
H. B. Zeff,
zeff@email.unc.edu

Citation:
Zeff, H. B., J. R. Kasprzyk, J. D. Herman, P. M. Reed, and G. W. Characklis (2014), Navigating financial and supply reliability tradeoffs in regional drought management portfolios, *Water Resour. Res.*, *50*, doi:10.1002/2013WR015126.

Received 2 DEC 2013
Accepted 27 APR 2014
Accepted article online 2 MAY 2014

Navigating financial and supply reliability tradeoffs in regional drought management portfolios

Harrison B. Zeff[1], Joseph R. Kasprzyk[2], Jonathan D. Herman[3], Patrick M. Reed[3], and Gregory W. Characklis[1]

[1]Department of Environmental Sciences and Engineering, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA, [2]Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, Colorado, USA, [3]Department of Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA

Abstract Rising development costs and growing concerns over environmental impacts have led many communities to explore more diversified water management strategies. These "portfolio"-style approaches integrate existing supply infrastructure with other options such as conservation measures or water transfers. Diversified water supply portfolios have been shown to reduce the capacity and costs required to meet demand, while also providing greater adaptability to changing hydrologic conditions. However, this additional flexibility can also cause unexpected reductions in revenue (from conservation) or increased costs (from transfers). The resulting financial instability can act as a substantial disincentive to utilities seeking to implement more innovative water management techniques. This study seeks to design portfolios that employ financial tools (e.g., contingency funds and index insurance) to reduce fluctuations in revenues and costs, allowing these strategies to achieve improved performance without sacrificing financial stability. This analysis is applied to the development of coordinated regional supply portfolios in the "Research Triangle" region of North Carolina, an area comprising four rapidly growing municipalities. The actions of each independent utility become interconnected when shared infrastructure is utilized to enable interutility transfers, requiring the evaluation of regional tradeoffs in up to five performance and financial objectives. Diversified strategies introduce significant tradeoffs between achieving reliability goals and introducing burdensome variability in annual revenues and/or costs. Financial mitigation tools can mitigate the impacts of this variability, allowing for an alternative suite of improved solutions. This analysis provides a general template for utilities seeking to navigate the tradeoffs associated with more flexible, portfolio-style management approaches.

1. Introduction

In many regions of the world, development has reached a point where water demand regularly stresses the limits of available water supply [*Gleick and Palaniappan*, 2010; *Vorosmarty et al.*, 2000]. Recent studies have advocated for managing through a wide range of options that reduce the need for the continued expansion of supply-side infrastructure [*Gleick*, 2003; *Kundzewicz et al.*, 2007; *Postel*, 2000]. To this end, work in the area of integrated water resource management has explored how adaptive techniques, such as demand management and water transfers, can be integrated with existing supply infrastructure, often leading to high-reliability strategies that reduce expected costs relative to supply-side approaches [*Lund and Israel*, 1995; *Wilchfort and Lund*, 1997; *Jenkins and Lund*, 2000; *Jaber and Mohsen*, 2001; *Zarghami*, 2010; *Rosenberg et al.*, 2008; *Padula et al.*, 2013]. Similar research has investigated the development of diversified "portfolios" of water management "assets" [*Characklis et al.*, 2006; *Kirsch et al.*, 2009; *Kasprzyk et al.*, 2009; *Kidson et al.*, 2013], with results suggesting the potential to provide greater adaptability to "nonstationary" hydrologic conditions with less supply capacity and lower expected costs. Although these more sophisticated strategies provide important tools to facilitate sustainable water use [*Gleick et al.*, 2009; *NRC*, 2012], they also result in highly variable costs and revenues for water utilities [*Leurig*, 2010]. The resulting financial instabilities have the potential to act as a substantial disincentive for utilities seeking to implement more innovative portfolio-type approaches [*Hughes and Leurig*, 2013], but mitigating these financial risks is an area that has received relatively little attention in the literature.

Historically, utility costs have been relatively predictable, with large, fixed costs driven by debt service payments on infrastructure investments (e.g., reservoirs and treatment facilities) dwarfing the marginal costs of water provision [*Beecher et al*., 1994; *Bishop and Weber*, 1996]. Utility rates have typically been set with the goal of recovering these constant costs [*Levin et al*., 2002; *ASCE*, 2013], but a more diversified supply management portfolio can disrupt this "cost recovery" model. For example, outdoor use restrictions, while an effective measure against drought, can significantly reduce water consumption, and thus revenues, leading to budget shortfalls as costs remain largely unchanged [*Leurig*, 2010]. Similarly, augmenting supply through the purchase of water transfers can lead to intermittent spikes in cost [*Caldwell and Characklis*, 2014]. These financial stressors are difficult to manage, given their uncertainty in both frequency and magnitude [*Hughes and Leurig*, 2013]. This can be especially difficult for water utilities, given their regulated status does not often afford them the flexibility to quickly raise prices (or "rates") to compensate [*Priest*, 1993]. More diversified supply portfolios have many advantages, but in order for them to reach their potential, utilities must better understand and address the tradeoffs between diversification and the consequent financial risks.

Concerns over the financial disruptions associated with the use of transfers and water use restrictions have recently led to investigations of how utilities might use tools such as pricing schemes, contingency funds, or financial instruments (e.g., index insurance) to mitigate variability in costs/revenues [*Brown and Carriquiry*, 2007; *Zeff and Characklis*, 2013]. However, integrating these tools into wider water management plans requires consideration of a number of tradeoffs between conflicting objectives which, particularly when transfers are involved, must be coordinated across multiple regional actors. Water transfers take different forms depending on the regional institutions governing water [*Getches*, 1997]. For example, transfers in the Western U.S. are largely "paper" (i.e., administrative) transactions in which rights to raw, untreated water are exchanged [*Hamilton et al*., 1989; *Michelsen and Young*, 1993; *Characklis et al*., 1999], while in the Eastern U.S., water transfers primarily occur as the sale of treated, pumped water between municipalities [*Lund*, 1988; *Getches*, 1997; *Palmer and Characklis*, 2009]. Under these conditions, transfers are constrained not only by the available supply but also by the physical capacities of treatment and conveyance infrastructure [*Reese et al*., 2001; *Caldwell and Characklis*, 2014]. These constraints cause interdependencies in which the actions of one utility can have unintended effects on others, driving the necessity for a regional analysis.

This work seeks to develop and evaluate coordinated regional portfolios across the four primary water utilities in the "Research Triangle" region of North Carolina, one of the fastest growing metropolitan regions in the United States and currently home to nearly 2 million people [*US Census*, 2010]. These utilities are attempting to meet projected water demand growth by integrating water transfers and use restrictions with existing supply capacity. Included in the portfolios is the consideration of the financial instability inherent to such strategies, as well as tools for mitigating this instability. Regional portfolios are explored through an evaluation of the tradeoffs between up to five competing operational and financial objectives, all of which were identified through consultation with water utility personnel. Although results focus on a particular region, the study's themes (e.g., rapid population growth, constrained supply, and sensitivity to cost/revenue swings) are becoming increasingly common throughout the U.S. [*Gleick et al*., 2009]. As a result, this analysis provides a template for utilities seeking to navigate the tradeoffs associated with more flexible, portfolio-style management approaches.

2. Methods

This study develops regional water management portfolios for the four primary water utilities in the Research Triangle region of North Carolina. The portfolios are designed to address tradeoffs between supply and financial risk by augmenting existing supply infrastructure with various combinations of water use restrictions and interutility transfers. Additional consideration is given to the use of financial instruments for mitigating the resulting instability in revenues/costs. When restrictions and transfers are combined in adaptive portfolios, it may not always be straightforward to determine strategies that provide an efficient mix of alternatives or appropriate levels of financial mitigation. This study builds on prior published efforts that have evaluated the effects of increasingly complex water supply strategies [*Kasprzyk et al*., 2009; *Mortazavi et al*., 2012] to consider the challenges of meeting regional demands, the severity of the financial risks associated with alternative management strategies, and the effectiveness of financial instruments designed to reduce this risk. Drawing on the constructive decision aiding approach to problem framing [*Tsoukias*, 2008; *Roy*, 2010], four water supply portfolio designs are considered, with each portfolio design representing a problem "formulation" that consider new portfolio actions available to utilities as well as objectives used for

