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Participatory Framework for Assessment and Improvement of Tools (ParFAIT): Increasing the impact and relevance of water management decision support research

Rebecca Smith [a, *], Joseph Kasprzyk [a], Lisa Dilling [b, c]

[a] Department of Civil, Environmental, and Architectural Engineering, University of Colorado, 428 UCB, Boulder, CO, 80309, USA
[b] Department of Environmental Studies, University of Colorado, 397 UCB, Boulder, CO 80309, USA
[c] Western Water Assessment, University of Colorado, CIRES, 216 UCB, Boulder, CO, 80309, USA

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A B S T R A C T

This paper proposes the Participatory Framework for Assessment and Improvement of Tools (ParFAIT) as a way to address low uptake of Water Resources Systems Optimization (WRSO) tools. ParFAIT is a transdisciplinary process conducted in five stages, two of which are participatory modeling (PM) exercises. Herein we describe the framework, introduce our candidate tool- Multiobjective Evolutionary Algorithm (MOEA)-assisted optimization, and present the results of our first PM workshop. MOEA-assisted optimization has been put forth as a planning and decision making aid for utilities facing a large number of decisions and highly uncertain futures. The PM workshop, designed to solicit input on a tool testbed, was held in February 2015 with representatives from six Front Range, Colorado, water utilities. Our results include an expanded characterization of the decision making landscape, feedback on water utility decisions and performance goals commonly employed in WRSO studies, and new questions that warrant future investigation by researchers.

1. Introduction

Since its inception during the Harvard Water Project (Maass et al., 1962), water resources systems analysis (WRSA) research has sought to bring about improved processes and outcomes in the water management industry. Many WRSA “tools”- any software or method intended to facilitate resource management activities-have achieved prominence in industry, e.g. simulation modeling (Jakeman and Letcher, 2003; Loucks et al., 1981; Loucks and van Beek, 2005) and stochastic hydrology (Linsley Jr. et al., 1975; Rajagopalan et al., 2006). However, the field still faces challenges when attempting to implement tools in real-world contexts, particularly in the area of systems optimization (hereafter referred to as WRSO- Water Resources Systems Optimization) (Brown et al., 2015; Junier and Mostert, 2014; Kok et al., 2008; Maier et al., 2014; McIntosh et al., 2011, 2005; Rogers and Fiering, 1986). WRSO involves using one or more computerized tools to automatically generate candidate solutions (combinations of actions and/or policies) to complex water management problems, especially in the context of long term planning and decision making.

Three reasons for this disjunction between WRSO research and water management practice are 1) practitioners' lack of exposure to promising research; 2) barriers to adoption within water management agencies; and 3) academia's failure to produce relevant tools. Lack of exposure is primarily due to the differences between research and water agency agendas (Borowski and Hare, 2006; Jacobs, 2002; McNie, 2007). Researchers are incentivized to publish in scientific journals that are often behind paywalls, and they write in language that may be unfamiliar to practitioners (Cvitanovic et al., 2015). Adding to this, water managers have many duties and may not have time or expertise to engage with research (Brown and Farrelly, 2009).

Even if water managers were able to regularly review WRSO literature, there are many complicated factors that impact adoption of research into water management (Dilling and Lemos, 2011). One is that water utilities are risk-averse, and unlikely to experiment (Farrelly and Brown, 2011). Another is that incorporating a new tool or method could require the backing of high level managers, necessitating a “champion” within the utility to advocate for the

* Corresponding author.
E-mail addresses: resm1653@colorado.edu (R. Smith), Joseph.Kasprzyk@colorado.edu (J. Kasprzyk), lisa.dilling@colorado.edu (L. Dilling).

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change and sustain its development (Farrelly and Brown, 2011; Taylor, 2009). Though efforts by researchers cannot overcome all barriers to adoption, addressing the lack of exposure would substantially reduce one of them. If managers are not exposed to promising research, one of the major predictors for adoption (a champion within the utility) is unlikely to arise. The result of this is that tools produced by WRSO research have little chance of being adopted by practitioners (Díez and McIntosh, 2009).

Funtowicz and Ravetz (1993) contend that in an age of great uncertainty and high stakes, improving the quality of scientific inputs to decisions requires an expansion of traditional boundaries, including meaningfully incorporating the experiences and values of previously un- or under-represented stakeholder communities. However, because of disincentives in academia for working with practitioners and across disciplinary lines, and the lack of accessibility of academic journals for many practitioners, there is often a disconnect between researchers and the target audience for their tools. According to the National Research Council (2009), "decision support strategies should be built on an understanding of decision makers' values and priorities". This calls for direct, two-way communication between researchers and practitioners, without which WRSO researchers may lack crucial understanding of how information and technology are acquired and used by water management agencies (Díez and McIntosh, 2009). While consultants could provide one route for research to be informed by and inform decision making, because they are focused on near-term applications demanded by clients, they may not often have the capacity to provide a conduit or pathway between new tools developed by academic research and practitioners themselves.

There has been a period of rapid technical development in WRSO research, but attention to research relevance and knowledge transmission warrant equal attention (Cosgrove and Loucks, 2015; Lawrence and Després, 2004; Sahota and Jeffrey, 2005; Smajgl and Ward, 2013; Thompson Klein, 2004; Voinov et al., 2014; Wen et al., 2015). In order to produce usable tools and methods, WRSO must avoid oversimplification of complex decision making environments and recognize political and social constraints (Allan, 1999; Asefa, 2015). Similarly to WRSO research, climate science has historically not seen widespread application in practice. Analysis of that field's challenges has shown that usability is the product of iterative interactions between producers and users, achieved through intentional engagement between researchers and practitioners (Dilling and Lemos, 2011), and there are groups that have been engaging in such practices for many years (e.g. NOAA's Regional Integrated Sciences and Assessments program). Other fields can benefit from the lessons learned by climate science; based on the dearth of evidence that WRSO research is influencing water management planning and decision making (Brown et al., 2015; Rogers and Fiering, 1986), it is likely that WRSO research may be lacking in this engagement and intentionality. Indeed, studies have shown that innovations in general are most successful when they result from close negotiations between developers and users (Díez and McIntosh, 2009; Smits, 2002).

Transdisciplinarity, especially as applied in participatory research, can be used to combat two of the three challenges for disseminating WRSO efforts-lack of exposure and low relevance (Lawrence and Després, 2004; Ruiz et al., 2015). Transdisciplinary research is collaboratively designed and executed by researchers and stakeholders to solve complex problems, often at the human-environment interface, incorporating methodological iteration and evolution, and with an emphasis on extended learning (Hadorn, 2008; Lawrence and Després, 2004; Thompson Klein, 2004; Wickson et al., 2006). One form of transdisciplinarity is participatory modeling (PM). The foundational precept of PM is stakeholder involvement in modeling as the major tool for decision making (Voinov and Bousquet, 2010). We posit that the definition of stakeholders for analysis of WRSO tools includes water management practitioners who are one of the target user groups. Researchers may use PM for anything from developing a decision support model, (e.g. Argent and Grayson, 2003), to creating a platform to facilitate mutual understanding between disparate stakeholders, e.g. (Eeten et al., 2002). Some examples of recent applications of PM are: participatory development of a model to solve persistent pollution problems in St. Albans Bay (Gaddis et al., 2010); participatory development of an integrated socio-ecological model to enable stakeholders in Reichraming, Austria, to understand the interactions between local policies, human behavior, and the environment (Gaube et al., 2009); and a workshop to assess water managers' perceptions of the output from a previously-developed water quality model in northeast Mexico (Robles-Morua et al., 2014). In light of the fact that government-funded research programs increasingly emphasize practicality and applicability (National Research Council, 2009), participatory research efforts, especially those aimed at evaluating existing tools, are likely to become more important for WRSO research (Voinov et al., 2016). Thus, explicitly bringing PM concepts to bear in a structured way to advance the WRSO field is an important undertaking.

The purpose of this article is to present a novel participatory framework and the first stage of our results from its application. The Participatory Framework for Assessment and Improvement of Tools (ParFAIT) is designed to obtain feedback on emerging WRSO tools while directly addressing the exposure and relevance challenges that inhibit WRSO research impacts. The core of ParFAIT is the use of two PM workshops. The first combines the expertise of researchers and practitioners to design a generic demonstration case study, or testbed, that captures broadly relatable management context. The second PM workshop assesses whether the *nature* of the information produced by the tool is seen as valuable to managers as they engage with the testbed. As described above, applications of PM have traditionally centered on pre-defined decisions or resource management projects. However, if a series of PM exercises is applied as laid out in ParFAIT, the purpose can be broadened to hone future applications of a tool, enhance its impact, and increase the relevance of WRSO research.

