DISSERTATION

TOWARDS INTEGRATED WATER RESOURCES MANAGEMENT THROUGH MODELING, OPTIMIZATION, AND STAKEHOLDER ENGAGEMENT WITH A DECISION SUPPORT GAME

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ABSTRACT

TOWARDS INTEGRATED WATER RESOURCES MANAGEMENT THROUGH MODELING, OPTIMIZATION, AND STAKEHOLDER ENGAGEMENT WITH A DECISION SUPPORT GAME

Integrated water resources management (IWRM) necessitates stakeholder engagement and integrated assessment of physical, ecological, and socioeconomic systems. Water resource literature has reflected a trend toward IWRM through increased focus on model integration, evolutionary and multiobjective algorithms, and stakeholder engagement through participatory modeling and role-playing games. A model data passing interface exemplifies integrated assessment with minimally invasive and interoperable code changes. IWRM is applied within the context of a rapidly urbanizing, semi-arid region with steadily declining agricultural production and community welfare.

Integrated modeling and assessment of the South Platte River Basin reveals lessons about management objectives, allocation institutions, and characterization of optimal solutions. High prices of water incentivize farmers to sell, while managing to sustain agriculture reduces price, saving money for cities. Freer trade can combat potential water supply vulnerabilities. Biased reservoir operations limit benefits from additional reservoir capacity. Optimized selection between a limited set of supply-side and demand-side solution strategies exposes the sensitivity of optimal outcomes to municipal raw water purchase requirements and the cost-effectiveness of xeriscaping and more efficient agricultural irrigation technology. A promising and novel, yet preliminary and proof-of-concept, decision support game is demonstrated to reconcile numerical simulation and optimization techniques with stakeholder engagement and preference-based alternative selection.

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DEDICATION

Every good gift and every perfect gift is from above, coming down from the Father of lights, with whom there is no variation or shadow due to change. James 1:17 (ESV)

I must be truthful to myself and the reader. If there is anything good in this work, it came from the one true Creator, Yahweh, my Lord and Savior Jesus the Christ to whom belongs all honor, glory, and praise. There is none better to whom to dedicate all my work and life.

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1 INTRODUCTION

Extreme weather-related events, climate change effects, aging water infrastructure, and degradation of freshwater resources present increasingly challenging dilemmas for water resource managers throughout the globe (Bouwer 2000; Foley et al. 2005; Moe and Rheingans 2006; Schwarzenbach et al. 2006, 2010; Trenberth et al. 2003). Growing populations and uncertain climate narrow the window of acceptable water system operations because of increased competition for water resources, uneven distributions of water in space and time, and encroachment on riverine-ecology landscapes due to development (Gourbesville 2008; Oki and Kanae 2006; Vörösmarty et al. 2000; Warner et al. 2013). Legal and environmental restrictions in addition to financial limitations further constrain operations and management of freshwater resources by discouraging transfers, new supply, and trans-basin development (Ansink and Ruijs 2008; Gupta and van der Zaag 2008; Lund 1993; Neuman 1998; Saleth and Dinar 2000). In semi-arid regions, potential water shortages necessitate exploration for adaptive and cost-effective water resource solutions.[1]

Traditional approaches, at least in most developed nations, have reliably delivered water supply to various water users, aiming for redundancy, resiliency, and vulnerability (Asefa et al. 2014; Hashimoto et al. 1982; Kjeldsen and Rosbjerg 2004). However, growing resource constraints, and sustainability and equitability concerns have highlighted a need for an integrated, comprehensive framework for incorporating socioeconomic factors and feedbacks in the modeling and decision-making process (Gleick 1998; Rogers et al. 2002). Although economic experiments have identified non-traditional economic values around water and its management (Ehmke and Shogren 2008; Kahneman and Smith 2002; von Neumann and Morgenstern 1944), these values are

[1] First paragraph adapted from Dozier et al. (2016)

difficult to model analytically or numerically (Charness and Haruvy 2002; Fehr and Gächter 2002; Fehr and Leibbrandt 2011; Giné and Yang 2009; Samuelson 2005). This disparity between technical (i.e., numerical or analytical modeling) approaches and stakeholder preferences, values, and actions can cause costly, engineered, technical solutions to fail politically as in the case of Two Forks Dam in the mountains of Colorado (Woltemade 1991).

The goal of this dissertation is to develop an integrative and adaptive framework for assessing water supply vulnerabilities and optimal water management solutions in rapidly urbanizing semi-arid regions commensurate with the preferences of diverse stakeholders (Figure 1). Benefits of the framework include i) integrated physical, socioeconomic, and ecological feedbacks to properly assess various stakeholder values, ii) optimization of key strategies to mitigate critical system vulnerabilities, and iii) identification of pivotal institutional or policy changes that will result in improved system performance. Specific objectives of the work are to:

1. Characterize agricultural, municipal, and industrial water demand and allocation in response to institutional change, new supply and conservation
2. Develop a platform from which to integrate across disciplinary models
3. Identify optimal mitigation strategies and institutional agreements that could reduce system vulnerabilities while enhancing opportunities for co-benefits across stakeholders
4. Develop a decision support tool to elicit stakeholder preferences and self-driven solutions

Application of the framework to the South Platte River Basin (SPRB) provides an ideal case study due to rapid urbanization, an already over-allocated supply of water, and steadily declining agricultural water ownership and consequently production (Figure 2). Decision-makers in the SPRB aim to mitigate the potential negative consequences of lost production to agricultural communities while providing for needs of a growing population with an uncertain climate (Figure 1).