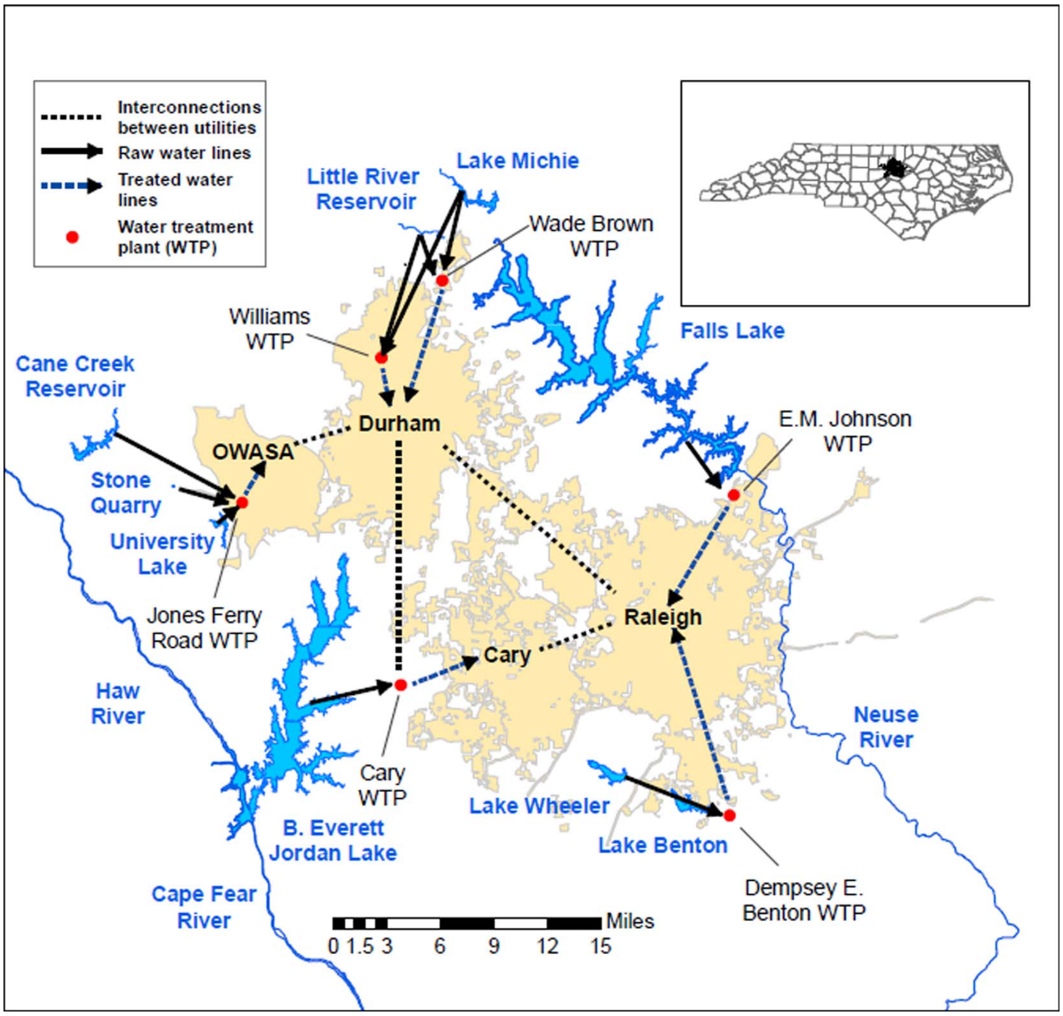

Figure 1. Water supply infrastructure in the Research Triangle region of North Carolina, including the service areas of the four water utilities (Durham, Raleigh, Cary, and OWASA), surface water reservoirs, water treatment plants, and regional treated water conveyance interconnections.

the evaluation of portfolio performance. The initial formulation serves as a base case that attempts to manage drought with only existing supply infrastructure and water use restrictions (a typical scenario in the Eastern U.S.). Through increasingly complex portfolio design, each subsequent formulation illustrates the effects of demand management, water transfers, and the mitigation of financial variability on utility objectives during drought. Formulation II adds interutility transfers and the coordinated use of shared transfer infrastructure, and Formulations III and IV introduce the use of two different types of financial tools. The analysis is designed such that lower dimensional formulations are subsets of the higher dimensional formulation, evaluating different possible frameworks for regional coordination of drought management, as suggested by *Kasprzyk et al.* [2009, 2012].

2.1. Research Triangle Case Study

2.1.1. Water Supply Infrastructure in the Research Triangle

This study focuses on building regional coordination across the four water utilities that serve the communities of Raleigh, Durham, Cary, and Chapel Hill/Carrboro (served by the Orange and Water Sewer Authority, or OWASA). The utilities receive water from nine different surface reservoirs straddling the Cape Fear and Neuse River basins (Figure 1). Individual storage capacities for each reservoir are summarized in Table 1. Most regional sources are being stressed by growing demands, but the largest regional supply, Jordan Lake, is significantly underutilized. The U.S. Army Corps of Engineers, which operates the reservoir, designates a portion of the lake for municipal water supply, which is partially allocated to several utilities. Cary, which uses Jordan Lake as its sole source of water supply, is allocated 35.5% of Jordan Lake's municipal water supply. Durham and OWASA are also granted "secondary" allocations of 10% and 5%, respectively, for use in conditions of scarcity [*NCDENR*, 2002], but neither has the infrastructure to directly access Jordan Lake (Figure 1). Raleigh currently has no allocation. A large portion of Jordan Lake's municipal water supply remains unallocated, and state authorities are investigating the potential benefits of granting utilities increased access to this storage.

Cary is also the only utility that operates a water intake on Jordan Lake, and other utilities seeking access must do so via the Cary-Apex water treatment plant (WTP), with the treated water then transferred via a network of "interconnections" (i.e., pipelines). Previous work has investigated the structure and cost implications of different transfer agreements between Triangle utilities [*Palmer and Characklis*, 2009; *Kirsch et al.*, 2013; *Caldwell and Characklis*, 2014]. The inclusion of treated water transfers complicates portfolio planning by introducing infrastructure constraints. The Cary-Apex WTP has a capacity of 56 million gallons per day (MGD), and risk-based rules for sharing the available treatment capacity among potential buyers are discussed in previous work [*Palmer and Characklis*, 2009]. Capacity sharing rules are based on a weighted strategy that assigns a greater share of unused WTP capacity to the purchasing utility with a greater "risk-of-failure" (ROF), calculated as the probability that a utility's reservoir storage will drop below 20% of capacity at any point over the subsequent 12 months using current storage, historical inflow records, and projected demands. Transfer rates are also constrained by the conveyance capacities of interconnections between the municipal systems. The Cary system has a 10 MGD interconnection to Durham's system and a 10.8 MGD interconnection with Raleigh. There is no direct connection between the Cary and OWASA systems, but Durham and OWASA have an interconnection of 7 MGD, forcing Durham and OWASA to share capacity in the Durham-Cary connection using the same rules governing the shared Cary-Apex WTP capacity. For technical reasons, OWASA must maintain a minimum output of 3 MGD from its own WTP, meaning that at least 3 MGD of water consumption must come from its own reservoirs (and not from Jordan Lake water transfers). Conveyance constraints make the consideration of output minimums at the Raleigh and Durham WTPs unnecessary.

2.1.2. The Research Triangle Water Supply Model

The Research Triangle Water Supply Model ("model") uses a Monte Carlo approach to simultaneously simulate storage levels in all nine regional reservoirs. This approach allows the model to incorporate detailed operations in the linked-reservoir system, such as infrastructure constraints and reservoir release requirements based on seasonality and downstream flow conditions. The model simulates reservoir levels on a weekly time step, returning probabilistic results driven by the use of 1000 distinct, synthetically generated streamflow records. The weekly time step minimizes the computational cost while still retaining the ability to closely approximate changes to reservoir levels during drought. Large storage volumes give utilities a cushion against short-term variability in streamflow, and a weekly time step also roughly correlates to the scale of utility decisions regarding water use restrictions and transfer purchases. The synthetic streamflow records are developed using a modified "Fractional Gaussian Noise" (mFGN) method that recreates the standard moments, as well as the autocorrelation, observed in a log-adjusted 80 year historical record [*Kirsch et al*., 2013]. Many standard autoregressive models make assumptions of complete stationarity and impose constant correlation levels between each time lag. Changes to evapotranspiration and/or infiltration, critical in determining the rainfall/runoff relationship in a watershed, may impart seasonal patterns on the autocorrelation that cannot be adequately recreated using these types of autoregressive models. The mFGN approach applies the correlation structure observed in a historic record to an uncorrelated time series, and thereby more effectively reproduces the seasonal variation in autocorrelation required to capture streamflow dynamics, particularly under more extreme hydrologic conditions (e.g., drought). This approach also allows for the generation of multiple distinct streamflow records of any length, expanding the range of hydrologic conditions experienced by the system beyond the historic record.

Streamflow records are generated so the model can be evaluated on a weekly time step over the 13 year period from 2013 to 2025, the minimum period over which the region is expected to remain without any substantial new supply expansions.

Weekly municipal water demand is computed considering annual growth and seasonal trends. Estimated growth in average annual water consumption, driven by expected population growth, has been provided

Table 1. Storage Capacities and Demand Growth for the Four "Research Triangle" Water Utilities

Utility	Storage Sites	Total Storage	Allocation	2013 Demands	2025 Demand (Estimated)
OWASA	Cane Creek Stone Quarry University Lake	3.0 billion gallons (BG)	100%	8 million gallons per day (MGD)	9 MGD
Durham	Little River Lake Michie	6.4 BG	100%	27.5 MGD	34.9 MGD
Raleigh	Falls Lake	34.7 BG	42.4% (100% of municipal supply allocation)	57.4 MGD	76.2 MGD
Cary	Jordan Lake	45.8 BG	12.7% (39% of municipal supply allocation)	23.1 MGD	34.0 MGD

by all four utilities. Seasonal multipliers, calculated from historical demand data, are applied to average annual demand projections to replicate intraannual trends. Weekly variations from these trends are estimated using joint probability density functions (PDFs) linking demand and reservoir inflow. Joint PDFs are derived for each utility from historical data, as described in *Zeff and Characklis* [2013]. Different joint PDFs are used for irrigation (April–October) and nonirrigation (November–March) seasons.

Synthetic streamflow records, surface evaporation, and consumptive withdrawals are combined with mandatory reservoir releases and discharges from wastewater treatment plants to create a water balance allowing for the simulation of water storage levels in each of the nine surface reservoirs. Because the reservoirs are situated in a linked system, inflows into some reservoirs and streamflow measured at monitored gauges include natural flows as well as "controlled" flows coming from upstream reservoir releases and wastewater discharges. Controlled flows are removed from the historical record used in the generation of synthetic flow records to create records reflective of only natural flows [*NCDENR and Hydrologics Inc*., 2009a, 2009b]. Controlled flows from reservoirs and wastewater treatment plants are then added to synthetically generated streamflows during simulation runs based on the simulated conditions. Mandatory reservoir releases attributable to agreements with downstream users and environmental regulators are based on season and downstream flow conditions, while wastewater discharges are based on utility water use and the individual treatment plant's recovery factor, as determined from historical records (*NCDENR and Hydrologics Inc*., 2009a; *NCDENR and Hydrologics Inc*., 2009b). Storage models for Durham and OWASA have been validated against observed reservoir levels in previous work [*Palmer and Characklis*, 2009; *Caldwell and Characklis*, 2014], and Raleigh's total water supply (municipal supply allocation at Falls Lake, Lake Wheeler, and Lake Benson) was validated against model output from the OASIS model developed by Hydrologics [*NCDENR and Hydrologics Inc*., 2009a, 2009b] and used by the North Carolina Department of Environmental Resources (NCDENR) for planning purposes. Allocations to Jordan Lake, used as a supply source for Cary as well as transfer sources for Raleigh, Durham, and OWASA, are modeled based on inflow, evaporation, and consumptive withdrawals only, with each allocation taking (or losing) a proportional amount of inflow and evaporation. Reservoir releases from Jordan Lake are drawn from a separate "Water Quality" allocation that does not impact municipal supply allocations and are not modeled.