We developed ParFAIT shown in Fig. 1 through the contributions of a transdisciplinary team made up of water managers, engineering researchers, climate scientists, and social scientists. In our application of the framework, we explore the use of Multiobjective Evolutionary Algorithms (MOEAs) for long term water utility planning, and solicit participation from water managers through two workshops. The purpose of the first workshop was to co-design an experimental MOEA testbed, which will be used to generate representative MOEA output (further explained in Section 3). A second workshop will assess how the type of information provided by the MOEA testbed results might contribute to water managers' decision processes in the context of long term utility planning.

In Section 2 we provide a detailed description of the elements of our framework. In Section 3 we introduce the MOEA research tool we will subject to our assessment framework, as well as the water management agencies participating in our study. Sections 4 and 5 will present the results of Workshop 1 and synthesize the insights they contribute to WRSO research. Section 6 will provide concluding remarks.

2. Participatory Framework for Assessment and Improvement of Tools

Several studies that reflect on forms and functions of participatory research agree that emphasis on a process, template, or framework is an important early consideration in any PM

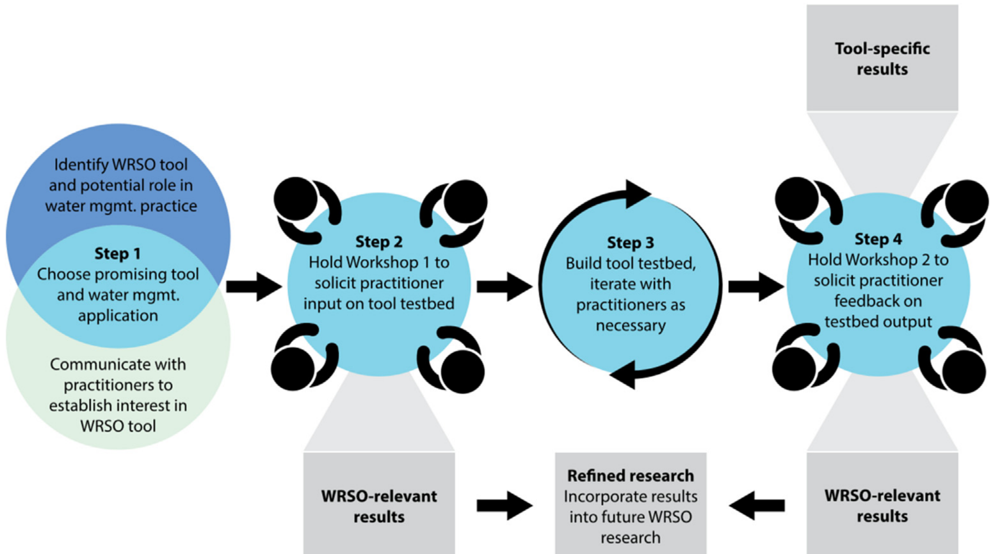

Fig. 1. Participatory Framework for Assessment and Improvement of Tools (ParFAIT).

undertaking; it improves the chances that roles of actors and purpose(s) of different phases of the project are clearly defined (Seidl, 2015). This conclusion underscores the value of defining and implementing the sequence of steps in the Participatory Framework for Assessment and Improvement of Tools (ParFAIT). Going forward, we will refer to specific steps as depicted in the diagram in Fig. 1.

Step 1 of ParFAIT is to identify a promising tool and a proposed use for the tool. An appropriate combination of tool and purpose should be informed by two factors. The first is the maturity of the tool. Has it been applied to multiple problems? Has it been systematically evaluated? The second factor is whether or not the tool has a ripe opportunity to be useful for water management practice. Tool maturity can be confirmed through knowledge of WRSO literature, but opportunity for practical application should be based on practitioners' experiences and input.

Purposeful interaction with practitioners about their needs and capabilities is the ideal way to design a ParFAIT study, and is a fundamental aspect of transdisciplinarity (Hadorn, 2008; Lang et al., 2012). Working with managers to assess the state of practice and identify their goals or interests (i.e. formulate the research goal) results in *substantive* contributions from water managers-the practitioners' involvement is necessary to ensure the quality of both the project and the knowledge it produces. Their continued involvement throughout the project also serves *normative* goals-to demonstrate the value of soliciting feedback about promising research tools as well as real-world context from intended users (Fiorino, 1990).

There are several avenues by which researchers can identify and recruit practitioners for the framework, such as exploiting existing relationships or surveying local managers who might be interested in contributing to a research project. The particular approach to identifying and recruiting practitioners is beyond the scope of this paper. Some useful resources for engaging practitioners in research are research foundations and professional societies such as the Regional Integrated Sciences and Assessments (RISAs) (http://cpo.noaa.gov/ClimateDivisions/ClimateandSocietalInteractions/RISAProgram.aspx), Climate Science Centers (https://nccwsc.usgs.gov), the Water Utility Climate Alliance (https://www.wucaonline.org), or the Water Research Foundation (http://www.waterrf.org).

The choice of tool and purpose will determine the elements of a "testbed", or generic, representative platform that serves as a vehicle for communicating a tool's capabilities to practitioners. These testbed elements are general categories of components, e.g. hydrologic data, models, and analytical tools. The rest of the framework is structured around the particular components needed to demonstrate the tool for the purpose.

During the framework's first workshop, Step 2, managers play a consultative role (Pretty, 1995); in-depth, substantive input from water managers is elicited to inform the foundation of the testbed and define the "problem" the tool will analyze (Reed and Kasprzyk, 2009). When planning this workshop, researchers and the workshop participants must decide what type of testbed to work on – the specific system of an agency (i.e., choose one city upon which to perform optimization) or create a generic testbed. When a tool is demonstrated via a case study using a specific agency's system, the modeling and forcing data are intrinsically relevant to a single utility. It may be difficult to engage a utility in experimental applications, however, because of risk aversion and data sensitivity (Farrelly and Brown, 2011), and the resulting insights may not be accepted as fundamentally valuable beyond the sponsoring agency (Brown et al., 2015). Therefore, our suggestion for achieving broad relatability and eliminating the need for any agency to commit to a new technology is to demonstrate a tool on a hypothetical, yet realistic, testbed. To produce a credible hypothetical testbed that captures important but generalized dynamics, input from practitioners is crucial (Jakeman et al., 2006).

The first workshop is intended to have a relatively low level of structure, or formalization, compared to the second workshop. Formalization refers to how researchers design the mechanisms for interaction, and therefore how open the design is to receiving unanticipated input. More formal structure includes mechanisms such as closed-ended questionnaires or pre-determined modeling exercises. In contrast, less formal mechanisms might include interviews or discussion groups where the conversations may be initiated from a specific question but allowed to generate responses in a more open, unrestricted manner (Newig et al., 2008). Since structure within a workshop acts as a filter, designing this workshop to be less structured meets the goal of casting a wide net around topics that are relevant to the construction of a testbed. We recommend open-ended questions or prompts to initialize brainstorming and discussions. Note that while limiting workshop structure to capture nuance and context for subject matter is desirable, researchers should take steps to ensure that they hear from all participants (e.g. actively facilitating discussions).

This workshop is an example of a co-learning, or social learning process wherein parties with different perspectives collaborate to develop a product but also achieve a better understanding of a problem (Mostert et al., 2008; Pahl-Wostl and Hare, 2004). Previous studies suggest that the results of co-learning experiences are valuable (McNie, 2007; Thompson Klein, 2004), and publishing the content can contribute to more relevant WRSO tools by informing a scientific agenda that is better able to reconcile supply and demand for the tools (Sarewitz and Pielke, 2007). Additionally, the results presented in this paper significantly shape the evolution of the project, and warrant full discussion apart from the results of Workshop 2.

The first workshop is designed to not only brainstorm direct responses about testbed components (e.g. modeling platform preferences and physical supply infrastructure to be modeled), but also to generate discussion and commentary on the real-world context of those components. In Step 3, researchers translate the participants' input from Step 2 into the hypothetical testbed on which the tool will be demonstrated. This enables researchers to convert the potentially diverse experiences and concerns of the managers into a coherent set of testbed components that a large group of participants will be able to connect with. The specific mechanics of the tool in question will dictate the testbed components. Regardless of tool or components, the process of building the testbed should include informal iteration with one or more practitioners to ensure proper scope, conceptual validity, and appropriate data and assumptions (Jakeman et al., 2006).