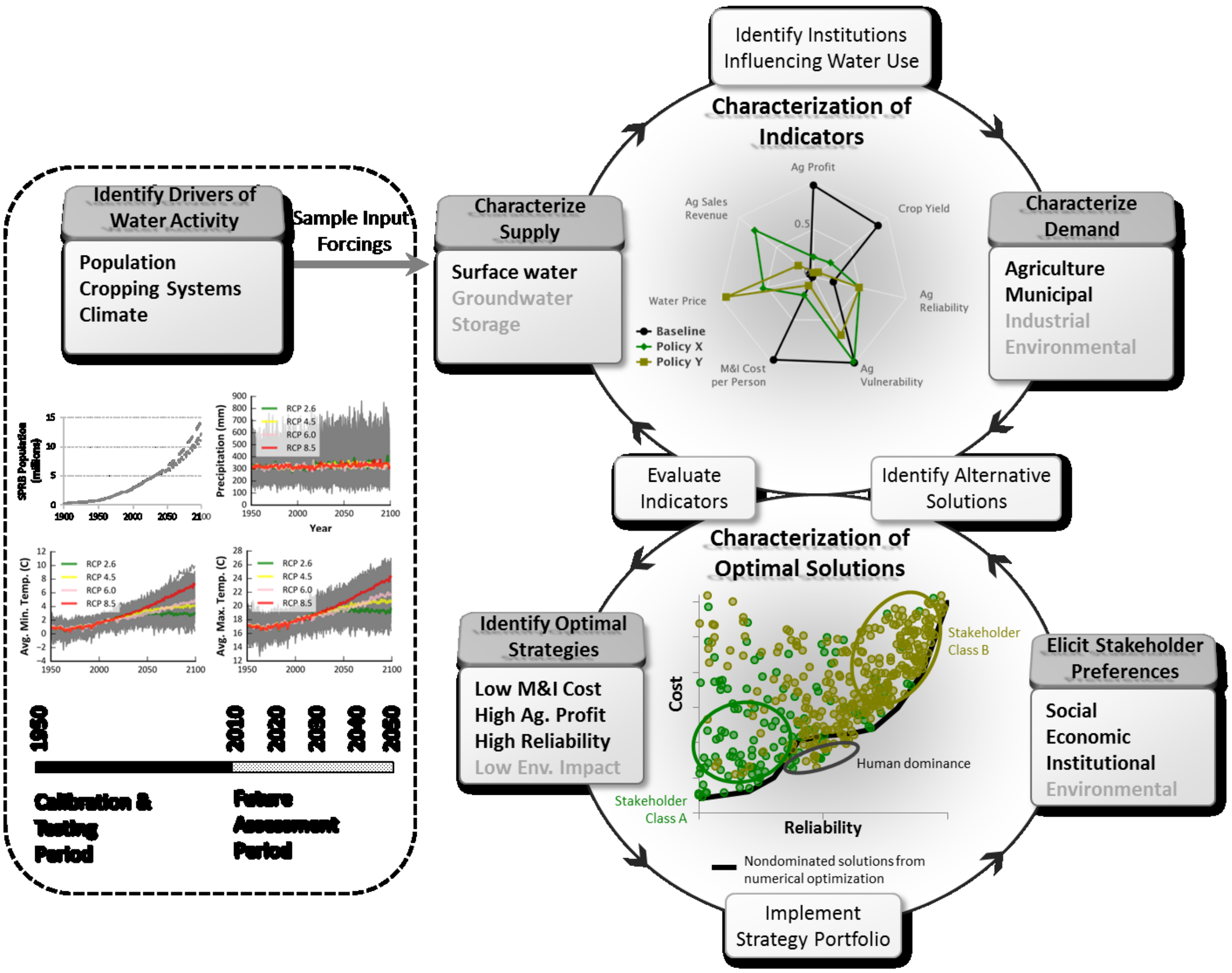


Figure 1: The integrated modeling and optimization water sustainability assessment framework for analyzing trade-offs of water supply vulnerabilities related to municipal and industrial (M&I) demand, agricultural (Ag.) production, and environmental (Env.) criteria. Grayed-out components of supply and demand are additional examples of the applicability of the framework, but are not the focus of its application in this study. Enhanced from Dozier et al. (n.d.).

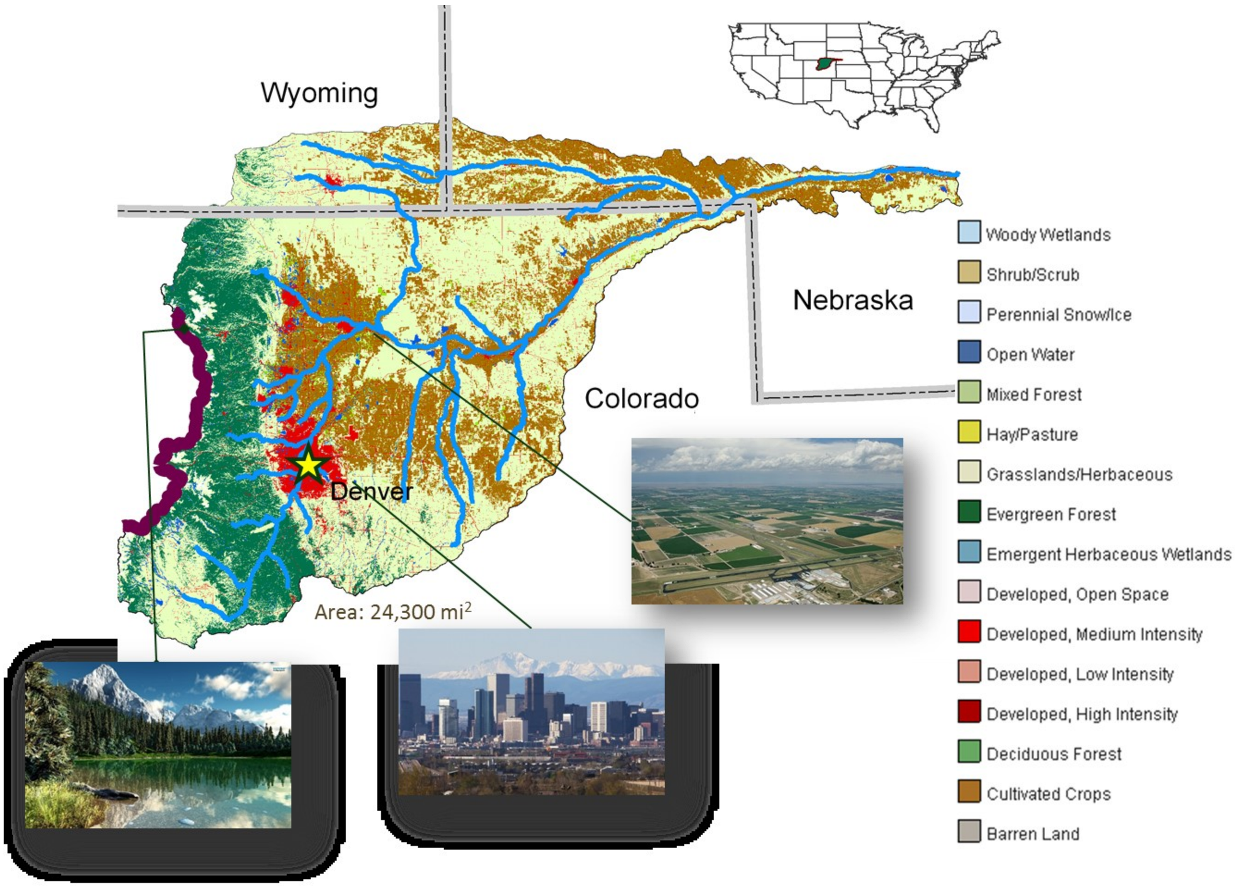


Figure 2: Diverse land and water use in the South Platte River Basin from mountainous headwaters, to the rapidly urbanizing "Front Range" close to the mountains, and the agricultural east

This dissertation is a compilation of six different independent papers aimed at addressing the goal mentioned above and in completion of the objectives. A literature review on approaches to Integrated Water Resources Management (IWRM) has informed and motivated the integrated, simulation-based, multiobjective, stakeholder-driven optimization approach utilized in this work (Chapter 2). Integrated representation of multiple systems within IWRM is required for evaluation of multiple stakeholder objectives, criteria and preferences. Interest in utilizing existing and well-tested models without requiring invasive model code changes led to the development of a model data passing interface for integrating biophysical system models (Chapter 3). Urban water use, agricultural crop production, and a market of water rights were represented in a biophysical modeling system (Chapter 4). Utilizing the integrated biophysical modeling system, impacts of urban growth on agricultural production and profitability were projected. Institutional agreements and policies regarding distribution and allocation of native and trans-basin water rights were considered and analyzed (Chapter 5). Because of their importance in the Western U.S., storage reservoirs, their institutions and management objectives, were specifically investigated. A loss to infrastructure value is incurred with inefficient allocation, and increased storage capacity can worsen global total social value when management objectives are biased toward one sector (Chapter 6). Trade-offs in management objectives resulting from technological, infrastructural, and institutional solutions were explored for mitigating water system vulnerabilities in the SPRB, particularly declining agricultural production. Solutions that sustain the value of farmer water result in more expensive water for municipalities (Chapter 7). A novel bottom-up, stakeholder-driven, simulation-based optimization methodology was developed for crowdsourcing potential solutions while eliciting stakeholder or public preferences. The preliminary "decision support game" places gamers in a water management role to plan for water resources using both supply-side and demand-side techniques (Chapter 8).