Each utility's revenue is estimated based on monthly billing data over the period 2008–2011, which contain consumption patterns by customer class (residential, commercial/industrial, indoor/outdoor, etc.) and pricing tier. Revenue losses are computed based on the difference between the potential revenues from unrestricted use and the revenues received when drought-related restrictions are employed. The utilities primarily employ increasing block fee structures, but some utilities charge different fees for irrigation, multifamily residential housing, or connections outside of the city limits. Considering all of these factors, utility revenues are determined from a weighted average of use across all pricing tiers, which changes according to seasonal water use patterns. When water use restrictions are triggered, this weighted average also changes based on the distribution of use reductions among the price tiers. Transfers are assumed, based on discussions with utilities, to have a constant volumetric price of $3000 per MG ($3.00/thousand gallons or kgal), the same price charged by Cary to their lowest tier of residential consumer. Durham also charges OWASA an additional "wheeling" fee of $500 per MG ($0.50/kgal) for water being passed through their system on its way from Cary to OWASA.

2.2. Problem Formulation

Water supply portfolios are designed to explore individual and coordinated regional supply management decisions that balance tradeoffs between utility objectives. Four distinct portfolio "formulations", each

Table 2. Model Objectives

Objective	Description	Purpose	Formulation	ε Value (%)
Reliability (f_{REL})	Probability that reservoirs storage will not drop below 20% of capacity in the worst performing 12 month period over the course of 1000 simulation over the period 2013–2025	A measure of a water supply portfolio's ability to meet water demand under drought conditions	I, II, III, and IV	0.1
Restriction frequency ($f_{RESFREQ}$)	The expected percentage of years over the course of the simulation (2013–2025) when at least 1 week of water use restrictions has been enacted	Utility managers have noted that frequent implementation of water use restrictions can be logistically difficult to implement and politically unpopular	I, II, III, and IV	5
Drought management costs (f_{DMC})	The revenue shortfalls, transfer costs, and mitigation expenses expected from a utility's water supply portfolio	To measure the expected level of financial disruption that occurs as a result of drought	I, II, III, and IV	0.25
Jordan Lake allocation (f_{JLA})	The total Jordan Lake allocation granted to all four utilities	How much of Jordan Lake should be allocated, and to whom, is an important policy question	II, III, and IV	2
Financial risk (f_{RISK})	Total revenue shortfalls, transfer costs, and mitigation expenses which have a 1% probability of being exceeded in a single year (10 of 1000 Monte Carlo simulations)	Utilities are vulnerable to large swings in revenue and/or costs: managers have indicated annual revenue swings as low as 3% could be difficult to manage and 5–10% could be catastrophic	III and IV	0.5

adding to the drought management options available to utilities, are evaluated with a suite of up to five objectives. The purpose and explanations of the objective functions are described in Table 2. The consideration of all five objectives for each of the four utilities would constitute a 20 objective optimization problem, which is beyond the capabilities of modern Pareto-ranking-based optimization tools [*Teytaud*, 2006] as well as the cognitive limits of decision makers [*Miller*, 1956]. An effective strategy of dimensional reduction can be achieved by reformulating individual objective values into regional portfolio objectives. For each objective, the regional objective value takes the value of the worst-performing utility, guaranteeing that all utilities attain an individual objective value equal to or better than the regional objective value. For example, if the regional reliability objective is 99%, then all four utilities will have reliabilities equal to or $>$99% (higher reliability values are better). The regional objectives reduce the dimension of the multicity planning problem while guaranteeing that individual utility solutions converge toward optimally identified objectives [*Woodruff et al*., 2013]. The problem formulations, with their respective decision variables and objective functions, are summarized in Table 3.

2.2.1. Decision Variables

The decision variables in each formulation describe the operational and financial makeup of each individual utility's water management portfolio (Table 4). These decision variables are used to calculate up to five objective functions, such that:

$$\begin{aligned} \mathrm{F}(\mathrm{x}) &= (\mathrm{f}_{\mathrm{REL}}, \mathrm{f}_{\mathrm{RESFREQ}}, \mathrm{f}_{\mathrm{JLA}}, \ \mathrm{f}_{\mathrm{DMC}}, \mathrm{f}_{\mathrm{RISK}}) \\ \mathbf{x} &= (R_i, T_i, A_i, \ C_i, \ I_i), \end{aligned} \tag{1}$$

where f_{REL} = utility storage reliability; $f_{RESFREQ}$ = frequency of the implementation of water use restrictions; f_{JLA} = Jordan Lake allocation; f_{DMC} = expected costs of drought management (revenue losses, transfer costs, and mitigation expenses); f_{RISK} = financial risk (drought management costs reached in highest 1% of simulations); i = utility index (i = 1, 2, 3, 4); R = ROF conditions that trigger water use restrictions; T = ROF conditions that trigger transfer purchases; A = Jordan Lake allocation (% of available capacity); C = funds to be used in "self-insurance contingency funds" to mitigate revenue shortfalls and transfer costs ($); I = inflow conditions that trigger payouts from third party insurance contracts used to mitigate revenue shortfalls and transfer costs.

Water use restrictions are used to reduce water consumption below normal demand levels. The restrictions primarily target outdoor irrigation and commercial/industrial consumers and are implemented in stages, where larger reductions in overall consumption are expected as drought conditions worsen. Total consumption reductions during each restriction stage are assumed to be deterministic in the model and are outlined

Table 3. Problem Formulations

Formulation	Objectives	Water Supply Portfolio Options
I	f_{REL}, $f_{RESFREQ}$, f_{DMC}	Water use restrictions
II	f_{REL}, $f_{RESFREQ}$, f_{JLA}, f_{DMC}	Water use restrictions, transfers
III	f_{REL}, $f_{RESFREQ}$, f_{JLA}, f_{DMC}, f_{RISK}	Water use restrictions, transfers, contingency funds
IV	f_{REL}, $f_{RESFREQ}$, f_{JLA}, f_{DMC}, f_{RISK}	Water use restrictions, transfers, contingency funds, third-party insurance contracts

in "Water Shortage Response Plans" (WSRP) published online by each utility [*Orange Water and Sewer Authority*, 2010; *Goodwin and Cefalo*, 2010; *Westbrook et al*., 2009; *City of Raleigh*, 2010]. Water use restrictions are triggered using the ROF metric (ROF ε [0,1]), calculated as the probability that a utility's reservoir storage will drop below 20% of capacity at any point over the subsequent 12 months. The ROF metric has been used by utilities in the Research Triangle and is described in detail in *Caldwell and Characklis* [2014]. When ROF exceeds a specified threshold (e.g., 10%), water use restrictions are triggered. In order to lift a restriction stage, reservoir storage must reach a level where the ROF exceeds the trigger for that stage by 5% of total reservoir capacity to avoid potentially confusing customers by toggling back and forth between stages of conservation.

Transfers are also triggered using the ROF metric. When transfer purchases are initiated, utilities will continue to purchase transfers until storage in their own reservoirs rises to a level at which ROF exceeds the trigger threshold. Although transfers of treated water are possible from any source in the region, all transfer activity in this model originates from Jordan Lake, the only regional supply with a substantial volume of unused capacity. Transfer water is treated at Cary's plant, and moved via interconnections to the purchasing utility. Durham and OWASA currently have allocations to Jordan Lake, but Raleigh does not. The amount of Jordan Lake water used for transfer allocations is of interest both as a modeling constraint and a potential policy question to determine how future allocations could be granted.

If a single utility requests transfers, they will receive as much of their request as possible given constraints to treatment and conveyance capacities. If more than one utility requests transfers, infrastructure capacity (both Cary-Apex WTP and conveyance) is divided between the utilities in proportion to their ROF levels (i.e., high risk translates to more transfers), as described by *Palmer and Characklis* [2009]. A floor of 25% is placed on the proportion of capacity (either treatment or conveyance) that is made available to any individual utility. One benefit of the simulation approach used here is the ability to capture the dynamics involved with a number of users sharing a source with variable capacity constraints.

Lost revenue from restrictions and the increased costs arising from transfers are dependent on the length and severity of drought conditions, and the resulting financial impact in any given year can grow quite large under conditions of extreme drought. Utilities can take advantage of different options to mitigate this financial risk, including drought surcharges, contingency funds, and third-party financial insurance contracts. A comparative analysis of the effectiveness of these techniques is performed in *Zeff and Characklis* [2013]. Although surcharges were evaluated in that work, utility managers have continually expressed pessimism that surcharges of the order required to maintain financial stability during drought remain politically infeasible. Consequently, no pricing options were evaluated in this work, limiting the financial mitigation

Table 4. Model Decision Variables

Decision	Description	Formulation	Range
Water use restriction threshold	ROF Triggers the implementation of water use restrictions	I, II, III, and IV	0–100 (% ROF)
Water transfer threshold	ROF Triggers transfer requests	II, III, and IV	0–100 (% ROF)
Jordan Lake allocation	Portion of Jordan Lake storage reserved for individual utility	II, III, and IV	Current Jordan Lake allocation–100 (%)
Contingency fund annual contribution	Annual amount of money put aside by utility for "self-insurance" from revenue shortfalls and transfer costs	III and IV	0–10 (% of utility annual volumetric revenue)
Third party insurance trigger	Specific flow conditions that trigger contract payout	IV	1, 2, 3, 4, or none (stages of restrictions that trigger insurance payouts)

strategies considered to some combination of (i) self-insurance through contingency funds and (ii) third-party financial insurance contracts.