Step 4 is a second workshop with the same participants as the workshop in Step 2 (or at least significant overlap and participants with similar backgrounds to the original attendees), during which the managers again play a consultative role (Pretty, 1995). In this second PM exercise, attendees should have direct interaction with output from the testbed's representative tool output,[1] with researchers, and with each other. This type of exercise is similar to previous studies such as Gaddis et al. (2010) and Smajgl and Ward (2013) in that participants interact with results. However, in our study, the purpose is not to use the results to make a decision, evaluate the testbed itself, or give feedback on the particulars of the output (though such feedback would be welcome). Rather, the workshop's purpose is to assess the usefulness of the *nature* of the information provided by the tool and the practicality of using it. In other words, through a combination of hands-on exercises and feedback, water managers can share how the type of information provided by the tool may or may not influence their utilities' planning or decision making approaches. For this workshop, using highly structured activities results in participation and responses that are more focused than those sought in Workshop 1 (Newig et al., 2008).

The second workshop is designed to address two challenges-lack of exposure and low relevance-that have inhibited the ability of WRSO tools to impact real-world decisions. The participants are exposed to a promising tool and they interact with representative tool output that is directly relevant to their management concerns. The use of the hypothetical water supply system allows them to react candidly because they are not responding to sensitive real-world decisions. This low-pressure interaction can provide the type of information that a water manager in search of planning solutions needs in order to begin petitioning for the tool's use in her/his agency. The data collected from practitioners' activity responses and discussions will be directly applicable to future development or application of the tool in question, and also broadly useful to WRSO researchers in their future innovations.

3. Application of the Participatory Framework for Assessment and Improvement of Tools

Although ParFAIT can be applied to a number of different WRSO tools, we provide an illustrative example here on a specific tool and its proposed use in practice. WRSA researchers have paid great attention to the call for decision support tools to help water providers develop long term plans for highly uncertain future conditions (Cosgrove and Loucks, 2015; Hallegatte, 2011; Ray and Brown, 2015; Reed and Kasprzyk, 2009; Sahota and Jeffrey, 2005). A tool that has been gaining prominence in academic long term planning studies in the past decade is Multiobjective Evolutionary Algorithm (MOEA)-assisted optimization. To confirm industry opportunity and practitioner openness to the tool, we built upon relationships that the Western Water Assessment (WWA) RISA has been developing since 1999 (http://wwa.colorado.edu/), and in the design of the study we consulted closely with two Colorado water managers[2] who are champions of innovation. Thus, the literature review and practitioner consultation for Step 1 of our ParFAIT application resulted in the goal of testing MOEA-assisted optimization for long term water utility planning.

Our geographic focus is the Front Range region of Colorado, USA. In the following section, we will describe the broad planning challenges faced by water utilities in this region, recognizing that many areas, especially in the Western U.S., face similar adverse conditions. After briefly introducing our participating utilities, we will present the tool choice we made in Step 1: Multiobjective Evolutionary Algorithm (MOEA)-assisted optimization. We describe the necessary components of an MOEA testbed that informed not only how we conducted our Step 2 workshop, but also how we structured the results presented in this document.

3.1. Front Range, Colorado, background

The Front Range is an urban corridor located just east of the Rocky Mountains that includes several large and many small cities. The region is projected to experience a 70% population increase by 2050, and since at least 1900 there have more claims on local water sources than can be met in most years (Eschner et al., 1983). Colorado experiences great seasonal and interannual precipitation and streamflow variability; over half of the state's precipitation falls as snow that runs off from about mid-April to mid-July (National Climatic Data Center, 2015), and annual streamflows can vary by up to 600% between lowest flow years and highest (Lukas et al., 2014). As the impacts of climate change intensify in the coming decades, Colorado will face anywhere from a 1.4 °C to a 3.6 °C temperature increase by 2050 relative to the 1970–2000 baseline (Lukas et al., 2014). The projected changes in precipitation are less clear, though; under a medium-low emissions scenario, the state could see anywhere from −15% to +25% change in precipitation, depending on hydrologic region and time of year (Lukas et al.,

[1] “Representative tool output” means a relatable but generic example of similar output that could result from adoption of the tool by participants' agencies. The meaning of representative tool output could vary in the application of ParFAIT – some applications could focus more specifically on creating a usable tool for agencies compared to a hypothetical tool. Regardless of the application, the goal of Step 4 is to have an interactive workshop.

[2] Leon Basdekas, a consultant with Black & Veatch (who worked for Colorado Springs Utilities at the time of this study) and Laurna Kaatz of Denver Water contributed to the design of this research.

2014). Given these substantial supply and demand challenges and uncertainties, water providers on the Front Range are highly motivated to pursue careful, adaptive, and innovative planning.

The Front Range utilities participating in this project are: Aurora Water, the City of Boulder, Colorado Springs Utilities, Denver Water, the City of Fort Collins, and Northern Water. All are operating under the same regulatory, population growth, and climatic circumstances, but they are diverse in their size, infrastructure, and water rights. The number of customers served ranges from about 113,000 (Boulder) to over 1.3 million (Denver) (City of Boulder and MWH, 2009; Denver Water, 2015a). The amount of storage controlled by each utility ranges from over 1.3 billion cubic meters (bcm) (Northern) to under 0.017 bcm (Fort Collins) (AMEC Environment and Infrastructure, 2014; Northern Water, 2015), and all have varying portfolios of storage, direct flow, and groundwater rights. All six utilities use water from the Colorado River and South Platte River basins and two also have Arkansas River basin resources (Aurora and Colorado Springs). Their current broad goals include balancing sources, increasing flexibility, or developing more storage (City of Boulder et al., 2009; Denver Water, 2015b; Gertig, 2015).

3.2. MOEA-assisted optimization

This section presents our chosen WRSO tool, its research background, and the components necessary to apply it. The tool we have chosen to test is Multiobjective Evolutionary Algorithm (MOEA)-assisted optimization. Both workshops, as well as the testbed development, are structured around the attributes and purposes of the targeted tool, so it is important to explain the elements of our test case that inform our application of the framework. Later sections will present contrasts between previous approaches to MOEA applications and what we learned at our workshop.

MOEA-assisted optimization consists of four parts: the evolutionary algorithm, the problem formulation, a water supply simulation model, and visualizations of tradeoffs. The MOEA is a search technology that finds solutions to optimization problems. The problem formulation is a set of structured concepts that define the “problem” or system to be optimized. The water supply simulation model is used to evaluate the performance of potential sets of actions. The output from the tool is a set of tradeoffs that quantitatively demonstrate the relationships between (potentially conflicting) system performance objectives, which can require creative visualization approaches to enable effective analysis of the results. The following three sub-sections will describe evolutionary algorithms, problem formulations, and simulation modeling. The problem formulation and modeling sections describe two aspects of our testbed that are informed by water managers in the Step 3 workshop.

3.2.1. Multiobjective Evolutionary Algorithms

MOEAs are engines used to perform simulation-optimization: the MOEA search intelligently finds new planning or operations alternatives for a system, and those alternatives are evaluated by the algorithm based on output from a simulation model. In the context of balancing water system objectives, the output of MOEA search is a set of portfolios that together demonstrate how improvement in one objective impacts performance in another. This quantified objective tradeoff information lends itself to visual analytics (discussed in Section 3.2.4).

Since the early 1990s, MOEAs have been used in research settings to explore objective tradeoffs in a variety of water management problems, including groundwater pollution (Ritzel et al., 1994), monitoring (Cieniawski et al., 1995; Reed and Minsker, 2004), and remediation (Erickson et al., 2002; Piscopo et al., 2013); water distribution (Farmani et al., 2005; Walters et al., 1999); planning and operation for multiple reservoirs (Labadie, 2004; Smith et al., 2016; Zeff et al., 2014); watershed management (Muleta and Nicklow, 2005), and water marketing for drought management (Kasprzyk et al., 2009). Notably, prior work by some of the co-authors of this paper contributed an application of MOEA-assisted decision support using a Texas utility's complex and sophisticated multireservoir supply model (Smith et al., 2016), and Basdekas (2014) offered his utility's use of an MOEA as proof of their readiness for industry application. However, the most prominent use of MOEAs in WRSO has been in the context of research. The success of MOEAs in research settings warrants conducting a structured study to investigate their potential for broader application by practitioners.

3.2.2. Problem formulation

The problem formulation is a structured characterization of a real-world management problem, which instructs the MOEA on how to construct candidate solutions and judge the solutions' performances. MOEA problem formulations have three components: decision levers, objectives, and constraints. Fig. 2 provides a schematic of how the elements interact within an MOEA search loop.