2 TRENDS IN SIMULATION-BASED OPTIMIZATION APPROACHES FOR INTEGRATED WATER RESOURCES MANAGEMENT: A REVIEW[2]

Meeting competing demands for water with adequate quality to support populations, economies, and ecosystems proves difficult due to uncertainties in climate, land use, and demographics. Increasingly, sustainability and equitability factors are included as additional criteria with which to assess performance of water management solutions, requiring stakeholder input and environmental assessment. Optimization methods provide systematic approaches to evaluate trade-offs in meeting integrated water resources management goals. This chapter analyzes trends in optimization techniques as research moves from single-objective technical solutions to multiobjective stakeholder-driven solutions. Linear programming and dynamic programming were the preferred optimization techniques until the turn of the 21st century, when heuristic or evolutionary methods became widely popular. Simulation-based optimization and decomposition techniques provide the means to improve system representation while performing optimization. A growing number of researchers have recognized that technical solutions do not perform well in addressing sustainability and equitability, and thus have proposed role-playing games and serious online video games as stakeholder-driven approaches. Future research should focus on increasing the efficiency of multiobjective analysis and simulation-based optimization, as well as further exploration of methods to harvest stakeholder solutions within optimization.

2.1 Introduction

Extreme weather-related events, climate change impacts, aging water infrastructure, and degradation of freshwater resources present increasingly challenging dilemmas for water resource

[2] Dozier, A. Q., M. Arabi, J. W. Labadie, and D. G. Fontane (2016), Optimization approaches for integrated water resources management, in Handbook of Applied Hydrology, edited by V. P. Singh, McGraw-Hill, Inc.

managers throughout the globe (Bouwer 2000; Schwarzenbach et al. 2006; Trenberth et al. 2003). Growing populations and uncertain climate narrow the window of acceptable water system operations because of increased competition for water resources, uneven distributions of water in space and time, and encroachment on riverine-ecology landscapes due to development (Gourbesville 2008; Oki and Kanae 2006; Vörösmarty et al. 2000). Legal restrictions and financial limitations further constrain operations and management of freshwater resources (Neuman 1998; Saleth and Dinar 2000). Geophysical processes, including hydrological processes, operate as a holistic system regardless of whether human-based management schemes view them as such (Reid et al. 2010). Detailed simulation models of water systems often aid decision-making by assessing the effects of solution strategies formulated by system managers in a very detailed and methodological manner (Rani and Moreira 2009). Simulation benefits from being intuitive and descriptive of the system it represents, but finding good solutions through simulation proves difficult in large, multidimensional, highly constrained decision spaces. Numerical optimization techniques efficiently explore these spaces for more beneficial solutions (Hashimoto et al. 1982).

Differing and sometimes conflicting stakeholder perspectives about water introduce multiple objectives, or criteria, with which to judge system performance (Reed 2008). Thus, for several decades, managers and scientists throughout the globe have searched for more integrated, sustainable, and equitable approaches to natural resource management, leading to widespread adoption of an integrated water resources management paradigm (White 1998). This paradigm shift led to development of management criteria within hydrographic, socio-economic, environmental, and political-administrative contexts for quantifying sustainability and equitability (Loucks and Gladwell 1999; van der Zaag et al. 2002). Such integrated water management imposes multiple objectives on traditional engineering approaches, rendering technical approaches potentially less efficient in a pragmatic sense (i.e., physically, financially, or politically) in favor of more equitable and sustainable management schemes (Giordano and Shah 2014).

The goal of this chapter is to portray the trends in optimization methods developed to address the challenges introduced by integrated water resources management. The objectives of this work are to:

1. Define optimization in the context of integrated water management,
2. Outline trends in optimization methods in water-related subdisciplines,
3. Discuss challenges and gaps to present a roadmap for future research.

Previous literature and textbooks already provide general formulations and algorithms for solving linear, convex, nonconvex, nonsmooth, discrete, stochastic, and dynamic optimization problems (Loucks and van Beek 2005). To avoid redundancy, this chapter instead highlights trends in optimization methodologies as the water management community moves toward an integrated water resources management (IWRM) paradigm.

2.2 Optimization in the Context of Integrated Water Resources Management

Although this chapter lies within a hydrology handbook, scientific investigations within hydrology rarely utilize optimization methods except in calibration of hydrologic models (covered in a different chapter) and briefly in the study and modeling of optimality in ecohydrological systems (Eagleson and Tellers 1982). For this reason, we focus on water resources management applications and problem perspectives. Integrated water resources management (IWRM) refers to a process that "promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Agarwal et al. 2000). Although some question the IWRM paradigm (Giordano and Shah 2014), its widespread adoption has set guiding principles that require a change from traditional engineering to integrated analysis of water projects (Bouwer 2000; Gourbesville 2008). Table 1 lists previous literature surveys that contextualize optimization problems and algorithms used within various water resource subsystems. Optimization in the context of IWRM integrates and synthesizes these various subproblems so as to address decision-making more holistically (Cai 2008; Kelly et al. 2013). Thus, a special focus is placed on integrative and multiobjective optimization techniques that combine traditional engineering approaches with economic, social, or environmental processes, impacts, and trade-offs.

Although every optimization problem embeds some kind of simulation or prescriptive model of the system under consideration, detailed and realistic simulation models have rarely appeared within the historical context of optimization. This has hindered adoption of these detailed models by stakeholders and operations engineers (Labadie 2004; Yeh 1985). Highly simplified system representation within optimization models leads to large uncertainty in the impacts and trade-offs of resultant management policies. As computing power and speed continue to improve, however, more complex system descriptions have entered into optimization methodologies. Simulation-based optimization techniques such as reinforcement learning and evolutionary computation offer promising capabilities to incorporate more realistic models within optimization (Belaineh et al. 1999; Lee and Labadie 2007; Rani and Moreira 2009; Rieker and Labadie 2012; Safavi et al. 2009).

Optimization in a traditional sense provides technical solutions through the use of computer-based numerical techniques. However, a number of researchers and practitioners within the water resource management community have come to believe that effective, sustainable, and equitable water management requires stakeholder participation (Barreteau et al. 2007a; Kelly et al. 2013; Seppälä 2002; Steins and Edwards 1999; Voinov and Bousquet 2010). The public tends to adopt stakeholder-driven, bottom-up solutions more easily than technical solutions within a democratic setting (Gaddis et al. 2010; Korfmacher 2001; Voinov and Bousquet 2010), whereas technical, top-down solutions in other political settings may be more efficient at achieving practical outcomes (Giordano and Shah 2014). Empirical evidence indicates that appropriate collective action effectively manages a multiple-use common-pool resource, which includes most water resource projects (Ostrom 1990; Steins and Edwards 1999). Today, many water management practitioners have taken to elicitation of stakeholder ideas by performing participatory modeling tasks with stakeholders, while others have utilized optimization techniques that directly incorporate stakeholder values as weighted objectives in multiobjective optimization or preferences in multi-criteria decision analysis (Voinov and Bousquet 2010). Analysis of literature indicates an emerging trend in the search for integrated, sustainable, and equitable water management: gamification.