Contingency funds are a type of financial mitigation that utilities use to buffer against financial uncertainties in a variety of areas, some more quantifiable than others, often with a single "reserve" fund used for multiple purposes. In this case, utilities contribute a portion of their revenue to build up a contingency fund that can be used to supplement revenues or cover additional costs in years when restrictions or transfers occur. A utility's annual fund contributions are normalized to the utility's annual revenue from volumetric water rates, or annual volumetric revenue (AVR). The funds carry over from year-to-year, and unused funds are assumed to accumulate 5% interest annually. Constant annual fund contributions are attractive to utilities from a budget planning perspective, but it is important to note that maintaining a fund large enough to mitigate the worst-case financial impacts requires annual contributions significantly greater than the expected value of drought-related variability in costs and/or revenues. If contingency funds are not designed with extreme conditions in mind, extended droughts or a succession of dry years could draw down a fund more quickly than expected and leave the utility financially vulnerable.

An alternative form of mitigation is third-party financial insurance, in which utilities pay a third party an upfront fee (i.e., "premium") in exchange for a payout when specified (drought) conditions prevail. Insurance contracts based on streamflow indices are described in previous work [*Zeff and Characklis*, 2013] and use reservoir inflows and estimates of reservoir withdrawals to estimate reservoir storage. When storage estimates drop below the contractually specified threshold, payouts are made to the utility. These contracts are structured such that payouts are higher in years when drought conditions are worse and revenue shortfalls from restrictions are larger, effectively transferring the financial risk from the utility to a third party insurer. In exchange, the third-party charges a price for the contract equal to the expected value of the contract, plus a risk/return premium based, at least in part, on the volatility of the contract payouts [*Alaton et al*., 2002; *Cao and Wei*, 2004]. By basing contract payouts on storage "threshold" levels, the contracts are easily scalable to provide mitigation against different levels of financial risk [*Zeff and Characklis*, 2013]. Contracts can be used alone or in combination with contingency funds as "hybrid" schemes. Hybrid schemes allow utilities to insure against extreme events with third-party insurance contracts while using a contingency fund (i.e., "self-insuring") against lesser, more frequent variations in costs/revenues using a contingency fund. By removing the need to both keep funds on hand in preparation of extreme events and pay a third party to insure against smaller, more frequent financial risks, utilities can reduce the size of their contingency funds and the overall cost of third party contracts. These hybrid schemes have the potential to lower the overall costs of mitigation compared to either individual strategy without sacrificing exposure to the financial implications of diverse water supply portfolios.

2.2.2. Objective Functions

Each objective function is calculated from the results of 1000 different 13 year (2013–2025) simulations. All four problem formulations are evaluated with respect to at least three objectives, reliability (f_{REL}), restriction frequency (f_{RESFREQ}), and drought management costs (f_{DMC}). Formulation II introduces a fourth objective to evaluate regional Jordan Lake allocations (f_{JLA}), and Formulations III and IV include a fifth, measuring exposure to financial risk (f_{RISK}). All five objectives were developed in consultation with utility personnel, who also provided input on constraints for some objectives, beyond which portfolio solutions would be unlikely to be implemented. These constraints included (i) portfolio reliability over 99% and (ii) restriction frequency under 20% (enacting restrictions less frequently than 1 year in five). Although they did not identify absolute constraints on financial risk, they also identified that (iii) revenue losses/additional cost of over 10% of AVR in a single year could place an extremely large burden on the budgetary process.

The reliability objective is measured as the probability that reservoir storage will reach the "failure point" described in ROF calculations ($<$20% supply capacity). In the simulation, demand is modeled to increase over time commensurate with population growth, causing a decrease in reliability in the absence of expanded supply capacity. Therefore, a separate reliability value is calculated for each 12 month period over the course of the simulation. The reliability objective value for each utility is determined to be their least reliable year over the course of the simulation, such that:

$$\max f_{REL} = \min_j \left[\min_y \left(\sum_{i=1}^{1000} \frac{V_{i,j,y}}{1000} \right) \right], \tag{2}$$

where $V = 0$ if there was a week in a given year of a particular simulation where reservoir storage drops below 20% of capacity and 1 if not; y = year index, $y = 1, 2, 3...13$; i = simulation run index, $i = 1, 2, 3, \ldots, 1000$; j = utility index, $j = 1, 2, 3, 4$.

Utilities have also expressed a need to control the frequency with which restrictions are implemented to minimize the burden placed on consumers and avoid measures that are unpopular with the public. Restriction frequency is defined as the fraction of years that will have at least 1 week of restrictions over the course of the simulation, such that:

$$\min \quad f_{RESFREQ} = \max_j \left[\sum_{i=1}^{1000} \sum_{y=1}^{13} \frac{U_{i,j,y}}{13^{*}1000} \right], \tag{3}$$

where $U = 1$ if there was a week in a given year of a particular simulation where water use restrictions were implemented and 0 if not.

Drought management costs refer to the expected financial impact of all noninfrastructure water portfolio assets, including revenue losses from restrictions, transfer costs, contingency fund contributions, and third party insurance contract costs. Although these costs are relatively small compared to the large, fixed costs which dominate utility budgets, drought management costs are a measure of the expected financial variability resulting from drought management efforts, plus any mitigation costs. Revenue losses from restrictions and transfer costs are not counted as drought management costs if there are sufficient mitigation funds (i.e., contingency fund accumulation, insurance contract payouts) to cover the financial losses. For more equivalent comparison across utilities of different sizes, drought management costs are calculated each year as a percentage of a utility's annual volumetric revenue (AVR). Annual values are then averaged over the course of the entire 13 year simulation, such that:

$$\min f_{DMC} = \max_j \left\{ \sum_{i=1}^{1000} \sum_{y=1}^{13} \frac{AC_{i,j,y} + CC_{i,j,y} + \max\left(RL_{i,j,y} + TC_{i,j,y} - CP_{i,j,y} - CF_{i,j,y},\ 0\right)}{13 * 1000 * TR_{i,j,y}} \right\}, \tag{4}$$

where AC = annual contribution to a contingency fund ($); CC = insurance contract cost ($); RL = revenue losses from water use restrictions ($); TC = transfer costs ($); CP = insurance contract payout ($); CF = available contingency funds ($); and TR = total annual volumetric revenue ($).

Although all problem formulations include a drought management cost objective, some of the terms drop out of (4) in Formulations I–III. Formulation I does not include transfers or any form of mitigation, removing the terms *TC*, *AC*, *CC*, *CF*, and *CP*. Formulation II includes transfer costs, but the financial mitigation terms (*AC*, *CC*, *CF*, and *CP*) are unused. Formulation III adds mitigation, but only self-insurance through contingency funds, leaving out the terms *CC* and *CP*. Formulation IV includes all terms as described in (4).

Formulations II–IV include transfers between municipalities, and an additional objective, Jordan Lake allocations, is introduced to measure how much of Jordan Lake will collectively need to be allocated to utilities in support of transfers. The unallocated portion of Jordan Lake's water supply pool is of interest as state regulators must soon make a decision regarding potential increases to allocations allotted to regional municipalities. Due to this focus on the unallocated portion of Jordan Lake, an objective is created to account for the minimum Jordan Lake allocations necessary to support a given volume of transfers by summing the four individual utility's Jordan Lake allocations, such that:

$$\min f_{JLA} = \sum_{j=1}^{4} A_j / C_L, \tag{5}$$

where A = Jordan Lake allocation (MG) and C_L = the municipal water supply capacity of Jordan Lake (MG).

In Formulations III and IV, water management portfolios include financial risk mitigation in the form of contingency funds (Formulation III) and/or third party insurance contracts (Formulation IV). To quantify the effect of this mitigation on financial variability, an additional objective function is used to measure utility exposure to financial risk. Financial risk refers to the single-year drought management costs that have a 1% probability of being exceeded over a 13 year simulation period. In financial literature, this is sometimes referred to as Value-at-Risk (VaR), calculated as:

$$\min f_{\mathrm{RISK}} = \max_{\mathrm{j}}\left\{ \left(\mathrm{SYC}_{\mathrm{i}} \; : \mathrm{P}\{\mathrm{SYC}_{\mathrm{i}} > SYC\} = 0.01\right)_{\mathrm{j}} \right\}, \tag{6}$$

where SYC is a modified version of (4) that calculates the largest single-year cost over the course of an individual 13 year simulation, such that:

$$\mathrm{SYC}_{i,j} = \max_{y} \left(\frac{AC_{i,j,y} + CC_{i,j,y} + \max\left(RL_{i,j,y} + TC_{i,j,y} - CP_{i,j,y} - CF_{i,j,y} \; , \; 0\right)}{TR_{i,j,y}} \right). \tag{7}$$

2.3. Multiobjective Evolutionary Algorithms

Tradeoffs between the planning objectives identified in this work are evaluated using a multiobjective evolutionary algorithm (MOEA) that returns the Pareto-approximate (or nondominated) set of solutions. MOEAs have been applied to a variety of complex water resources engineering problems [*Nicklow et al*., 2010], with specific applications to, among others, groundwater monitoring [*Kollat and Reed*, 2006; *Wu et al*., 2005; *Reed and Minsker*, 2004], water resource system design [*Farmani et al*., 2005; *Suen and Eheart*, 2006], and hydrologic model calibration [*Tang et al*., 2006; *Efstratiadis and Koutsoyiannis*, 2010]. This study makes use of the Borg MOEA [*Hadka and Reed*, 2012, 2013; *Hadka et al*., 2013], which employs multiple operators adaptively selected based on a demonstrated probability of improvement over the course of the optimization process. As a result, the Borg algorithm is able to select the most appropriate operators for a given problem and has demonstrated superior performance on difficult optimization problems and specifically stochastic water portfolio planning [*Reed et al*., 2013]. The Borg algorithm also uses ε-dominance archiving [*Laumanns*, 2002], which allows the user to control the resolution of the solution set and provides theoretical guarantees of convergence to a diverse approximation of the Pareto approximate set [*Rudolph and Agapie*, 2000; *Laumanns*, 2002; *Reed et al*., 2013]. This ε-dominance defines precision for each objective, dividing the solution space into *n*-dimensional "blocks" (where *n* is the number of objectives) that possess at most one solution per block.