Decision levers are the set of all options at a utility's disposal to meet its performance goals. A decision lever can take different forms. For example, a binary decision lever might have values that are either “on” or “off”, such as a decision of whether or not to build some infrastructure. A real-valued decision lever may have many different potential values, such as the capacity of a new reservoir, or the amount of new water supply to obtain. The set of enacted decisions makes up a portfolio. The levers relevant to this particular study range from conservation education campaigns to new reservoirs, and the act of cataloguing and quantifying them is a useful undertaking in itself (Girard et al., 2015; Miller and Belton, 2014). Within the MOEA problem formulation, the utility's planning goals are represented with a set of quantitative variables termed *objectives*. Defining objectives requires a utility to translate goals into quantifiable metrics that intelligently and comprehensively represent those goals. It is informative for water managers to separate objectives from *constraints*, or limits to acceptable performance. A solution satisfies a constraint if it meets a particular criterion (e.g., reliability being over a given numerical threshold). As long as the solution meets this performance, the solution is considered feasible. An objective, on the other hand, is a quantity that is minimized or maximized, and a decision maker *does* care about the relative magnitude of a solution's performance in an objective. In other words, the difference between these categories, objectives and constraints, is the difference between “we ***want*** to …” and “we ***have*** to …” achieve a particular goal. Because the problem formulation is one quarter of the MOEA-assisted optimization tool, defining the problem formulation is a critical, often iterative process through which new system insights and evolving goals are revealed (Piscopo et al., 2015; Smith et al., 2016). It is most beneficial for both the optimization results and the parties seeking information through optimization if the process involves stakeholders (Hitch, 1960; Liebman, 1976).

3.2.3. Simulation model and scenarios

To represent the system that is being optimized, a water supply simulation model is embedded into the search loop of the MOEA. Simulation models play an increasingly important role in utilities' planning and management (Labadie, 2004). Though many different approaches and platforms are used, they all seek to provide detailed representations of water collection and delivery infrastructure to help managers quantify system performance under “what if” scenarios. In the MOEA-assisted optimization process, a

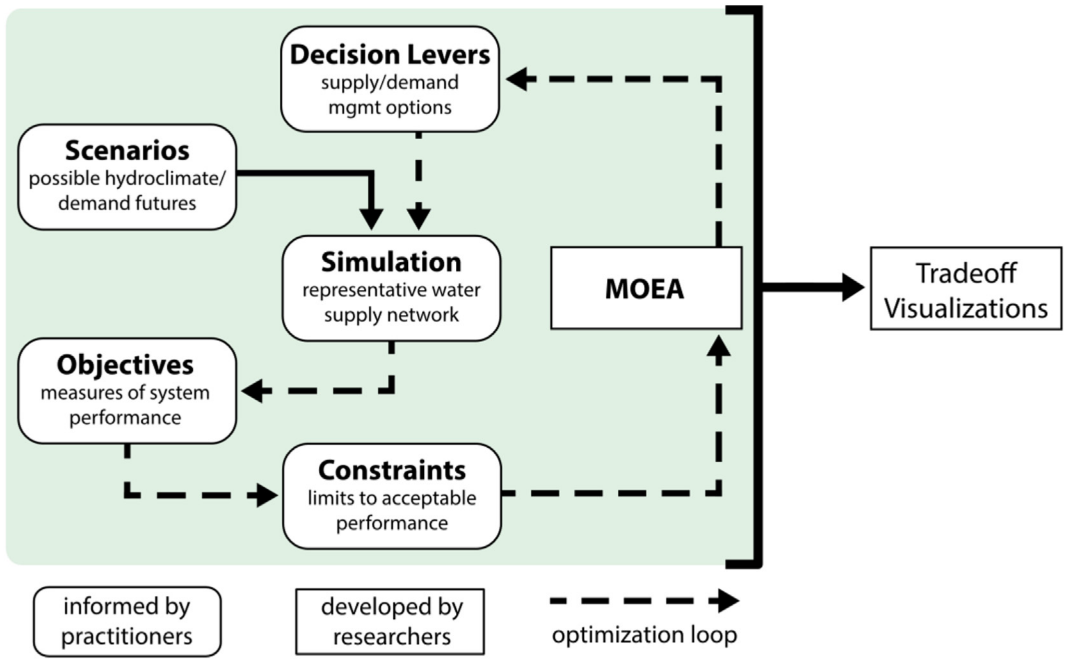

Fig. 2. MOEA optimization loop and how its components were informed by water managers. The MOEA automatically generates combinations of decision levers which are fed to a simulation model. The simulation runs in one or more supply and demand scenarios, and outputs values that are translated into objectives. The MOEA evaluates the portfolios of decisions and recombines "traits" of high-performing portfolios to produce new generations of portfolios.

solution from the MOEA represents a particular operations and/or infrastructure scheme, fully defined by values of decision levers. This solution is loaded into the simulation model, which simulates multiple time steps until the end of the time horizon. At the end of simulation, the model returns values to the algorithm that describe how the model (i.e. the water supply system) performed using that solution; the values could be timeseries of system performance or scalar quantities (e.g., average pumping rate, total volume spilled). These values are translated into objective values, and the MOEA assesses the solutions' performances based on those objectives.

With advances in modeling software and computing power, simulation models have improved in detail and fidelity to real systems, increasing water managers' trust in the simulations (Rani and Moreira, 2010). Because these models are becoming more trustworthy and ubiquitous, optimization tools that use them to search for promising solutions should become more appealing. However, system models developed within utilities, or "legacy" models, have rarely been coupled with MOEAs, and this fact suggests an investigation into the applicability and relevance of MOEA-assisted optimization is warranted.

Using simulation models in water resources planning requires hydrology and demand inputs that reflect plausible states of the world. Multiple scenarios can be useful for utilities since their systems face substantial uncertainty in future demand trajectories (Black et al., 2014; Mahmoud et al., 2011), as well as uncertainties introduced by climate variability and change (Means et al., 2010; van der Keur et al., 2010). These multiple scenarios can also contribute to MOEA studies, since their use within optimization can help identify management strategies that are robust (Hamarat et al., 2013; Herman et al., 2014; Kasprzyk et al., 2013; Smith et al., 2016).

3.2.4. Tradeoff visualizations

MOEA-assisted optimization produces performance information about multiple objectives, often with three or more objectives. In order to fully appreciate the complicated tradeoffs between different objectives, many objectives must be shown simultaneously. Previous MOEA studies have used glyph plots that can show up to seven dimensions at once (see Fig. 3) or parallel coordinates plots that can represent one objective per vertical axis, with no limit on the number of axes (see Fig. 4) (Kasprzyk et al., 2013; Smith et al., 2016; Zeff et al., 2014). These visualizations, when interactive, can greatly enhance the ability to work with the tradeoffs and enable users to apply subjective criteria to reduce the often large sets of portfolios down to a more manageable number of solutions (Kollat and Reed, 2007; Wu et al., 2016).

In accordance with components presented in Section 3, our first workshop included educating participants about MOEAs, and eliciting input on 1) specific challenges they faced in planning and

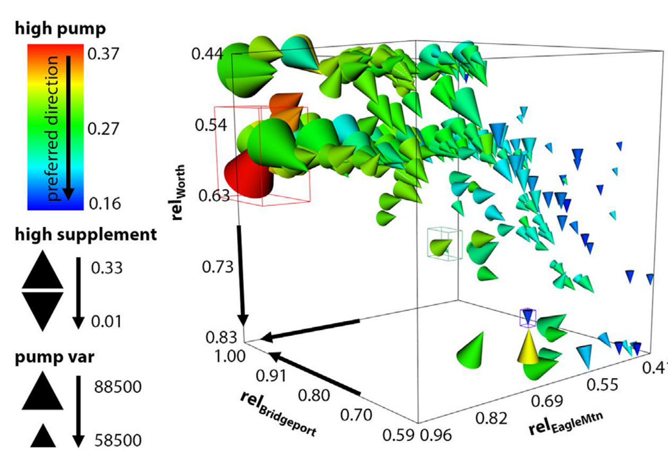

Fig. 3. Glyph plot of the results from a multi-reservoir MOEA optimization study, adapted from Smith et al. (2016). It is presented here to illustrate how to use three-dimensional plots to show MOEA results. The optimized portfolios are shown in six dimensions (for six objectives), and three solutions have colored boxes around them to call attention to different management approaches. These boxed solutions are also highlighted in Fig. 4.