2.3 Trends

Previous literature reviews cover more specific topics within water management (see Table 1), and a few papers broadly review water management as a whole (Loucks et al. 2005; McKinney et al. 1999; Singh 2012). We therefore briefly analyze trends in optimization methods used in each field. Emphasis on the development of methodologies over time highlights the rapidly growing popularity of multiobjective analysis and the use of evolutionary computation techniques to solve both single-objective and multiobjective problem formulations. Figure 3 displays a water-related literature trend analysis (Appendix A) clearly indicating that evolutionary algorithms have surpassed every other form of optimization in water-related topics since the early 2000s. Multiobjective analysis has also been rapidly climbing to a prominent position in water system operations research. Most multiobjective analyses consist of techniques constrained to multiple objectives such as epsilon-constraint, the weighting method, multi-criteria decision analysis, and analytical hierarchy process, while about one third of multiobjective analyses stem from multiobjective evolutionary algorithms. These trends show a growing desire within water-related research fields to improve realistic system representation, search nonsmooth objective functions, and incorporate more sustainable and equitable solutions. Selected subdisciplines are discussed in the subsections below, followed by elaboration on techniques useful for interdisciplinary synthesis and incorporation of stakeholder input.

2.3.1 Reservoir Operations and Management

Reservoir operations problems represent classic testing grounds for new optimization techniques due to their large degree of nonlinearity, multiobjective purposes, and significant economic impact. Common objectives of reservoir operations problems include maximizing revenue from sale of hydropower or water supply, minimizing shortages, maximizing energy production, and minimizing vulnerability and damage due to floods, among many others (Wurbs 1993). Since the 1960s, many researchers have utilized **linear programming** (LP) in addition to its stochastic variants such as **chance-constrained linear programming** (CCLP) and **stochastic linear programming** (with decomposition) to perform reservoir system optimization (Labadie 2004; Yeh 1985). N**etwork flow optimization** solves a subset of linear optimization problems and remains a popular simulation and optimization approach in practice due to its speed and graphical representation of system constraints (Labadie 2004; Wurbs 1993).

Techniques such as interior point (IP), quadratic programming (QP), sequential linear (and sequential quadratic) programming (SLP and SQP), Frank-Wolfe (or conditional gradient) method, generalized reduced gradient (GRG), and conjugate gradient method (CGM) comprise some of the mathematical, gradient-based techniques used in reservoir optimization to solve nonlinear problems, commonly referred to as nonlinear programming (NLP) techniques (Dai and Labadie 2001; Labadie 2004; Wurbs 1993; Yeh 1985). Some methods such as CGM do not directly handle constraints, and therefore do not generally apply to a large number of problems. Integer programming methods such as branch-and-bound, cutting plane, and branch-and-cut help to address introduction of discrete variables in addition to nonlinear constraints and objective function terms (Higgins et al. 2011; Labadie 2004). Optimization of problems with nonlinear constraints can be performed using Lagrange multipliers and duality theory, a methodology also known as the method of multipliers (MOM) or the Augmented Lagrangian method (Bertsekas 1996; Labadie 2004).

Researchers have preferred to use **dynamic programming** (DP), **optimal control theory** (OCT), and **reinforcement learning** (RL) due to the sequential, nonlinear, nonconvex, nonsmooth, and stochastic nature of many reservoir system management and operational problems (Labadie 2004; Lee and Labadie 2007; Rieker and Labadie 2012). After the discovery of DP by Richard Bellman in the mid-1950s, DP quickly rose in the 1960s as a technique to solve reservoir operations problems, outpacing application of LP techniques even though LP was formulated first (Cottle et al. 2007; Dreyfus 2002). To alleviate the so-called "curse of dimensionality" when considering multi-reservoir systems, researchers in the late 1960s and early 1970s began to develop DP variants that enhance solution speed of multidimensional problems such as **Incremental DP** (IDP) and **DP Successive Approximations** (DPSA) (Labadie 2004; Yeh 1985). Additionally, functional approximation methods such as **orthogonal polynomials**, **cubic splines**, and **artificial neural networks** (ANNs) can be used to speed objective function evaluation (Bertsekas and Tsitsiklis 1995; Tejada-Guibert et al. 1995).

Since the advent of the personal computer in addition to rapidly increasing processing speeds in the early 1990s, literature in reservoir operations research highlights a widespread, growing interest in evolutionary programming techniques, also referred to as heuristic techniques. Evolutionary computation can handle nonsmooth, nonconvex, multi-modal, and stochastic problems, but typically requires many more objective function evaluations, converges more slowly, cannot guarantee convergence on an optimum, and is often unsuitable for dynamic optimization problems due to the large search space (Rani and Moreira 2009). Heuristic techniques used for reservoir operations problems include **genetic algorithms** (GAs), **particle swarm optimization** (PSO), **ant colony optimization** (ACO), **honey-bee mating optimization** (HBMO), **simulated annealing** (SA), **tabu search** (TS), and **shuffled complex evolution** (SCE) (Baltar and Fontane

2008; Labadie 2004; Rani and Moreira 2009; Wardlaw and Sharif 1999). Hybrids of these heuristic techniques with mathematical techniques have served to address computational inefficiency and highly-constrained systems.

Methods such as **epsilon-constraint**, the **weighting method**, **goal programming**, **compromise programming**, **multiobjective GAs** (MOGAs), and other variants of heuristic techniques search multiobjective problems for a Pareto optimal solution (Labadie 2004; Rani and Moreira 2009). **Multi-criteria decision analysis** (MCDA) techniques optimize over a finite number of alternatives using stakeholder input to assign preferences or otherwise rank the alternatives based on multiple criteria (i.e., objectives) (Labadie 2004; Voinov and Bousquet 2010). Similar trends are observed in other subdisciplines of water resources management.

2.3.2 Irrigation Systems

Irrigation systems herein may refer either to operations of conveyance systems or single farm crop selection and patterns. Common objectives for operating irrigation systems include maximization of farm profit or water productivity, and minimization of waterlogging, groundwater depletion, or transpiration (Ali and Talukder 2008; Singh 2013). Since the 1970s, linear and dynamic programming in addition to stochastic variants of these techniques have dominated irrigation system operations research, where nonlinear programming remains less popular (Kipkorir et al. 2001; Singh 2013). When linked with design or economic objectives, **Lagrangian multiplier** methods aid solution of nonlinear terms and relaxation of nonlinear constraints (González-Cebollada and Macarulla 2012). Since the late 1990s, researchers have rapidly introduced GAs as the dominant heuristic technique (Singh 2013).