2.4. Computational Experiment

The large number (1000) of simulations in each function evaluation (FE) was important to accurately capture the extreme drought scenarios which typically dominate the planning process. The optimization process entailed 1,000,000 FE to develop a solution set for each of the four formulations. The number of function evaluations explored in this study, while rigorous, was more than would be necessary for a utility to apply our proposed framework. In an effort to ensure the Pareto-approximate sets identified solutions that adequately characterized the "true" Pareto frontier, a conservative approach was used. Additionally, the use of parallelization in this study dramatically reduced the "wall-clock time" required for each run of the Borg MOEA. It should be noted that parallel processing is becoming more prevalent even in independent utility planning processes [*Basdekas*, 2014] and that this study highlights the value of compressing significant search in relatively modest wall-clock time periods (i.e., millions of computing hours but approximately a week of actual time). Table 2 summarizes the epsilon values used to speed search and limit the solution sets to a size sufficient for practical decision making [*Kollat and Reed*, 2007]. To improve solution diversity and avoid dependence on randomness, the solution set from each formulation is the set of best Pareto approximate solutions accumulated over 50 random optimization trials (i.e., 50 seeds with 1 million FE yields 50 million FE per formulation, completed in $<$2 days). The default Borg MOEA parameters were used in this study (Appendix A). Use of the default parameters is justified, as the Borg algorithm has shown to be robust across the full parameterization space [*Hadka et al*., 2012]. This study was performed on the Texas Advanced Computing Center's (TACC) Ranger Cluster (http://www.tacc.utexas.edu). The TACC Ranger system contains 15,744 AMD Opteron Quad-Core processors (2.3 GHz), for a total of 62,976 processing cores.

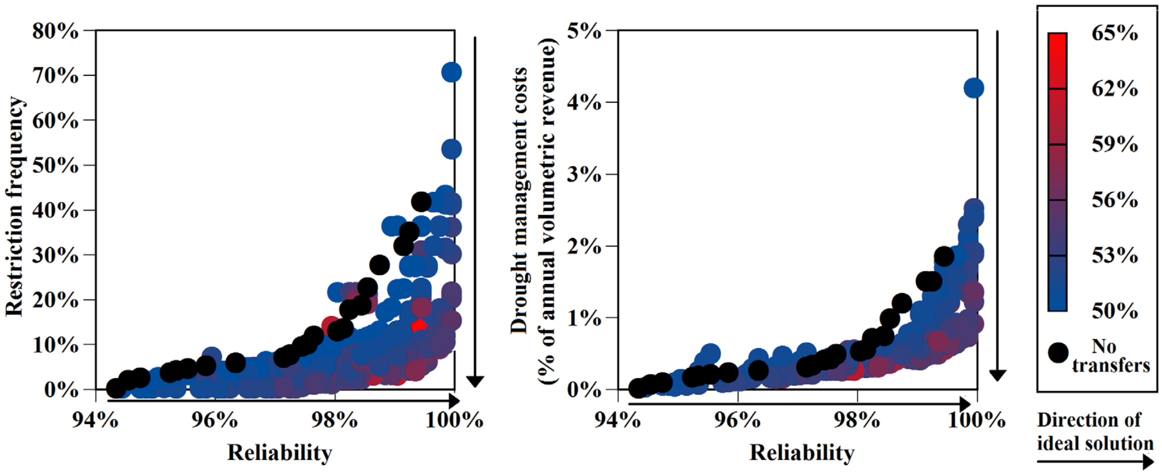

Figure 2. (a) Tradeoffs between performance objectives reliability and restriction frequency (b) as well as reliability and drought management costs for different total Jordan Lake allocations (color). Formulation I solutions are shown in black and include no Jordan Lake allocations (no transfers between utilities). Formulation II solutions are shown in color, corresponding to the total Jordan Lake allocations to all four water utilities.

The TACC resources were used for diagnosing the problems difficulty as well as visualizing the algorithms' convergence behavior. Each optimization run was parallelized to be run on 1024 processing cores simultaneously. In total, approximately 2 million computing hours were expended over the course of a week to complete the study, ensuring the best possible approximation to the Pareto-optimal solution set within the limits of current computational resources.

3. Results

3.1. Formulations I and II: Benefits of Utility Cooperation

In Formulation I, regional water supply portfolios are limited to current supply infrastructure (Table 1) and conservation via water use restrictions during drought. This serves as a "status quo" baseline, closely approximating a typical utility approach to water supply management. Figure 2 provides a comparison between the tradeoffs that result from the three objectives in Formulation I and the four objectives in Formulation II. The Pareto approximate solutions from Formulation I are shown as black points, with color illustrating the additional (fourth) objective included in Formulation II, Jordan Lake allocations. Figures 2a and 2b show the tradeoffs between reliability on the horizontal axis and, respectively, drought management costs and restriction frequency on the vertical axes. Formulation I portfolios are evaluated with respect to reliability, restriction frequency, and drought management costs (in this case, limited to revenue losses from restrictions). The sole use of water use restrictions in Formulation I yields portfolio reliabilities ranging from 94% to 99.4%, with higher reliabilities corresponding with prohibitively high restriction frequencies (Figure 2a) and correspondingly higher drought management costs (Figure 2b). The marginal increases to restriction frequency and drought management cost grow rapidly as reliability approaches the maximum value of 99.4%. In contrast, Formulation II (colored points in Figure 2) portfolios are able to exploit transfers between utilities as well as allocations to Jordan Lake to enhance reliability at substantially lower restriction frequencies and drought management costs. Total Jordan Lake allocations have a floor of 50.5% of usable capacity, consistent with the current allocations to Cary, OWASA, and Durham, and reach a maximum of 65%, beyond which treatment and conveyance infrastructure limit access to additional transfers (as illustrated with the color shading in Figure 2). The introduction of transfers allows Formulation II to achieve reliability values exceeding those in Formulation I (up to 99.9%) using restriction frequencies as low as 10% (Figure 2a) and drought management costs as low as 1%. It should be noted that in Formulation II drought management costs include both revenue losses from restrictions and transfer costs (Figure 2b). The improvements observed in Formulation II correspond with higher Jordan Lake allocation values, consistent with the increased use of transfers. The addition of transfers leads to significant improvements in reliability, cost, and restriction frequency. These improvements are made even with relatively small ($<$15%) increases to the portion of Jordan Lake allocated to municipalities, mostly granted to Raleigh. Current allocations to OWASA and Durham are large enough (5% and 10%, respectively) to make the capacity constraints of treatment and conveyance infrastructure, and not their Jordan Lake allocations, the limiting factor for transfer deliveries to each utility, even under the most severe drought.

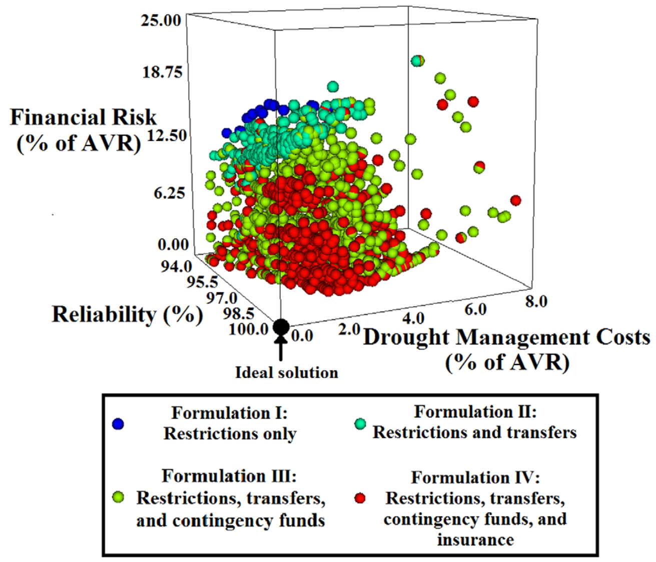

Figure 3. Three-dimensional tradeoffs between reliability, drought management costs, and financial risk for each of the four problem formulations. Note that these objectives represent regional aggregation where all four water utilities perform at least as well as the regional objective solution shown. The inclusion of financial mitigation in Formulations III and IV introduce a tradeoff between financial risk and drought management costs that allow for the design of portfolios with high-reliability, low-financial risk solutions.

3.2. Formulations III and IV: Benefits of Financial Mitigation

Although the addition of transfers in Formulation II causes significant improvements in reliability, drought management costs, and restriction frequency, many portfolios still display high-financial risk (>10% of annual VAR) when plotted in this objective space (Figure 3). In contrast to the drought management costs shown in Figure 2, which represents expected costs, financial risk shown in Figure 3 represents the variability of these costs when subject to extreme drought. The only solutions in Formulations I and II with financial risk below this benchmark correspond to low-reliability solutions. These solutions make infrequent use of water use restrictions and transfers, leading to lower financial risk but increased risk of reservoir failure. Formulations III and IV add contingency funds and third party insurance contracts, respectively, as financial tools to mitigate the financial risk shown in high-reliability solutions. Solution sets in both formulations are optimized with respect to this financial risk objective, defined as the single-year drought management costs with a 1% probability of being exceeded over a 13 year simulation period. The use of financial mitigation instruments in these formulations allows utilities to reduce financial risk without sacrificing water supply reliability. A rotating three-dimensional version of Figure 3 can be found in the supporting information to help visualize the expanded solution space. Portfolios developed in Formulation III use contingency funds to mitigate this risk. Annual contingency fund contributions increase expected drought management costs but reduce financial risk as the funds are used to offset revenue losses or transfer costs in drought years. In Figure 3, the effect of contingency funds can be seen as the Formulation III (light green) solutions occupy a space that includes low-financial risk values, even for high-reliability solutions. Formulation II (teal) solutions are contained in a portion of this space mostly restricted to high-financial risk values, with the exception of low-reliability solutions. Contingency funds used to reduce financial risk increase expected drought management costs, introducing a tradeoff between cost expectation (drought management costs) and variability (financial risk). As the drought management costs, driven by annual contingency fund contributions, increase, financial risk decreases until the contingency fund is maintained at a size large enough to compensate for any drought-related revenue losses or transfer costs. However, utility personnel have consistently pointed out that large contingency funds can be difficult to maintain either as a result of bond covenants or because unused funds are often appropriated for non-water uses, particularly by cash-strapped local governments.