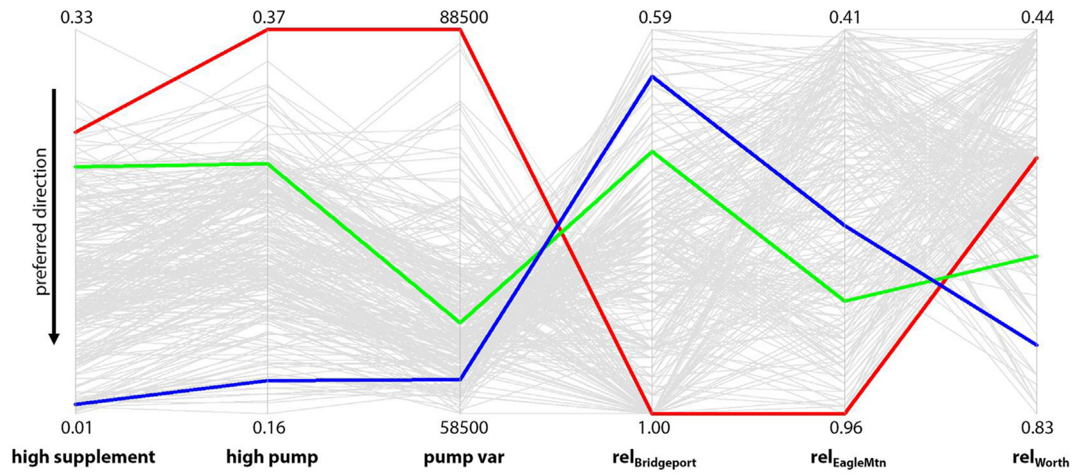

Fig. 4. Parallel plot of the results from Fig. 3 adapted from Smith et al. (2016). The results are presented again to demonstrate another visualization approach where each of six objectives is represented by a vertical axis. The full set of optimized solutions is shown in grey lines, while the highlighted solutions are representative of the different management strategies highlighted in Fig. 3.

managing water supply; 2) decisions, objectives, and constraints to inform problem formulations; 3) preferred simulation software; 4) critical infrastructure and management dynamics to include in our testbed model; and 5) supply and demand scenarios of interest. We did not consult the participants about visualization techniques because their unfamiliarity with the nature of MOEA results would prevent them from reasonably asserting a preferred technique.

4. Workshop 1 results

We focus in this paper on presenting the results from Steps 1 and 2 of the framework, including the first workshop. Workshop 1 was a participatory modeling exercise used to elicit practitioner input on the MOEA testbed, extract relevant water management context, and co-learn for a better understanding of water utility planning. We begin by briefly describing how the workshop was designed and carried out. The remainder of the section is devoted to presenting and discussing the findings from the workshop that will influence the production of our MOEA testbed as well as contribute to improved understanding of real-world water management context for future WRSO research: water management challenges, decision levers, objectives, constraints, modeling considerations, and scenarios.

Effective PM workshops involve preparatory activities (Stave, 2002). After identifying and establishing contact with our participant group with the help of WWA, we consulted with a subset of managers several months prior to the workshop to develop a workshop agenda. We also emailed an “Introduction to MOEAs” background document and short survey to all participants three weeks beforehand in order to make efficient use of workshop time.

The workshop was held on 3 February 2015 at the University of Colorado Boulder (CU) and lasted six hours. Twelve water managers from six agencies attended, along with seven researchers from different departments and organizations associated with CU. Throughout the workshop, the facilitator and researchers encouraged all water managers to share their experiences through direct conversation and individual prompts. These efforts, along with the pre-workshop survey, ensured that every utility was represented on fundamental topics (e.g. relevant decisions and objectives, scenarios of interest, etc.). Discussion developed as a result of questions from researchers to water managers as well as through interactions between water managers. Our workshop program consisted mainly of open-ended prompts to discuss testbed components, creating space in order to gather a wide range of information from participants (Newig et al., 2008). To promote discussion and brainstorming, researchers presented examples of decisions levers, objectives, and modeling considerations that were subsequently updated throughout the workshop as participants shared ideas and feedback. Please note that the content included below is summarized from across the six utilities, and was produced in a research context; it is not reflective of any one utility's position or intentions.

4.1. Water management challenges

One of the fundamental areas WRSO researchers should understand is the decision making landscape in which managers operate. Greater appreciation for the complexities of decision making will help researchers recognize the limitations of technical contributions, spur creative approaches to address problems that may not be well-characterized in previous literature, and gain insight into the ultimate usability of research (Dilling and Lemos, 2011). Therefore, we began our workshop by asking participants to discuss the management challenges they face both within and outside their organizations. Because we laid this foundation, we were better able to understand the later discussions about specific testbed elements and ask more relevant follow-up questions. Presenting this information here provides context for the content in subsequent sections of the results.

The first concept we established was that water managers face management challenges that are different depending on the time scale. The development of WRSO tools, and their demonstrative applications, should be aware of how these challenges operate across timescales and which ones might be important to the development of new tools and their testbeds. Our participants identified challenges in the following time ranges: operational, <1 year; short term, 1–5 years; mid term, 5–20 years; long term, >20 years. A complete list of the challenges brought up during the workshop can be found in Table 1, but below we will discuss some of the responses that were particularly important. Not all of these challenges can be addressed through the use of better decision support tools of course, but understanding the larger context for water management helps to identify the opportunities for innovation and advancing decision support as well as the limits that might be anticipated.

All of the utilities agreed that the biggest challenge they face is

Table 1
Full list of challenges described by water managers at Workshop 1.

Short Term (1–5 years)
Politics- lack of continuity on city councils/utility boards; Prioritizing capital development projects; Lack of reliable hydrologic forecasting; Wildfires; Floods; Budgets; Conflicting objectives- conservation vs. adaptability; De facto rate ceilings due to public fatigue; Incorporating lessons learned from crises; Drought restrictions
Mid Term (5–20 years)
Capital planning; Budgets; Population growth; Changes in water use & population density; Lack of conjunctive land/water use planning; Social values; Extremes (floods/droughts); Aging infrastructure; Increasing uncertainty (in every arena); Regulatory/governance changes; Major ecosystem shifts; Renegotiation of Upper and Lower Colorado Basin dynamics; Costs of compliance with Endangered Species Act (ESA), National Environmental Policy Act (NEPA)
Long Term (>20 years)
*Everything from mid term category but with increased uncertainty; Climate change; Opportunity hardening (for new supply); Lack of clarity on the State of Colorado's response to potential Colorado River shortages; Impact of increased reuse on return flows; Regional responsibilities between utilities; Unforeseen takeovers of neighboring utilities/changes to buildout expectations; Ecosystem management

"politics", and it was mentioned for all time periods. Politics, from the level of utility boards all the way to interstate negotiations, have major implications for their water planning (Blomquist and Schlager, 2005; Cocklin and Blunden, 1998). In the short term, water managers felt they generally had answers to looming problems, but political will could prevent them from moving quickly enough to address them. For short and mid terms, participants noted that councils and boards change, often triggering a shift in support for a planning direction or various projects, tools, and policies (especially if there is not a mandate from local citizens). Regardless of any particular administration continuity or lack thereof, the planning perspective of water utilities is 10 or 15 years further into the future than that of any board member or politician, and it can be a major hurdle to get sustained support to achieve acceptable water management outcomes. On a longer timescale, lack of certainty about how the state of Colorado will respond to potential future shortages in the Colorado River Basin is considered a major factor in these utilities' plans (they all rely heavily on water from Colorado River tributaries). Furthermore, renegotiation of Interim Guidelines for shortage sharing between Lakes Powell and Mead will begin around 2020, and the outcomes could have major implications for utilities across the western United States (U.S. Bureau of Reclamation, 2007).

Another issue that researchers had not considered, which is related to politics, is the importance of "buildout" conditions and the uncertainty around them. Every utility is planning toward a future with specific parameters related to which land will be within their service area and the expected population density and water use. Several utilities expressed some doubts about whether they could expect the future to play out as delineated, but they are prevented by sensitive political circumstances from including other possibilities in their plans. In reality, most of the participating utilities are surrounded by smaller providers and there could very well be a future where changes to development or tax codes (which currently prohibit takeovers) lead to the exploitation of economies of scale, meaning service areas would combine and increase the responsibilities of our participating utilities.

Federal regulations, local control, and social and environmental stewardship greatly impact utility planning and decision making. Managers said that their organizations "think hard" before pursuing a project that requires a lengthy and expensive NEPA or ESA permitting process with uncertain outcomes. In Colorado, utilities must also contend with the requirement to satisfy the concerns of county governments who may legally block a project that does not adequately address the impacts of the project on their communities (Stengel, 2009). These regulations hold utilities accountable for environmental and social impacts, but utilities are increasingly going beyond them in recognition that negotiating directly with community and environmental stakeholders contributes to good will and more equitable sharing of costs and benefits as growing cities pursue new water supplies and infrastructure. One recent successful example of this new dynamic is the Colorado River Cooperative Agreement between Denver Water and 17 regional stakeholders ("Colorado River Cooperative Agreement," 2012).