2.3.3 Groundwater

Groundwater management can take many different forms, but in general aims to improve groundwater quantity, quality, or allocation (Wagner 1995). Objective functions include minimizing pumping costs, maximizing profit, minimizing storage requirements or stream depletion, minimizing water deficit in scarce locations, and maximizing well production or hydraulic head, among many others (Gorelick 1983). Since the late 1960s and early 1970s, LP has been the most commonly used method to optimize groundwater management, and methods such as the embedding method or response matrices were introduced to spatially and temporally approximate groundwater response to management decisions within an LP formulation (Gorelick 1983; Yeh 1992). Other early methods included mixed integer programming techniques, QP, OCT, and DP (Gorelick 1983; Singh 2012; Yeh 1992). As in other water subdisciplines, evolutionary optimization methods such as GA, SA, and PSO applied to groundwater management problems rapidly replaced the prominent optimization methods in the late 1990s to early 2000s (Singh 2012; Wagner 1995). Many simulation-based optimization techniques have been explored to ensure proper solution of groundwater flow equations (Gorelick 1983; Wagner 1995). These simulation techniques present mechanisms for integrating surface water into groundwater management (Singh 2012).

2.3.4 Water Distribution Networks

Water distribution system design cannot easily be obtained through use of traditional mathematical programming techniques due to the discrete nature of the decision variables and cost functions, uncertain demand, and complex energy function (Taher and Labadie 1996). Thus, design techniques tend towards direct search or simulation-based optimization. Objective functions usually include minimizing total cost (both construction and operation of pipes, pumps, etc.) with constraints regarding pressure and flow criteria (Kang and Lansey 2011; Walski 1995). Researchers have historically utilized hybrid variants of mathematical and heuristic techniques, trading off accurate system representation with computational tractability (Cunha and Sousa 1999). To improve system representation, researchers have more recently employed fully heuristic programming techniques such as GAs, PSO, ACO, SA, TS, SCE, **harmony search** (HS), **immune algorithms** (IAs), **memetic algorithms** (MAs), and **shuffled frog-leaping algorithms** (SFLA), among others (Cunha and Sousa 1999; di Pierro et al. 2009). MCDA methods also help to support decision-making around design and planning for water distribution networks (Scholten et al. 2014).

2.3.5 Floodplain Management

The application of optimization for floodplain management represents a relatively small field of study, perhaps due to its excessively large data and modeling requirements for land use change, or perhaps because of the small number of floodplain managers. Flood planning aims at minimizing expected value of flood damages through various permanent and emergency actions consisting of both structural and non-structural flood mitigation strategies (Lund 2002). Very few researchers have applied LP, NLP, mixed-integer programming, or dynamic programming to the field of floodplain management (Lund 2002). Starting in 1997 with the optimization of layout and sizing of detention systems by Yeh and Labadie, GAs have been used to optimize floodplain decisions in both single- and multiple-objective forms (Woodward et al. 2013; Yeh and Labadie 1997). Expert systems and MCDA techniques have also been applied to flood management (Kumar et al. 2010).

2.3.6 Water Supply Planning and Conjunctive Use

Water supply planning and conjunctive use of surface water and groundwater resources aim at diversifying water sources to improve reliability of water supply and water quality (Singh 2012). Optimization in the context of conjunctive use has evolved from determining irrigation water source decisions in the 1960s to integrating other aspects of water resources management such as demand-side management, groundwater remediation, and water ownership transfers (Pulido-Velázquez et al. 2006). Surface water and groundwater interactions complicate conjunctive use modeling, and have thus consumed a large portion of research in the field (Safavi et al. 2009). The earliest formal optimization techniques used for conjunctive water supply planning consisted of DP and LP, with LP and its stochastic variants emerging as the dominate approach (Singh 2012). Due to discrete variables and model integration requirements of water supply problems, decomposition, integer programming, and mixed-integer programming techniques have dominated the nonlinear mathematical approaches to conjunctive use optimization (Cai et al. 2001; Watkins and McKinney 1998). Since the 2000s, evolutionary methods such as GAs and MOGAs have quickly entered literature as simulation-based solutions to optimize conjunctive use problems (Peralta et al. 2014; Safavi et al. 2009; Singh 2014). To improve hydrologic system representation without significantly increasing computation time, ANNs and other linear and nonlinear regression techniques often act as a surrogate for more sophisticated, physically-based approaches. For example, stream-aquifer interactions often require excessive computations through a finite difference model such as MODFLOW, but not when represented within an ANN (Triana et al. 2010c).

2.3.7 Integrated Analysis of Multipurpose Water Resource Systems

As discussed previously, integrated water resources management requires accurate representations of water systems in order to manage water sustainably and equitably across economic, socio-political, and environmental (ESE) spheres (Cai 2008; Cai et al. 2003; McKinney et al. 1999). Optimization applications for floodplain and water quality management integrate social, environmental, and legal systems due to their proximity to land use change and management (Lund 2002; Tong and Chen 2002). Land use and change, ecosystem water use, and societal interactions with and perspectives on water will increasingly play larger roles in simulation and optimization as research progresses to provide more representative modeling of water systems.

Hierarchical optimization employs mature optimization techniques to solve subproblems of an overarching master optimization problem, the dual of which is often solved with subgradient or evolutionary techniques (Cai et al. 2001; Labadie 2004). **Dantzig-Wolfe decomposition** has benefited irrigation ditch planning by linking higher-level water allocation optimization with lower-level cropping-pattern optimization (Paudyal and Gupta 1990). Among other decomposition techniques, **Lagrangian relaxation** (LR), or the **method of multipliers** (MOM), remains perhaps one of the most popular techniques used for optimization and model integration within hydro-thermal coordination studies (Dozier 2012), as well as in conjunctive surface-water and groundwater management (Gorelick 1983). Hierarchical techniques have thus demonstrated utility in integrating across disciplines.

Optimal control theory (OCT) offers a very similar technique to LR that allows optimization of a multistage, sequential decision problem simultaneously constrained by potentially complex system dynamic equations through use of the Hamiltonian (Labadie 2004). OCT has been utilized to link economics optimization with natural resource management, mainly forests and fisheries, since 1969, where recent research focuses on fine-tuning spatial and temporal resolution (Dorfman 1969; Sanchirico and Wilen 2005). Unlike OCT, **dynamic programming** (DP) is an easily discretized and constrained form of dynamic optimization, and has thus been highly utilized within water management subdisciplines to perform integrated hydro-economic optimization (Harou et al. 2009). With the notable exception of **reinforcement learning** (RL) (Lee and Labadie 2007; Rieker and Labadie 2012), most DP techniques require addition of multiple artificial state variables to incorporate processes beyond a simple Markov decision process, where the state is transferred through more than one discretized timestep (Shim et al. 2002). Addition of state variables significantly increases computation time, but methods such as IDP and DPSA help to alleviate the large computation time associated with large multidimensional problems (Labadie 2004). Some authors have adapted the **differential dynamic programming** (DDP) technique to incorporate more detailed simulation (Culver and Shoemaker 1993). Simulation-based optimization techniques like RL, although less mature than traditional optimization techniques, provide a straightforward and intuitive platform for integrating system representation across various disciplines (Harou et al. 2009).

Simulation-based optimization techniques require a methodology to represent operating rules given current system state. **Tables**, **linear** or **polynomial rules**, **expert systems**, **regression**

models, **fuzzy rule based systems**, ANNs, and hybrid approaches provide mechanisms to map system state to operating rule decisions (Labadie 2004; Rani and Moreira 2009). Because no structure is assumed a priori, optimization methods that utilize fuzzy rules or ANNs often outperform those using simple operating rule structures such as linear operating rules (Wan et al. 2006).