In an attempt to limit the contingency fund size required to provide high reliability, low financial risk portfolios, Formulation IV expands mitigation measures to include combinations of both contingency funds and third-party insurance contracts. The third party contracts provide payouts commensurate with drought severity, such that payouts are larger in years with extreme conditions and more financial risk. When used in combination with contingency funds, thresholds for contract payouts can be set at levels that are only triggered by extreme droughts, keeping the overall contract costs low. Contingency funds can be used as mitigation in years with more moderate drought (and correspondingly lower revenue losses and/or transfer costs) that do not trigger contract payouts. The inclusion of third party insurance contracts facilitated the discovery of regional portfolios that simultaneously reduced financial risks and limited drought management costs without sacrificing reliability or increasing the frequency of usage restrictions. This is observed in Figure 3 as the Formulation IV solution set (red spheres) inhabit a space closer to the ideal solution than those in other formulations. Analyzing the succession of Formulations I–IV distinguishes the benefits and tradeoffs of water use restrictions, transfers, and financial mitigation tools.

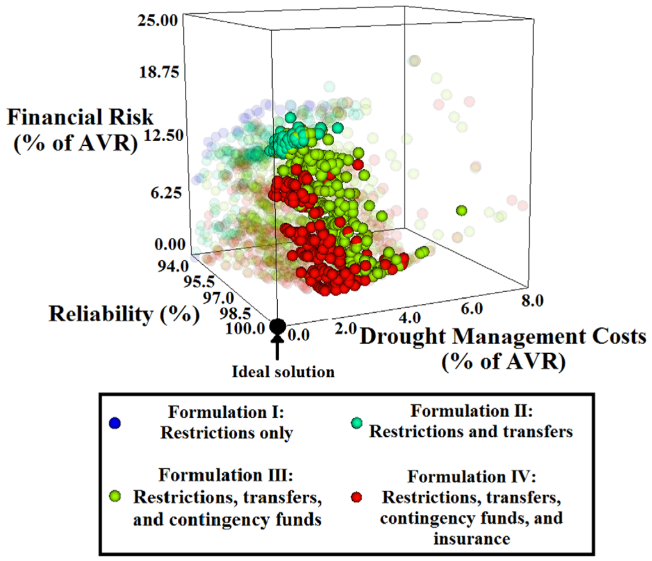

Figure 4. Three dimensional tradeoffs between reliability, drought management costs, and financial risks, with solutions that do not meet utility constraints (>99.0% reliability, <20% restriction frequency) "grayed-out". No solutions from Formulation I (blue) meet both constraints, and the solutions from Formulation II that do meet the constraints display a high level of financial risk. Opaque solutions from Formulations III and IV display a clear tradeoff between financial risk and drought management costs (solutions generally slope from top-left to bottom-right).

3.3. Constrained Solutions

Many potential portfolio solutions included in Figures 2 and 3 fail to meet stated performance requirements elicited from utility personnel. These discussions indicated portfolios that provide reliabilities of <99% would not be acceptable. The utilities also expressed the need to limit the frequency with which water use restrictions are implemented, indicating that a rate higher than once every 5 years (20% restriction frequency) would put an undesirable burden on consumers. By applying constraints to these two objective values a posteriori, the feasible solution space shrinks considerably (Figure 4). Portfolios designed in Formulation I drop out of the space completely (as indicated by the transparent solutions), meaning that utilities need to engage in water transfers if they are to develop drought management plans which meet their expressed criteria. Although some Formulation II solutions remain (teal in Figure 4), none can be achieved without financial risk exceeding levels utility managers identify as a significant deterrent when evaluating candidate portfolios. *In order to meet the utility managers' stated reliability and restriction frequency objectives while maintaining manageable levels of financial risk, portfolios need to be designed with both interutility transfers and some degree of financial risk mitigation*. Formulation III portfolios, which reduce financial risk through self-insurance with contingency funds, and Formulation IV portfolios, which also make use of third-party insurance contracts, have the ability to meet managers' design objectives, although they include some increases in expected drought management costs. However, unlike revenue losses from restrictions and transfer costs, the costs associated with contingency funds and third-party insurance are constant, making them more attractive from a planning perspective. It is important to note that Formulation IV solutions that include consideration of third-party contracts generally dominate the Formulation III contingency fund solutions (i.e., they are better in all objectives).

3.4. Individual Solutions

Four individual water management portfolios, one from each formulation, are presented to further highlight the changes in performance as interutility transfers and financial mitigation tools are used, represented by the colored lines in Figure 5 (gray solutions represent all other solutions in all four Formulations, as shown in Figure 3). The four portfolios were selected to represent different water management scenarios that provided the exact same reliabilities (99.4%). The portfolio taken from Formulation I (Case 1) only uses

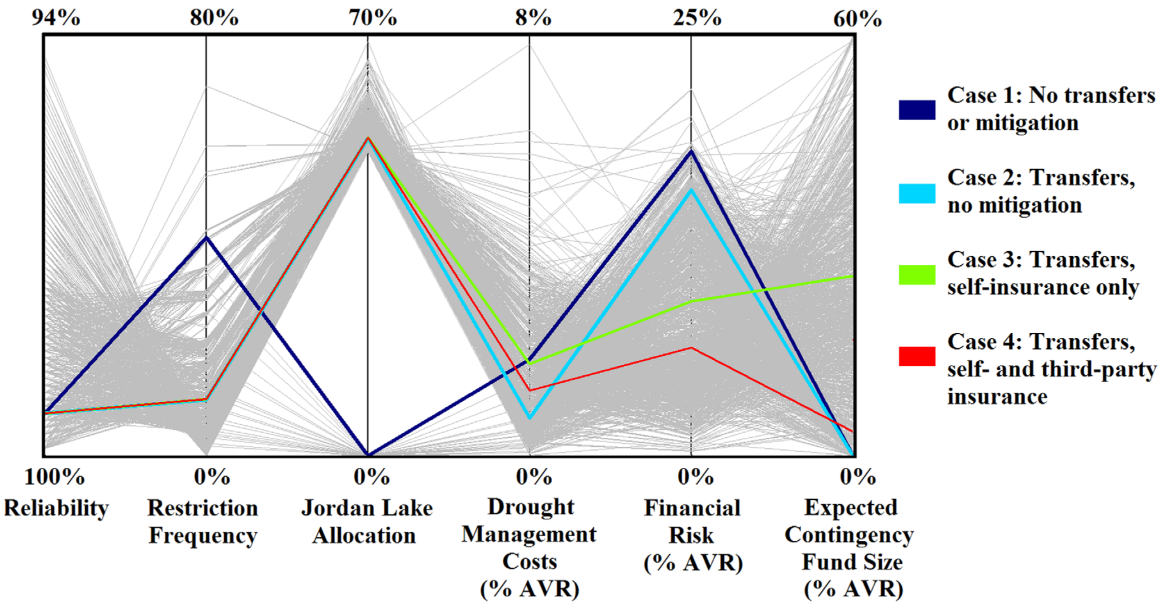

Figure 5. Parallel axis plot of the five performance objectives with expected contingency fund size included as a variable of interest for utilities. One high-reliability solution from each problem formulation is selected and shown in color, with the remaining solutions from all formulations shown in gray in the background. Axes are oriented so that the "ideal" objective values are placed along the bottom of the plot.

restrictions, and must employ restriction triggers that are much more conservative (i.e., triggered more frequently) than the other three portfolios to achieve the same reliability. In the other three cases, each portfolio is constructed with the same mix of transfers and restrictions to achieve a reliability of 99.4%. The

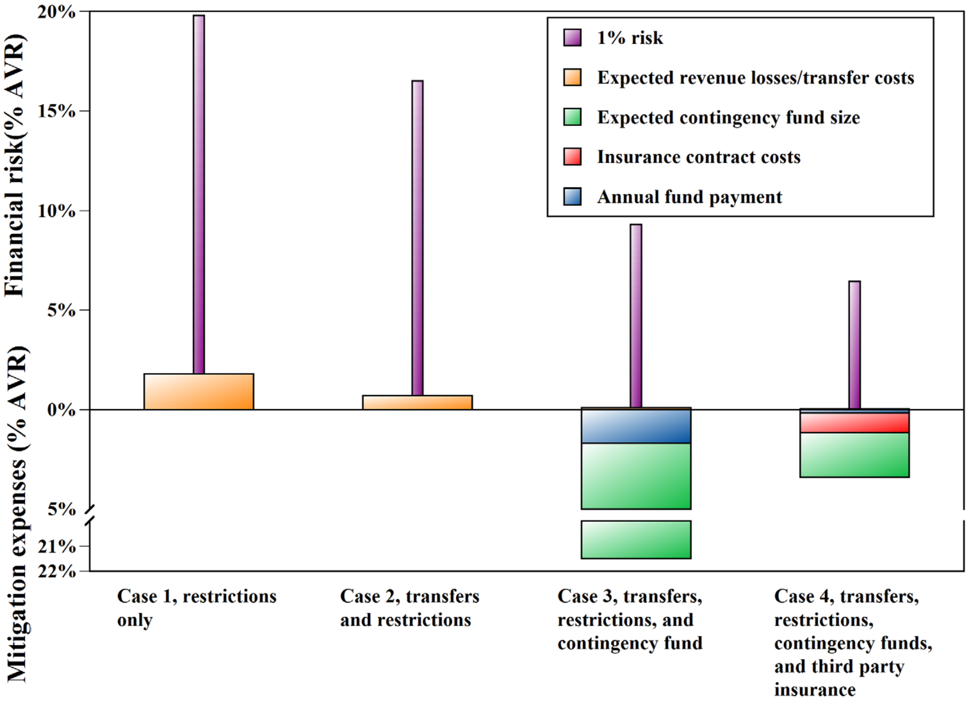

Figure 6. Bar chart showing the makeup of financial risks and mitigation costs for each of the four portfolio solutions chosen as "cases" from each formulation. Expected revenue losses/transfer cost increases are shown as the thick blocks above the *x* axis, while the constant annual mitigation costs, as well as expected contingency fund size, are shown below the *x* axis. The thin columns above the *x* axis represent the revenue losses/transfer costs that have a 1% probability of occurring in a single year over the course of the simulations. The cost of financial mitigation used in Cases 3 and 4 is larger than the expected revenue losses/transfer costs in Case 2, but the 1% risk is reduced significantly.