Finally, participants brought up the fundamentally conflicting nature of several of the expectations placed on municipal utilities. For instance, in this water-scarce region, conservation is advocated by many groups, and water utilities are generally held responsible for promoting conservation; however, conservation may result in revenue reductions, making it difficult to meet fixed costs and maintenance needs, and thus impacting the ability of water utilities to build adaptable systems.

In WRSO research, these realities are often not acknowledged due to the fact that they are not strictly engineering problems. Some of the feedback directly informs the technical work in this study, e.g. modeling a Lower Colorado River demand. Other information, e.g. buildout demand, helps us understand the motivations for certain planning scenarios over others. Such context is important, and our results strengthen recent arguments for greater integration of engineering research with social sciences to ensure a more comprehensive approach to difficult water management problems (Lund, 2015; Rosenberg and Madani, 2014).

4.2. Decision levers

Water utilities must have infrastructure and operations in place to react to potential supply and demand imbalances. In order to be prepared for challenging times, they take actions to either increase supply or reduce demand; these actions are called decision levers. There is no "right" answer or perfect decision combination to insure a utility against all possible futures. In the workshop, Front Range water providers described a complicated water management context with many independent actors and discussed using a wide range of decision levers to try to maintain or increase future security.

The discussions of decision levers were separated into two subtopics: supply and demand levers. Supply levers included any decisions a utility might make to increase the amount of water available to them overall, improve the security or quality of their existing supplies, or manage their supplies to account for various supply situations. In advance of the workshop, researchers used their previous experience, literature findings, and knowledge of the region to create the list of examples found at the top of Table 2[3].

[3] Because the participating utilities all operate under similar social, regulatory, and hydrologic conditions, there was general consensus around acceptance or rejection researchers' suggestions. This consensus, developed through discussion, is reflected in the tables below. Wherever we encountered opposing views, we explore those in the text.

Table 2
Supply levers proposed by researchers and water managers at Workshop 1.

Supply Levers Suggested by Researchers	Managers' Response
Buy agricultural rights	Agreed and expanded
Exercise dry year options/other interruptible supply options	Agreed and expanded
Buy shares from water wholesalers	Agreed
Develop new transmountain water	Agreed
Develop groundwater	Disagreed
Build/expand reservoir	Agreed and expanded
Maintain more carryover storage	Agreed
Negotiate temporary contractual storage	Agreed
Additional Levers Proposed by Water Managers	
Buy *any* senior water rights (not just agricultural)	
Lease water from agriculture	
Watershed management	
Add redundancy to facilitate maintenance	
Develop reuse- indirect or direct, potable or non-potable	
Build any type of storage- aquifer, gravel pit, on channel, off channel	
Increase efficiency- e.g. line canals, enlarge pipes	
Cloud seeding	

Table 3
Demand levers proposed by researchers and water managers at workshop 1.

Demand Levers Suggested by Researchers	Managers' Response
Non-drought conservation	Disagreed (already standard procedure)
Rate changes	Disagreed
Change triggers for various restriction levels	Agreed
Temporary rate increases	Disagreed (rephrased)
Education campaigns	Disagreed (already standard procedure)
System improvements- e.g. fix leaks	Agreed
"Behavioral water efficiency" (e.g. smiley faces on bills)	Disagreed (already standard procedure)
Additional Levers Proposed by Water Managers	
Drought surcharges	
Encourage xeriscaping/lawn replacement	
Change building codes	
Provide incentives for appliance updates	
Land use planning (politically difficult; rare and informal)	

Participants agreed that all of the suggestions provided were relevant decisions that their agencies would consider, and they provided additional ideas, listed below in Table 2. One action that researchers found particularly interesting was deliberate watershed management, which could serve both to increase the security of supply (several of the utilities obtain water from basins that were impacted by recent forest fires) as well as to promote environmental stewardship. A participant compared watersheds to other types of infrastructure and noted that they needed to be maintained just as are pipes, pumps, and dams. Decisions about maintaining infrastructure were considered very important. Thus, it would be helpful to incorporate maintenance in this and future optimization studies. A participant noted that there was a substantial difference between levers that increase yield and those that prevent failure/increase resilience, and that an exploration of which category of levers is more important to achieving good objective performance in different scenarios would be interesting. Some participants also suggested that levers could be ranked according to various criteria such as social acceptability, cost, length of time to results, and probability of successful permitting and achieving expected yield.

Both researchers and participants found it difficult to come up with more than a handful of demand levers; the "appropriate" level of municipal water use is a social, political, and environmental issue, and water utilities have a first priority of simply meeting demands, whatever they may be. Managers emphasized the fact that utilities are limited both legally and socially in the influence they have over customer behavior and future demand growth; their rates must be based on their cost of service, and they are not involved in the land use planning decisions made by separate agencies or departments. Despite these limitations, it was clear that the participating utilities take seriously their duty to promote responsible water use in a region where water is a very sensitive issue.

Managers rejected several of the demand levers suggested by researchers (see the top of Table 3). Rate changes were roundly dismissed as a lever; though utilities *do* use a tiered pricing structure to encourage low water use (Bonbright et al., 1988; OECD, 1999), our participating utilities do not implement price increases to lower demand. Even the phrasing "temporary rate increases" was deemed too broad; participants said that although pricing has substantial impact on their customers' use, a potential supply shortfall is not a socially or politically acceptable reason for increasing rates, even temporarily. These utilities only temporarily increase their water prices to recover lost revenue *after* a period of restrictions by enacting "drought surcharges". Other demand levers were already being implemented regularly and thus seen as standard operating procedure in this region: non-drought conservation, education campaigns, appliance rebates, and xeriscaping incentives.

For modeling purposes, the utilities seemed to agree that representation of a utility's influence on demand was commonly undertaken in a lumped and bracketed fashion. That is, the utilities' demand management actions are lumped together into a single percentage reduction in demand. Then, uncertainty about the impacts is incorporated by creating high and low estimates around the reduced demand, where it would be desirable to meet the higher estimate.

4.3. Objectives

Water suppliers seek to provide water responsibly and efficiently. In order to evaluate their system's ability to meet these broad goals, a utility must define quantitative ways to measure how well their system is performing, or how well proposed system modifications will perform. For MOEA-assisted optimization, these measures are called objectives.

During our objectives section, we learned that "reliability" is by far the most important objective for all utilities. In WRSO literature, reliability has a specific meaning: the frequency of a metric being in a satisfactory state, which is defined by a failure threshold. For example, a reservoir that must stay above a certain elevation for its outlets to work would be considered 99% reliable if it fell below that elevation threshold for 1 day out of 100. Researchers developed this definition to help characterize system performance that varies over time (Hashimoto et al., 1982). Since its formal definition, reliability has figured prominently in optimization research as an objective that is maximized (Herman et al., 2014; Karamouz and Nazif, 2013; Kasprzyk et al., 2013; McMahon et al., 2006; Moy et al., 1986; Paton et al., 2014).

We found that the utilities use the term "reliability" to refer to the ability of their system to satisfy customer demands. As the participants explained in the workshop, they treat the concept of reliability as a goal that must be met at a value of 100%. One participant commented that reliability was so important that it trumped the marginal costs (not necessarily monetary) of not meeting other goals. In other words, reliability may not be considered an objective where, through multiple simulations, various outcomes of the objective function are compared (e.g., 98% vs. 99%). This finding challenges some previous conceptions of optimization problem formulations that presumed that water suppliers might sacrifice reliability performance once the benefits of doing so were quantified. Additionally, each utility has a different definition for reliability: one considers their system reliable if they can meet 100% of average annual demand through a 1-in-50 drought event without going into restriction; another uses a threshold of maintaining at least 1.5 years' worth of annual demand in storage at all times; several utilities used different definitions of reliability depending on the level of drought.

Other objectives were offered over the course of the discussion (see the bottom of Table 4 for the full list): minimizing spills (and flooding, though not much detail was provided on this), minimizing pumping (one utility has a mandate to minimize greenhouse gas emissions), and minimizing uncollected water (complicated water rights schemes and spatial limitations of infrastructure make it a challenge to move water around a system to take full advantage of spring runoff). We had an interesting discussion about how realistic it is to minimize costs in the mid-to long-term; many aspects of costs, whether they are associated with new infrastructure, pumping, or other activities, are very uncertain. Though the managers confirmed that it is a critical consideration in any plan or decision, a participant noted that including cost as an objective may unjustifiably affect the results produced in multiobjective optimization. In response, another participant noted that other aspects of planning, such as population density affecting peak demand and sizing of water treatment plants or distribution pipes, were equally uncertain. This discussion helped researchers recognize that accounting for supply and demand uncertainty through simulation scenarios can partially address some types of uncertainty, but that the scenarios that affect cost may not be adequately represented in most simulation models. In light of this, care should be taken before including cost in a problem formulation. A final interesting note on the objectives discussion is that only one utility referenced resilience and vulnerability, or speed of recovery after a failure and severity of failure (Hashimoto et al., 1982). These are well-established objective definitions in optimization literature, but seem not to have been widely adopted by practitioners at our workshop. It is unclear whether this is due to a failure of knowledge transfer or if the objectives do not translate well in practice.