2.3.8 Incorporating Stakeholder Values and Human Knowledge in Optimization

As mentioned above, properly implemented integrated water management requires stakeholder input, yet most of the optimization techniques discussed so far are purely numerical mechanisms guided by water managers, researchers, and engineers. MCDA, **Bayesian belief networks** (BBN), **compromise programming**, and the **analytic hierarchy process** (AHP) incorporate stakeholder values as preferences associated with the various criteria, and thus guide technical solutions towards stakeholder values (Voinov and Bousquet 2010). **PROMETHEE** and **ELECTRE III** apply fuzzy sets within MCDA to represent uncertainties that can exist in representing stakeholder preferences (Labadie 2004). MCDA methods have been successfully applied within reservoir operations and water distribution system design (Labadie 2004; Scholten et al. 2014). Other methods such as **expert**, or **knowledge-based systems** directly take past human experience to build a model of the decision-making process that finds solutions to a previously recognized problem (Liao 2005).

Stakeholder participation has progressed from building decision support systems through use of simulation and optimization methodologies (Voinov and Bousquet 2010) to being the decision support system itself (le Bars and le Grusse 2008; Lankford et al. 2004). A growing community has attempted to optimize allocation of resources in a more equitable and sustainable manner by utilizing **experimental games**, also referred to as **simulation games** or **role-playing games** (Barreteau et al. 2007a; Valkering et al. 2012). Since the 1930s and 1940s, the field of experimental economics has utilized experimental games to study human behavior and economic values (Kahneman and Smith 2002; von Neumann and Morgenstern 1944). Economists now view these lab experiments as a common tool to study behavior, perform conflict resolution, test policies, and develop new solutions for natural resource management (Barreteau et al. 2007a; Ehmke and Shogren 2008). One role-playing game showed that human adaptation tended toward nonstructural flood control measures (Valkering et al. 2012).

Several physical board games, computer simulation games, and hybrids have also been utilized in localized contexts to solve water management issues throughout the globe (le Bars and le Grusse 2008; Dray et al. 2006; Lankford et al. 2004; Rebolledo-Mendez et al. 2009). Experience from one study suggests that a computer-assisted board game simplifies system representation enough to aid stakeholder understanding, expression of opinions, and generation of solutions so as to consequently reduce collective disagreement (Dray et al. 2006). **Serious online video gaming**, or **games with a purpose**, extends economic experiments by crowdsourcing the search for integrated water management solutions, in addition to the more important immediate and decentralized analysis of the impacts and trade-offs associated with those solutions (le Bars and le Grusse 2008). Games also provide a mechanism to arouse awareness over specific water issues (Rebolledo-Mendez et al. 2009; Rizzoli et al. 2014). When applied to water resources management, video gaming simultaneously improves system representation through simulation and optimizes management strategies that are driven by stakeholders, a difficult, if not impossible, task for traditional optimization methods (Harou et al. 2009).

2.4 Challenges and Research Gaps

Researchers recognize a need to integrate across scales of analysis and across disciplines within optimization to improve water system representation. For example, integration of transmission and distribution scales in water distribution network design improves the search for cost-effective solutions (Kang and Lansey 2011). Detailed simulation models offer the most straightforward capability to synthesize across subdisciplines in addition to being more attractive and intuitive to water managers and other practitioners than less-detailed, prescriptive optimization models (Labadie 2004). Utilization of simulation models within hierarchical optimization techniques through use of Lagrange multipliers, Hamiltonian functions, and simulation-based dynamic optimization methods serves to synthesize across various scales (Pulido-Velázquez et al. 2006). Heuristic or evolutionary computation methods also offer direct search capabilities by running a simulation model and evaluating the objective function from model outputs, as is often performed in automating model calibration.

Difficulties with simulation-based optimization approaches arise due to computational limitations. Within water resource management literature, high performance computation through massive parallelization, cloud computing, and distributed data stores remain underutilized even though computational benefits are clear. Promising and particularly useful techniques to hasten simulations are functional approximation methods and incremental or successive approximation approaches (Bertsekas and Tsitsiklis 1995; Johnson and Rogers 2000; Labadie 2004; Safavi et al. 2009). Future research will focus on reducing the computation time, improving convergence characteristics, and generalizing software implementations of simulation-based optimization methods.

Technical optimization can produce top-down, pragmatic solutions to specific problems, but may not incorporate equitable or sustainable criteria with meaningful stakeholder input. Thus, a variety of methods including MCDA, BBN, AHP, expert systems, role-playing games, and serious online video games have applied stakeholder values and even stakeholder-driven ideas within the searching mechanisms for solutions to various water resource management issues (Barreteau et al. 2007a; le Bars and le Grusse 2008; Voinov and Bousquet 2010). Although they remain far from being mature and stable fields of study and practice in water resources management, role-playing games and serious online video games offer a promising mechanism to incorporate stakeholder-driven solutions directly within the optimization technique. Such stakeholder-driven optimization results in large oscillations and adjustments in the search for optimal water management strategies due to uncertainties, trial and error, inaccuracies, misperceptions and insufficient knowledge of the systems (le Bars and le Grusse 2008; Cronin et al. 2009; Diehl and Sterman 1995; Sterman 1989). These issues acknowledge the formidable challenges faced in applying stakeholder-driven approaches, but also present exciting new research to enhance human-computer interactions for crowdsourcing water management solutions.

2.5 Conclusions

Integrated water resources management served as a context for the goal of this chapter to analyze trends in optimization techniques. Motivations for focusing on IWRM stem from a growing interest in more integrative and holistic modeling solutions that incorporate multiple, nontechnical objectives within economic, social, and environmental spheres. Simulation modeling offers the best platform on which to build accurate models of physical water systems. Over the past 60 years, operations research literature in water management clearly indicates a trend towards more accurate system representation within optimization models through use of evolutionary computation and other forms of simulation-based optimization. Due to their capability to break large optimization problems into subproblems of a vastly simpler nature, decomposition methods have become commonplace in hydrothermal coordination studies, and are of growing interest in conjunctive use and water quality management studies. Due to the excessive computation time of heuristic and simulation-based techniques, parallel implementations of simulation models and optimization methods may provide future research directions, in addition to improving algorithm searching capabilities, search space reduction, and functional approximation methods.

Integrated water resources management imposes economic, social, and environmental criteria on a traditionally engineering-based field of study. Multiobjective analyses of water management strategies now often incorporate sustainability and equitability metrics across such criteria. Due to the difficulty in establishing suitable metrics, practitioners have attempted to incorporate stakeholder values in settling on pre-determined solutions through multi-criteria decision analysis and other similar techniques. Others have recognized the need to involve stakeholders in identifying the solutions, and have held workshops in which stakeholders directly participated in modeling exercises and role-playing games. An emerging crowdsourcing practice, serious online video gaming, also promises to incorporate stakeholder-driven solutions and analyses into challenging integrated water management problems.