remaining differences between portfolios taken from Formulations 2–4 (Cases 2–4) are a result of the types of financial mitigation employed (none, contingency fund only, and contingency fund/third-party insurance combination, respectively). In the portfolio taken from Formulation I (Case 1), water use restrictions are used in 41.5% of years. In the subsequent portfolios, taken from Formulations II, III, and IV, transfers are also used, reducing the implementation of restrictions to 10.7% of years (satisfying utility constraints), while maintaining a reliability of 99.4%. In these portfolios, Raleigh is granted a small (2.4%) allocation to Jordan Lake, while the other utilities make use of their existing allocations. The portfolio taken from Formulation II (Case 2) is able to reduce expected drought management costs to 0.7% of AVR (down from 1.8% in Case 1) through the use of transfers. The utilities buying transfers charge a higher rate to their own customers than they are charged by Cary for transfers ($3.00/kgal), so the lost revenue from restrictions is higher than the cost of the same volume of transfers, assuming the utility's marginal cost of water provision is very low [*Tiger*, 2000]. When utilities can replace some water use restrictions with transfers, as they do in Case 2, drought management costs decrease. However, financial risk in both Cases 1 and 2 is high (18.0% and 15.8% of AVR, respectively).

The portfolios from Formulations III and IV (Cases 3 and 4) take advantage of financial mitigation tools to reduce this risk. While the portfolios have the same restriction frequency (10.7%) and total Jordan Lake allocations (53%) as Case 2, these tools give utilities flexibility to fine-tune their financial objectives. In Case 3, contingency funds reduce the financial risk from 15.8% to 9.2%, with only a small increase in expected drought management costs (0.7%–1.8%). For Raleigh, the utility most affected by drought management costs and financial risk, nearly all of their drought management costs come from annual contingency fund contributions (1.7% of AVR). The fund is only depleted in years when extreme drought conditions cause exceptionally large revenue losses and/or transfer cost increases, exposing the utility to a 1% probability of drought management costs reaching 9.2% of AVR. Because these extreme conditions are rare, Raleigh's contingency fund has an expected size of 21.5% of AVR ($40.5MM) at the end of the 16 year simulation and has the potential to be much larger. Utility personnel consistently emphasized the challenges of maintaining such a large contingency fund size, particularly in the face of cash-starved municipal budgets. Combining contingency funds with third-party insurance contracts (Case 4) can reduce financial risk (6.4% of AVR) while also lowering drought management costs (1.2% of AVR). For the utility facing the deepest challenges, Raleigh, their drought management costs in Case 4 are primarily a result of insurance contract costs (1.0% of AVR), with a much smaller share going toward contingency fund contributions (0.16% of AVR) (Figure 6). The utility can maintain a small contingency fund (expected to be only 3.4% of total AVR, or $6.4MM, in 2025) for protection against moderate droughts, while relying on third party insurance payouts in extreme years. This approach actually reduces drought management costs, despite the estimated 20% risk/return premium on the expected value of the insurance contract, because the reduction in contingency funds contribution significantly outweighs the additional costs of third party insurance used during extreme events.

4. Conclusion

Relative to the expansion of supply infrastructure, adaptive techniques such as demand management and water transfers have the potential to provide improved solutions to water resource management challenges. However, more thought must be given to approaches for reconciling the resulting tradeoffs between diversification of supply portfolios and financial instability. Results indicate that the utilities in the Research Triangle can develop high-reliability approaches to water management in the short term (2013–2025) without jeopardizing their financial stability by employing financial tools alongside water use restrictions and transfers. In fact, results strongly suggest that utilities cannot achieve their stated operational goals without introducing unacceptable amounts of financial risk unless those financial tools are a part of their water management strategy. Traditional methods of financial mitigation, such as drought surcharges and contingency funds, can leave utility managers politically vulnerable to concerns over large price increases or require large fund accumulations to be defended from other organizational interests. A new class of financial mitigation instruments, third-party insurance contracts, is shown to provide reductions in financial risk while lowering the expected costs of mitigation. These insights were made possible using a framework of multiple problem formulations to identify improvements and tradeoffs involved with portfolio designs of increased complexity. Moreover, the use of many-objective parallel search enabled the rapid discovery of high-quality regional water supply portfolios that were able to "encourage" cooperation among a number of regional actors. These results could be of general interest to water managers concerned about the financial implications of providing reliable supplies in the face of growing populations and dwindling opportunities for the development of traditional, supply-side solutions.

Appendix A

Table A1. Parameters Used for the Borg MOEA[a]

Parameter	Value
Initial population size	100
Tournament selection size	2
SBX rate	1.0
SBX distribution index	15.0
DE crossover rate	1.0
DE step size	0.5
PCX parents	3
PCX offspring	2
PCX eta	0.1
PCX zeta	0.1
SPX parents	3
SPX offspring	2
SPX epsilon	2
UNDX parents	3
UNDX offspring	2
UNDX eta	0.5
UNDX zeta	0.5
UM rate	1/number of DV
PM rate	1/number of DV
PM distribution index	20

[a] The following operators are included: simulated binary crossover (SBX), differential evolution (DE), parent centric mating (PCX), simplex crossover (SPX), uniform normally distributed crossover (UNDX), uniform mutation (UM), and polynomial mutation (PM).

Acknowledgments
The authors would like to thank the National Oceanic and Atmospheric Administration's Climate Program Office, Sectoral Applications Research Program (SARP), for its support of this work (Award NA11OAR4310144). Thanks also to individuals at the Durham Department of Water Management (Vicki Westbrook), Orange Water and Sewer Authority (Ed Holland, Pat Davis, and Ruth Rouse), the Town of Cary (Leila Goodwin and Syd Miller), and the City of Raleigh (Kenneth Waldroup and Ed Buchan) for their data and knowledge regarding their water supply systems, as well as Jeff Hughes, Mary Tiger, and Shadi Eskaf of the UNC Environmental Finance Center. Concepts related to the third-party index insurance products described in this work are subject to a pending patent.

References

Alaton, P., B. Djehiche, and D. Stillberger (2002), On modeling and pricing weather derivatives, *Appl. Math. Finan.*, *9*, 1–20.
ASCE (2013), *ASCE's 2013 Report Card for America's Infrastructure*, Am. Soc. of Civ. Eng., Civ. Eng. Res. Found., Washington, D. C.
Basdekas, L. (2014), Is multiobjective optimization ready for water resources practitioners? Utility's Drought Policy Investigation, *J. Water Resour. Plann. Manage.*, *140*(3), 275–276.
Beecher, J. A., P. C. Mann, Y. Hegazy, and J. D. Stanford (1994), Revenue effects of water conservation and conservation pricing: Issues and practices, *Rep. 94-18*, Natl. Regul. Res. Inst., Columbus, Ohio.
Bishop, D. B., and J. A. Weber (1996), *Impacts of Demand Reduction on Water Utilities*, Am. Water Works Assoc., Denver, Colo.
Brown, C., and M. Carriquiry (2007), Managing hydroclimatological risk to water supply with option contracts and reservoir index insurance, *Water Resour. Res.*, *43*, W11423, doi:10.1029/2007WR006093.
Caldwell, C., and G. W. Characklis (2014), Impact of contract structure and risk aversion on inter-utility water transfer agreements, *J. Water Resour. Plann. Manage.*, *140*(1), 100–111, doi:10.1061/(ASCE)WR.1943-5452.
Cao, M., and J. Wei (2004), Weather derivatives valuation and market price of weather risk, *J. Futures Markets*, *24*(11), 1065–1089.
Characklis, G., B. R. Kirsch, J. Ramsey, K. E. Dillard, and C. T. Kelley (2006), Developing portfolios of water supply transfers, *Water Resour. Res.*, *42*, W05403, doi:10.1029/2005WR004424.
Characklis, G. W., R. C. Griffin, and P. B. Bedient (1999), Improving the ability of a water market to efficiently manage drought, *Water Resour. Res.*, *35*(3), 823–831.
City of Raleigh (2010), *City of Raleigh's Water Shortage Response Plan*, NCDENR, Dep. of Water Resour., Raleigh, N. C.
Efstratiadis, A., and D. Koutsoyiannis (2010), One decade of multi-objective calibration approaches in hydrological modeling: A review, *Hydrol. Sci. J.*, *55*(1), 58–78.
Farmani, R., D. A. Savic, and G. A. Walters (2005), Evolutionary multi-objective optimization in water distribution network design, *Eng. Optim.*, *37*(2), 167–183.
Getches, D. H. (1997), *Water Law in a Nutshell*, 3rd ed., West Publ. Co., St. Paul, Minn.
Gleick, P. H. (2003), Global freshwater resources: Soft-path solutions for the 21st century, *Science*, *302*(5650), 1524–1528.
Gleick, P. H., and M. Palaniappan (2010), Peak water limits to fresh water withdrawal and use, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(25), 11,155–11,162.
Gleick, P. H., H. Cooley, M. J. Cohen, M. Morikawa, J. Morrison, and M. Palaniappan (Eds.) (2009), *The World's Water 2008–2009: The Biennial Report on Freshwater Resources*, Isl. Press, Washington, D. C.
Goodwin, L., and M. Cefalo (2010), *Town of Cary Water Shortage Response Plan*, NCDENR, Dep. of Water Resour., Raleigh, N. C.
Hadka, D., and P. M. Reed (2012), Diagnostic assessment of search controls and failure modes in many-objective evolutionary optimization, *Evol. Comput.*, *20*(3), 423–452.

Hadka, D., and P. M. Reed (2013), Borg: An auto-adaptive many-objective evolutionary computing framework, *Evol. Comput.*, *21*(2), 231–259.