4.4. Constraints

In optimization studies, constraints can be used for many purposes, such as physical infrastructure limitations, limits for decision variables, or preserving mass balance restrictions, which may be especially important in classical optimization methods (Rani and Moreira, 2010). However, when an analyst sets up an MOEA to be linked to a sophisticated simulation model, physical feasibility constraints may be handled internally within the simulation model itself (Smith et al., 2016). Therefore, at our workshop, the discussion of constraints was oriented toward the managers' ideas for acceptable management outcomes.

Past studies have used performance constraints such as maintaining 98% supply reliability (Kasprzyk et al., 2009) or 99% reservoir elevation reliability (Zeff et al., 2014). Because we anticipated that there would be a fairly limited number of constraints, we opted not to provide examples and instead let the managers lead. They widely agreed on the absolute requirement to meet 100% of *indoor* demand no matter what, as well as meeting environmental flow agreements. Refer to Table 5 for the complete list of managers' suggestions.

Table 4
Objectives proposed by researchers and water managers at workshop 1.

Objectives Suggested by Researchers	Managers' Response
Minimize time spent in restriction	Agreed
Minimize costs	Agreed (with caution)
Maximize total year-end storage	Agreed
Maximize time reservoir spends above a given elevation	Agreed
Additional Objectives Proposed by Water Managers	
Meet reliability criteria (various)	
Minimize spills	
Maximize hydropower production	
Minimize pumping	
Minimize greenhouse gas emissions	
Maximize resiliency	
Minimize vulnerability	

4.5. Modeling

Utilities build simulation models in order to simulate how their systems will react to different internal and/or external circumstances. Models are useful for exploring a range of future supply and demand scenarios and for evaluating new infrastructure or operations schemes. The nature of the “what if” questions being asked will dictate modeling choices.

We discussed four issues related to modeling during the workshop: time horizon (length of simulation), timestep, modeling platform, and network features. No participants voiced a strong preference for any particular time horizon, but they were interested to compare optimization results from shorter simulations (10–25 years) with optimization over a longer period. There were also no strong feelings about using a daily versus monthly timestep, but it was pointed out that changes in snowmelt timing on the order of days or weeks could not be captured by a model that used a monthly timestep.

To inform the discussion of choosing a modeling platform, researchers began by presenting some important things to consider when choosing software to be part of an MOEA search loop: simulation time, ease of linking to the MOEA, and ease of defining levers and objectives. A complex water supply network on a sophisticated platform with advanced, intricate features such as MODSIM (Labadie and Baldo, 2000) or RiverWare (Zagona et al., 2001) will enable out-of-the-box, in-depth investigation into properties of solutions but may entail a longer simulation time that leads to compromises on scenarios and simulation horizons. A platform with minimal or no graphical user interface (GUI) and fewer pre-packaged features, like the Central Resource Allocation Model (CRAM) or StateMod (Brendecke et al., 1989; Parsons and Bennet, 2006) could mean a streamlined MOEA link and fast simulation time but potentially limit a user's ability to explore the implications of solutions in detail. Having performance information that was not originally part of the problem formulation readily available was shown to be useful in Smith et al. (2016). The attendees generally agreed that the specific platform was not important, as long as relevant model structure and levers were well represented.

This study's simulation model is a representation of a hypothetical water supply network designed to resemble the systems of participating utilities. Though it may have been possible to use a specific model of one participating utility, we deliberately chose to create a hypothetical, more generic model to increase the generalizability of our findings. Brown et al., recently asserted that the prevalence of context-specific models has impaired the water

Table 5
Constraints proposed by water managers at Workshop 1.

Constraints Proposed by Water Managers
Meet 100% of indoor demand
Meet environmental flow requirements
Do not strand assets- e.g. pursue projects that fail permitting process, acquire unusable water rights

resources systems analysis community's ability to provide fundamental insights (2015).

In order for the hypothetical network to be engaging and capture a reasonable amount of the complexity of Front Range water management dynamics, we asked workshop participants for a list of important water supply system features. We recognize that no model can fully capture the complex interactions within a built system or between different users, nor the impacts that utility decisions have on water and environmental quality. Our intention is to capture our participating agencies' current approach to long term modeling even though the systems represented are incomplete (Glynn, 2015). The structure of the network will be informed by the feedback on levers, objectives, and features, as well as take into account the real systems of the participating utilities. The feature list is located in Table 6.

4.6. Scenarios

Planning for climate change and climate variability via scenarios is an important part of the modeling process within the MOEA Testbed. Fortunately for our study, the participating utilities were very familiar with the concept of climate change scenarios through their involvement in a 2012 project called the Joint Front Range Climate Change Vulnerability Study (JFRCCVS). In that study, the utilities' feedback was used to develop a methodology and set of hydrologic traces that incorporated for downscaled GCM output (Woodbury et al., 2012). The JFRCCVS used output from CMIP3 (Meehl et al., 2007) to develop temperature and precipitation offsets with which to calculate streamflows at important points around Colorado, encompassing five temperature and precipitation scenarios applied to two different time horizons (2040 and 2070). During our study's workshop, attendees expressed that this previously developed approach to incorporating climate change was acceptable, and that it was unnecessary to update the offsets using CMIP5 output (Taylor et al., 2011). Along with climate change scenarios, participants asked that this study incorporate scenarios not necessarily related to climate change as well. They felt strongly that the historic hydrology should be included, as well as a resequencing of the record to develop more challenging droughts that still resemble what they have experienced. Of particular importance was the sequence from 2000 through 2002 which can be roughly summarized as a very dry year followed by a moderately dry year and culminating in an extremely dry 2002 that resulted in severe regional supply challenges (Pielke et al., 2005). Qualitative scenarios, such as wild fires and infrastructure failures were also considered important.

5. Synthesis of results

Typically, research in water resources decision support has relied on modeling and methods created without input from those who might use the insights or findings (Lund, 2015; Voinov and Bousquet, 2010). However, a wide range of sources suggest that it is critical to work with water management practitioners when conceptualizing and developing WRSO tools (Jacobs, 2002; Liu et al., 2008; McNie, 2007; Melillo et al., 2014; Tsoukias, 2008). To that end, ParFAIT is applied as a process for researchers and practitioners to engage directly over the design and assessment of an MOEA testbed. By using a less formal structure for Workshop 1, we were able to take advantage of the diverse knowledge and experience of attendees to efficiently hone in on ideas that will improve the relevance of the testbed and future research (Newig et al., 2008). Specifically, the managers very readily compiled a list of model features that reflect the attributes they consider important in their systems that will feed into the hypothetical supply systems designed in Step 4. Also, the managers added to and refined our potential decision levers and objectives, increasing the pertinence of our problem formulations. Workshop 1 revealed some of our faulty assumptions. For example, we overestimated the role that groundwater will play in improving future supply outlook, and underestimated the prominence of different types of reuse. We had made the assumption that non-drought conservation was a lever, but the managers roundly agreed that on the Front Range there is a culture of water conscientiousness regardless of drought status. Finally, throughout the workshop, but especially during the Challenges section, we gained substantial insight into the *context* of water management in the region. The influence of water politics and regular politics on management decisions is hard to overstate. Utilities must be respectful of geographical and sectoral sensitivities (for example, a utility may consider enacting restrictions before supply shortfalls require it if its neighbors are forced to cut back). They must also navigate changing local, regional, state, and interstate political agendas while maintaining or increasing their future water security.

During the Objectives section of the workshop, several issues arose which have not formally been addressed in multiobjective optimization research to date. First, each utility has a different set of criteria to define the achievement of 100% system-wide (i.e. not component-specific) reliability. There were two broad categories of definitions: storage-based and restrictions-based. An example of storage-based criteria is requiring a minimum of 150% of average annual unrestricted demand in storage at all times. An example of restrictions-based criteria is not exceeding a Level 1 restrictions frequency of 13 times in 350[4] years, not exceeding a Level 2 restrictions frequency of 7 times in 350 years, and so on (where increasing restriction Levels correspond to greater water use reductions). Most of our utilities use a combination of both types of reliability, but note that if both types were individually incorporated as objectives into a multiobjective problem formulation, they could conflict. The variety of reliability definitions prompts several questions:

1. How do the two reliability categories impact performance in other objectives?
2. Is one category sufficient, and if so, is one or the other more useful?
3. If a composite definition of reliability is warranted, are there any general insights to be gained about how it should be constructed?