Table 1: Literature surveys of optimization methods used for operations research and management of various water resources systems

System	Surveys
General overviews	(Loucks and van Beek 2005; McKinney et al. 1999; Singh 2012)
Reservoirs	(Labadie 2004; Wardlaw and Sharif 1999; Wurbs 1993; Yeh 1985)
Irrigation networks	(Singh 2013)
Groundwater	(Gorelick 1983; Wagner 1995; Yeh 1992)
Distribution network design	(Kang and Lansey 2011; Walski 1995)
Floodplain management	(Kumar et al. 2010)
Conjunctive use	(Singh 2014)

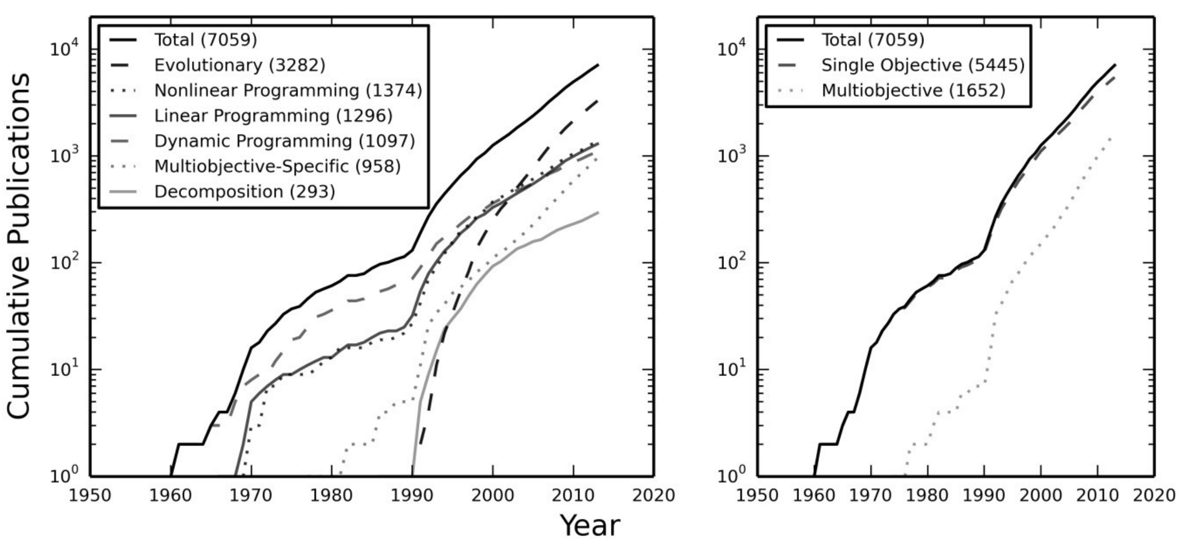


Figure 3: Literature trends on a semi-log scale from 1950 to 2013 showing the number of articles that mention various optimization methods over time (left panel), and the number of articles that are identified to be either single-objective or multiobjective analyses (right panel). "Multiobjective-Specific" optimization methods consist of those specific to

multiobjective analysis such as epsilon-constraint, compromise programming, and multi-criteria decision analysis, but do not include those methods that can also be used for single-objective analysis such as multiobjective genetic algorithms. Matching articles are constrained to those with a match for water-related topics in the title, abstract, or keywords sections of publication metadata. Metadata is provided by Web of Science ®. More information on how this figure is produced is found in Appendix A.

3 A MINIMALLY INVASIVE MODEL DATA PASSING INTERFACE FOR INTEGRATING LEGACY ENVIRONMENTAL SYSTEM MODELS[3]

This paper presents an approach to model integration utilizing the Model Data Passing Interface (MODPI). The approach provides fine-grained, multidirectional feedbacks between legacy environmental, biophysical system models through read and write access to relevant model data during simulation using a event-based, publish-subscribe system. MODPI only requires commented directives in the original code and an XML linkage file with an optional custom data conversion module. Automated code generation, compilation, and execution reduce the programming burden on the modeler. Case study results indicated that MODPI required less code modifications within each model code base both before and after automated code generation, outperforming a baseline subroutine approach. Performance overhead for MODPI was minimal for the use case, offering speedup in some cases through parallel execution. MODPI is much less invasive than other techniques, encouraging adoption by the modeling community and improving maintainability and reusability of integrated model code.

3.1 Data and Software Availability

Software developed for the purposes of this paper are open-source and publicly available. The implementation of MODPI presented in the paper is found at https://bitbucket.org/adozier/fortmodpi (2.1 MB), and the implementation of events is found at https://bitbucket.org/adozier/fortevents (11 KB). A summary of the packages is found at https://www.erams.com/resources/Platform/MaaS/Model_Integration. This software requires an implementation of the Message Passing Interface (MPI) or ZeroMQ. Models (3 MB), performance

[3] Dozier, A. Q., O. David, M. Arabi, W. Lloyd, and Y. Zhang (2016), A minimally invasive model data passing interface for integrating legacy environmental system models, *Environ. Model. Softw.*, 80, 265–280, doi:10.1016/j.envsoft.2016.02.031.

test results (370 kB), a shell script that reproduces the results (2 kB) in this paper are found at https://erams.com/resources/Platform/MaaS/Model_Integration.

3.2 Introduction

Model integration frameworks, or environmental modeling frameworks, allow a plug-and-play methodology in connecting submodels of a biophysical system to enhance model representation of the overall system. However, framework invasiveness restricts reuse and maintenance of framework-dependent models (Donatelli and Rizzoli 2008; Lloyd et al. 2011). Thus, instead of using the frameworks, many biophysical system model developers incorporate transplanted, and often outdated, submodels of other disciplines into their codes (Laniak et al. 2013a). Although modeling frameworks have been used to integrate such models across disciplines, model developers often maintain the model code base separate from its support of the framework.

Lloyd et al. (2011) defines framework invasiveness as "the quantity of dependencies between model code and a modeling framework". Modeling frameworks that aim at minimizing imposed dependencies on a legacy model improve maintainability and reuse (Lloyd et al. 2011). Historically, modeling frameworks that attempt to be less invasive have focused on coarse-grained interaction between "components" or submodels of a larger model (Donatelli and Rizzoli 2008; Lloyd et al. 2011). Finer-grained feedback schemes that exchange data from within a component or submodel have previously taken more invasive approaches or require extensive computer programming expertise (Becker and Schuttrumpf 2011). We argue that the amount of work required within a legacy model for integration with another model or support of a framework interface is another obstacle to framework adoption. Thus, we define invasiveness here to be the dependencies within each model on either the integration platform or other models, and the amount of work required within each model for integration or implementation of a framework interface.

Attempts to incorporate multidirectional feedback between legacy models include iterative, subroutine, and inter-process communication approaches that are discussed in detail in the next section. To remain minimally invasive, inter-process communication techniques are the most promising approaches as demonstrated by (Becker and Schuttrumpf 2011) in making a closed-source model compliant with the OpenMI standard (Moore and Tindall 2005) within a timestep loop. Inter-process communication techniques have previously required too much programming knowledge for most modelers. Thus, there still remains a need for a minimally invasive, fine-grained, generic model integration interface that does not require such extensive programming expertise (Laniak et al. 2013a).

The goal of developing the Model Data Passing Interface (MODPI) is to facilitate and abstract the legacy model integration process to reduce framework invasiveness while minimizing programming knowledge requirements. Objectives of this study include:

1. Develop an abstracted interface for minimally invasive model integration that simplifies complex interactions between legacy models and modeling platforms of disparate disciplines,
2. Automate code generation of MODPI-compatible wrappers for legacy models to support ease-of-use, and
3. Evaluate invasiveness and performance of MODPI as compared to other approaches.