Hadka, D., P. M. Reed, and T. W. Simpson (2012), Diagnostic assessment of the Borg MOEA for many-objective product family design problems, paper presented at 2012 IEEE Congress on Evolutionary Computation (CEC), Brisbane, Australia, pp. 1–10, IEEE, Piscataway, N. J.

Hadka, D., K. Madduri, and P. M. Reed (2013), Scalability analysis of the asynchronous, master-slave Borg multiobjective evolutionary algorithm, paper presented at 27th IEEE International Parallel and Distributed Processing Symposium, IEEE, Boston, Mass.

Hamilton, J. R., N. K. Whittlesey, and P. Halverson (1989), Interruptible water markets in the Pacific Northwest, *Am. J. Agric. Econ.*, *71*(1), 63–75.

Hughes, J. A., and S. Leurig (2013), *Assessing Water System Revenue Risk: Considerations for Market Analysts*, Ceres, Boston, Mass.

Israel, M., and J. R. Lund (1995), Recent California water transfers: Implications for water management, *Nat. Resour. J.*, *35*, 1–32.

Jaber, J. O., and M. S. Mohsen (2001), Evaluation of non-conventional water resources supply in Jordan, *Desalination*, *136*(1), 83–92.

Jenkins, M. W., and J. R. Lund (2000), Integrating yield and shortage management under multiple uncertainties, *J. Water Resour. Plann. Manage.*, *126*(5), 288–297.

Kasprzyk, J. R., P. M. Reed, B. R. Kirsch, and G. W. Characklis (2009), Managing population and drought risks using many-objective water portfolio planning under uncertainty, *Water Resour. Res.*, *45*, W12401, doi:10.1029/2009WR008121.

Kasprzyk, J. R., P. M. Reed, G. W. Characklis, and B. R. Kirsch (2012), Many-objective de novo water supply portfolio planning under deep uncertainty, *Environ. Modell. Software*, *34*, 87–104.

Kidson, R., B. Haddad, H. Zheng, S. Kasower, and R. Raucher (2013), Optimising reliability: Portfolio modeling of contract types for retail water providers, *Water Resour. Manage.*, *27*(9), 3209–3225.

Kirsch, B. R., G. W. Characklis, K. E. Dillard, and C. T. Kelley (2009), More efficient optimization of long-term water supply portfolios, *Water Resour. Res.*, *45*, W03414, doi:10.1029/2008WR007018.

Kirsch, B. R., G. W. Characklis, and H. B. Zeff (2013), Evaluating the impact of alternative hydro-climate scenarios on transfer agreements: A Practical improvement for generating synthetic streamflows, *J. Water Resour. Plann. Manage.*, *139*(4), 396–406.

Kollat, J. B., and P. M. Reed (2006), Comparing state-of-the-art evolutionary multi-objective algorithms for long-term groundwater monitoring design, *Adv. Water Resour.*, *29*(6), 792–807.

Kollat, J. B., and P. M. Reed (2007), A computational scaling analysis of multiobjective evolutionary algorithms in long-term groundwater monitoring applications, *Adv. Water Resour.*, *30*(3), 408–419.

Kundzewicz, Z., L. Mata, N. Arnell, P. Doll, P. Kabat, B. Jimenez, K. A. Miller, T. Oki, Z. Sen, and I. Shikomanov (2007), Freshwater resources and their management, in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. Parry et al., pp. 173–210, Cambridge Univ. Press, Cambridge, U. K.

Laumanns, M. (2002), Combining convergence and diversity in evolutionary multiobjective optimization, *Evol. Comput.*, *10*(3), 263–282.

Leurig, S. (2010), *The Ripple Effect: Water Risk in the Municipal Bond Market*, Ceres, Boston, Mass.

Levin, R. B., P. R. Epstein, T. E. Ford, W. Harrigton, E. Olson, and E. G. Reichard (2002), US drinking water challenges in the twenty-first century, *Environ. Health Perspect.*, *110*(S1), 43–52.

Lund, J. R. (1988), Metropolitan water market development: Seattle, Washington, 1887–1987, *J. Water Resour. Plann. Manage.*, *114*(2), 223–238.

Lund, J. R., and M. Israel (1995), Water transfers in water resource systems, *J. Water Resour. Plann. Manage.*, *121*(2), 193–204.

Michelsen, A. M., and R. A. Young (1993), Optioning agricultural water rights for urban water supplies during drought, *Am. J. Agric. Econ.*, *75*, 1010–1020.

Miller, G. A. (1956), The magical number seven, plus or minus two: Some limits on our capacity for processing information, *Psychol. Rev.*, *63*(2), 81–97.

Mortazavi, M., G. Kuczera, and L. Cui (2012), Multiobjective optimization of urban water resources: Moving toward more practical solutions, *Water Resour. Res.*, *48*, W03514, doi:10.1029/2011WR010866.

National Research Council (NRC) (2012), *Challenges and Opportunities in the Hydrologic Sciences*, Natl. Acad. Press, Washington, D. C.

Nicklow, J. W., et al. (2010), State of the art for genetic algorithms and beyond in water resources planning and management, *J. Water Resour. Plann. Manage.*, *136*(4), 412–432.

North Carolina Department of Environment and Natural Resources, Division of Water Resources (2002), Jordan lake water supply storage allocation round three hearing officers' report, Raleigh.

North Carolina Department of Environment and Natural Resources, Division of Water Resources and Hydrologics (NCDENR and Hydrologics Inc.) (2009a), *Modeling the Cape Fear River Basin Operations With OASIS: Addendum to the User Manual for OASIS With OLC*, Raleigh, N. C.

North Carolina Department of Environment and Natural Resources, Division of Water Resources and Hydrologics (NCDENR and Hydrologics Inc.) (2009b), *Modeling the Neuse River Basin Operations with OASIS: Addendum to the User Manual for OASIS with OLC*, Raleigh, N. C.

Orange Water and Sewer Authority (2010), *Water Shortage Response Plan*, NCDENR, Dep. of Water Resour., Raleigh, N. C.

Padula, S., J. J. Harou, L. G. Papageorgiou, L. Ji, A. Mohammad, and N. Hepworth (2013), Least economic cost regional water supply planning: Optimizing infrastructure investments and demand management for South East England's 17.6 million people, *Water Resour. Manage.*, *27*(15), 5017–5044.

Palmer, R., and G. W. Characklis (2009), Reducing the costs of meeting regional water demand through risk-based transfer agreements, *J. Environ. Manage.*, *90*(5), 1703–1714.

Postel, S. (2000), Entering an era of water scarcity: The challenges ahead, *Ecol. Appl.*, *10*(4), 941–948.

Priest, G. L. (1993), The origins of utility regulation and the theories of regulations debate, *J. Law Econ.*, *36*, 289–326.

Reed, P. M., and B. S. Minsker (2004), Striking the balance: Long-term groundwater monitoring design for conflicting objectives, *J. Water Resour. Plann. Manage.*, *130*(2), 140–149.

Reed, P. M., D. Hadka, J. D. Herman, J. R. Kasprzyk, and J. B. Kollat (2013), Evolutionary multiobjective optimization in water resources: The past, present, and future, *Adv. Water Resour.*, *51*, 438–456.

Reese, A. G., R. N. Palmer, and S. E. Nelligan-Doran (2001), Tied by water, *Civ. Eng. ASCE*, *71*(2), 50–53.

Rosenberg, D. E., R. E. Howitt, and J. R. Lund (2008), Water management with water conservation, infrastructure expansions, and source variability in Jordan, *Water Resour. Res.*, *44*, W11402, doi:10.1029/2007WR006519.

Roy, B. (2010), Robustness in operational research and decision aiding: A multi-faceted issue, *Eur. J. Oper. Res.*, *200*, 629–638.

Rudolph, G., and A. Agapie (2000), Convergence properties of some multi-objective evolutionary algorithms, *Congr. Evol. Comput.*, *2*, 1010–1016.

Suen, J. P., and J. W. Eheart (2006), Reservoir management to balance ecosystem and human needs: Incorporating the paradigm of the ecological flow regime, *Water Resour. Res.*, *42*, W03417, doi:10.1029/2005WR004314.

Tang, Y., P. M. Reed, and T. Wagener (2006), How efficient and effective are evolutionary multiobjective algorithms at hydrologic model calibration?, *Hydrol. Earth Syst. Sci.*, *10*, 289–307.

Teytaud, O. (2006), How entropy-theorems can show that on-line approximating high-dimensional pareto fronts is too hard, *Tech. Rep. CR1*, INRIA, Sacalay, France.

Tiger, M. (2000), Utility financing confusion, *NC Currents AWWA-WEA*, *40*, 37–55.

Tsoukias, A. (2008), From decision theory to decision aiding methodology, *Eur. J. Oper. Res.*, *187*, 138–161.

U.S. Bureau of the Census (2010), *Population Distribution and Change: 2000 to 2010*, U.S. Gov. Print. Off., Washington, D. C.

Vorosmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global water resources: Vulnerability from climate change and population growth, *Science*, *289*(5477), 284–288.

Westbrook, V., R. Hicks, and J. Lim (2009), *City of Durham Water Shortage Response Plan*, NCDENR, Dep. of Water Resour., Raleigh.

Wilchfort, O., and J. R. Lund (1997), Shortage management modeling for urban water supply systems, *J. Water Resour. Plann. Manage.*, *123*(4), 250–258.

Woodruff, M. J., P. M. Reed, and T. W. Simpson (2013), Many objective visual analytics: Rethinking the design of complex engineered systems, *Struct. Multidisiplinary Optim.*, *48*, 201–219.

Wu, J., C. Zheng, C. C. Chien, and L. Zheng (2005), A comparative study of Monte Carlo simple genetic algorithm and noisy genetic algorithm for cost-effective sampling network design under uncertainty, *Adv. Water Resour.*, *29*(6), 899–911.

Zarghami, M. (2010), Urban water management using fuzzy-probabilistic multi-objective programming with dynamic efficiency, *Water Resour. Manage.*, *24*(15), 4491–4504.

Zeff, H. B., and G. W. Characklis (2013), Managing water utility financial risks through third-party index insurance contracts, *Water Resour. Res.*, *49*, 4939–4951, doi:10.1002/wrcr.20364.