Future optimization research that investigates these interactions may yield information that improves utilities' approaches to defining system-wide reliability.

Though the deficiencies of the concept of reliability have been noted (Brown, 2010), it appears to be alive and well in the water management industry. The participants overwhelmingly focused

[4] Water management agencies sometimes use tree ring data to extend their hydrologic records and expand the range of conditions for which they can test their modeled systems. See http://www.treeflow.info/applications.

Table 6
Important hypothetical water supply network features as suggested by water managers at Workshop 1.

Network Features Proposed by Water Managers
Complicated water exchanges
Priority system with suites of rights that vary by seniority and season
Significant reuse
Downstream requirements- e.g. competing rights, environmental flows
Multiple water sources
Return flows
Alter use of groundwater (but no new groundwater sources)
Water-type tracking (for reuse purposes)
Alternative transfer methods, e.g. dry-year options
Leased water to and from agriculture

on system-wide reliability as *the most important* planning goal, but seemed to discuss it in a way that suggests it should be represented as a constraint in the problem formulation, and not as an objective that could have varying levels of performance. One manager said that degraded performance in other objectives is always warranted in pursuit of 100% reliability. As a general statement about the priorities of water utilities, this makes sense, but if managers were presented with quantified information about how other objectives benefit from minor reduction of the value (magnitude) of their reliability objective (one that is likely to be defined very conservatively), would they consider making small sacrifices to reliability? In other words, if managers *perceive* a particular level of reliability as inviolable, can tradeoff information change their minds? This is especially relevant in the context of uncertainty in defining reliability in these simulations, since changes in the input data or assumed scenarios could lead to different values of a reliability output. It was evident from workshop discussions that, in practice, utilities do end up violating their 100% reliability standard; should the optimization problem formulation reflect the utilities' ideals and define reliability as a constraint or reveal tradeoffs by defining it as an objective?

Throughout WRSO research history, cost has been a prominent metric by which water management options are evaluated (Cui and Kuczera, 2003; Kasprzyk et al., 2009; Maass et al., 1962; Watkins and McKinney, 1997; Zhu et al., 2015); indeed, monetized costs and benefits have often been the most influential factors in making project decisions (Arnold, 1988; Maass, 1966). Some reasons to optimize using direct project costs (not necessarily monetized estimates of the costs of other impacts) are readily apparent-funds are limited, public funds must be used responsibly, etc. However, the calculation of project costs is highly sensitive to the chosen discount rate, among other assumptions (Hallegatte, 2011), and there is a long history of over-budget projects to suggest that predicting costs is a very uncertain endeavor (Liu and Frangopol, 2005). During our workshop, a participant noted that allowing the MOEA to evaluate a solution based on such an uncertain calculation may prevent ultimately preferable (to decision makers) solutions from surviving the optimization. Another participant aptly pointed out that if utilities did not consider cost important, they would build completely drought-proof systems that could meet demands in any scenarios, but they do not. In considering this exchange, we find another reason that cost is frequently used as an objective in optimization literature: unless there is an objective that penalizes solutions that require more resources than other solutions, an algorithm will prefer solutions that bring all resources to bear in order to improve, for example, reliability objectives. The larger point being made by the first participant was that cost is not the most important consideration when searching for solutions to very challenging potential supply shortfalls. For researchers, it is worthwhile to examine how including or excluding cost can impact optimization results, and possibly investigate avenues other than highly uncertain cost calculations to penalize the incorporation of expensive projects. For example, one potential alternative to cost is to give each decision lever a complexity score. This could capture the relative challenges inherent to different projects, thereby signaling a cost-like preference to the algorithm, since the algorithm would be less likely to select portfolios that would be too complex to implement.

Research applications of MOEAs have shown them to be useful for efficiently suggesting innovative solutions, promoting learning about a system via iterative problem formulation, and quantifying objective tradeoffs, (Kasprzyk et al., 2009; Paton et al., 2014; Smith et al., 2016; Zechman and Ranjithan, 2007), but we recognize that many issues that influence water utility decision making cannot be addressed by application of the MOEA-assisted decision support tool. Consider uncertainty, for example; using an MOEA method can incorporate, but not reduce, hydroclimate and demand uncertainties. Similarly, when planning under a challenging political climate, considered to be the greatest challenge for our participants, MOEAs can generate innovative solutions that may lead to more politically palatable management options, or provide quantitative tradeoff information to help justify politically challenging decisions, but they cannot shield water utilities from changing political agendas.

6. Conclusion

Rogers and Fiering (1986) noted several reasons that WRSO research tools had not played a more prominent role in water management decision making. Among them were the existence of conflicting objectives, a focus on finding a single optimal solution, the challenge of high dimensionality in water resources problems (i.e. many system variables and performance metrics), and the oversimplification of system representations. Many of these shortcomings have been addressed through technical advancements such as greater access to computing power and the advent of tools like MOEAs that incorporate a full-complexity model and generate many solutions that capture performance across conflicting objectives.

Despite these developments, however, there are still fewer examples of successful WRSO tool adoption than might be expected by researchers and practitioners familiar with the field (Asefa, 2015; Brown et al., 2015; Maier et al., 2014). We posit that there are three main challenges that account for the discrepancy: water managers' lack of exposure to promising tools; institutional and cultural adoption barriers within water management agencies; and low relevance of WRSO tools. The Participatory Framework for Assessment and Improvement of Tools (ParFAIT) contributes a formal approach, anchored by two participatory modeling workshops, through which researchers and practitioners can work together to overcome the exposure and relevance challenges. The results discussed here demonstrate that the early steps of this framework are particularly important for improving the relevance WRSO research as a whole.

By integrating practitioner experience, social science concepts and methods, and engineering innovations, ParFAIT may increase the impact of a specific tool by exposing practitioners to the tool in an in-depth but risk-free way that inspires new thinking about the tool and empowers managers to consider whether the resulting information can help them. Furthermore, their feedback may improve the tools itself. Additionally, as demonstrated in this paper, the framework provides a channel through which researchers can elicit information from practitioners about their management context and the needs of water supply agencies. Here, we report the direct feedback on our suggestions for decision levers and objectives for use with MOEAs. This information was constructive not only for building our testbed but also in reshaping our understanding of the roles that modeling and optimization can play in what are ultimately political decisions. We have also provided direct input from managers about ideas they have for future studies: comparing the effects of actions that increase supply yield (e.g. building a reservoir) to those that help prevent failures (e.g. managing watersheds to lower the risk of forest fires); methods to determine how long term planning outcomes interact with shorter term decision making; and how the introduction of subjective decision lever assessments would affect quantitative optimization.

In this study, we demonstrate the application of ParFAIT to assess MOEA-assisted optimization for long term water utility planning, but the framework is much more broadly valuable. The field of WRSA could greatly benefit from similar evaluations of other tools, e.g. agent-based modeling (Zechman Burgland, 2015) and hydroeconomic modeling (Harou et al., 2009). ParFAIT can test water resources systems *methods* (i.e. not necessarily highly-technical tools themselves), e.g. info gap (Hipel and Ben-Haim, 1999) and dynamic adaptive policy pathways (Haasnoot et al., 2013). Furthermore, other fields with emerging but under-utilized tools and methods can easily adopt this research approach.

Ultimately, we hope that the further use of this methodology can help to impact WRSO research agendas at small and large scales, thereby improving the relevance of tools intended for use by practitioners. The framework and subsequent results demonstrated here represent a new approach that can be followed to deliberately engage water managers so that the interaction and collaboration necessary for more usable decision support tools can be “built in.” The dialogue facilitated by an intentional, less formal workshop approach designed to elicit more open input and responses was critical to researchers selecting the most relevant elements of the problem formulation, which increased the chances of building a suitable and usable tool testbed. While this framework requires additional time and resources to implement, we believe in the end it results in a more effective method for shaping WRSO tools. As WRSA research increasingly seeks to improve “real-world” outcomes in water management, ParFAIT may provide a useful path to that future.

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Software and data availability

The content in this paper was not produced with any computing or software. The data is qualitative, and fully represented in the paper. We do mention several computer programs, and offer locations for more information about them below.

Borg MOEA: http://borgmoea.org/.

RiverWare: https://cadswes.colorado.edu/creative-works/riverware.

StateMod: http://cdss.state.co.us/software/Pages/StateMod.aspx.

MODSIM: http://modsim.engr.colostate.edu/.

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