To accomplish these objectives, a publish-subscribe concept is combined with inter-process communication to provide external processes read and write access to any relevant state variable within a legacy model during its execution. A framework is built that automates wrapper generation, and a case study serves to benchmark MODPI against another common approach to the same problem.

3.3 Background and Related Work

Many researchers have previously addressed specific model integration challenges, and some have even developed generic interfaces for model integration. However, no generic interface exists for fine-grained, multidirectional feedbacks that preserves the individuality and maintainability of legacy models. Implementing interfaces for existing frameworks requires significant work within the model, and often requires addition of code dependencies on the framework.

This section identifies previous studies that have integrated legacy models to support fine-grained, multidirectional feedbacks, which is the primary functional requirement for the integration studies we summarize here. Fine-grained feedbacks refer to linkages of internal (and relevant) data or calculations between multiple models that cannot be represented by one model as a whole, but are required to represent a particular process more accurately. Multidirectional feedbacks refer to data or calculations within one model that depend on another model and vice versa. When the need for such feedbacks between models arises, there are various implementation considerations such as 1) implicit versus explicit numerical solution techniques, 2) passing data via subroutines or put/get calls, 3) hardware mechanism for communication, and 4) single or multiple executable approaches (Valkering et al. 2012). The following framework design targets for MODPI are used to qualitatively assess the different approaches:

1. Minimally invasive
2. Minimal interface requirements
3. Interoperable across languages and platforms
4. Links closed-source models
5. Reconciles data structure differences
6. Performance overhead is minimal

Interoperability and data structure reconciliation are functional requirements for specific model integration tasks, which also may be true for linking closed-source models and performance overhead in some cases, but not for a generic model integration interface.

Framework design targets are prioritized to make the interface more acceptable to a diverse modeling community that individually maintains or uses large legacy models. We argue that the first two targets, invasive changes within a model code base and difficult or extensive interface requirements, represent the largest factors that inhibit maintenance and reuse of integrated modeling systems (Lloyd et al. 2011). The design target for minimal interface requirements is aimed at reducing the amount of programming work and knowledge required to be able to implement MODPI for a model. Since modelers are often limited by an unfamiliarity with advanced programming techniques to improve interoperability or link closed-source models, minimizing difficult code changes and refactoring requirements may provide a path to encourage adoption and reuse of model integration frameworks. Ensuring interoperability of languages, platforms, and linkages with closed-source models would also broaden the applicability of an integration platform within an increasingly diverse community of modelers (Laniak et al. 2013b).

3.3.1 Implicit versus Explicit Approaches

Both implicit and explicit solution approaches have advantages and disadvantages. Although solving equations explicitly may intuitively seem numerically faster, implicit approaches may utilize assumptions to solve much more efficiently without sacrificing too much accuracy (Balaji 2012). Within hydrology, several approaches based on successive approximations allow models to be run separately, maintaining model individuality in partial fulfillment of Target 1 (Fredericks et al. 1998; Ibanez et al. 2014). Lagrangian relaxation techniques are systematic implicit numerical methods that allow for parallel execution of submodels (Dozier 2012). Because implicit approaches utilize original forms of equations, model individuality may be more easily attained than explicit approaches addressing Targets 1, 3, 4 and 5. However, most explicit solutions can improve geophysical model integration through guaranteeing numerical solutions for feasible inputs (Balaji 2012; Dozier 2012).

3.3.2 Subroutines versus Producer-Consumer Approaches

In model integration, data can be passed through subroutine arguments or through an exchanging mechanism such as a buffer that handles producers and consumers through put/get calls (i.e., publishers and subscribers). These are distinguished from hardware communication mechanisms because both subroutine arguments and buffers could potentially utilize memory, hard disk, or network communications, although there are typical implementations.

Implementing a subroutine approach often entails decomposing submodels into smaller components: initialization, run or update, and finalization (Argent 2004). For example, the Basic Model Interface (BMI) specifies initialize and finalize methods in addition to an update function that is used to advance a model or component to the next timestep while data is passed by name via interface subroutines between updates. Kim et al. (2008) and Peckham et al. (2013) integrated a surface water model (SWAT) with a subsurface water model (MODFLOW) by splitting MODFLOW up into its sub-components, calling the computational component of MODFLOW within the groundwater module of SWAT, and compiling the models together. In the case of the Object Modeling System (OMS), data is exchanged between multiple models during their simulation through separate (and potentially parallel) execution of model subcomponents based on data availability (David et al. 2013). OMS avoids framework dependence through annotations and custom wrappers in partial fulfillment of Target 1, but requires decomposing models into smaller components for fine-grained analysis (Lloyd et al. 2011).

In most cases with put/get approaches, data has previously been passed through specific inter-process communication (IPC) or framework dependencies within the original model code base (Armstrong et al. 2009; Valcke et al. 2012). Dozier (2012) showed that event constructs can be utilized to decouple models from the integrated modeling system while using the subroutine approach, which could be extended to the producer-consumer approach. Although the Earth System Modeling Framework (ESMF), the Common Component Architecture (CCA), and Bespoke Framework Generator (BFG2) primarily utilize subroutine-based data passing techniques, they allow subcomponents to use producer-consumer types of data interactions through shared memory or some form of IPC (Allan et al. 2006; Armstrong et al. 1999; Collins et al. 2005; Hill et al. 2004; Larson et al. 2004; Lefantzi et al. 2003; Valcke et al. 2012). In cases where the framework removes required IPC dependencies from the model, only coarse-grained interactions between model subcomponents are allowed, requiring the model to be broken into smaller components for fine-grained analysis (Collins et al. 2005; Hill et al. 2004).

3.3.2.1 Hardware Communication Mechanisms

Mechanisms for communicating data between models primarily include memory, hard drives, and network communications. For typical hardware speeds, Dean (2009) describes that in general a disk seek is 100,000 times slower than a reference to main memory, and reading 1 MB from disk is 80 times slower than from memory. To communicate data through slower hardware such as hard drives or network infrastructure may prove to have unacceptable overhead, although most model integration tasks require little data exchange compared to model computations. For example, automating the model integration in the cases of Fredericks et al. (1998) and Ibanez et al. (2014) would have little framework overhead regardless of hard drive reads and writes because of extremely long model runtimes relative to the small data passing requirements. In designing a framework, though, care should be taken to minimize overhead because it may be applied to a large variety of models with different runtimes and data passing requirements.

3.3.2.2 Single versus Multiple Executable Approaches

Single executable applications typically require language interoperability, which has been enhanced through tools like Babel (Dahlgren et al. 2012) as used by Peckham et al. (2013). IPC techniques are well-known multiprocessing methods for establishing interoperability by being platform-, framework-, and language-independent (Magnoni 2015). As discussed in Section 2.2, prior frameworks have either required models to implement IPC mechanisms or major refactoring to break models into subcomponents for fine-grained interactions in multiple executables, trading off invasiveness with the number of interface requirements.

3.3.2.3 Discussion of Previous Work

With regard to Targets 1 and 2, when a model requires significantly refactoring for model integration purposes or dependencies on the integrated modeling system (i.e., either other models or a model integration framework), it often no longer retains individuality or separability from the framework. That is, we argue that invasiveness and excessive interface requirements discourage adoption, maintainability, and reusability of the integrated model code base by splitting legacy models into two code bases, one that implements the interface and one that does not. These two model code bases can sometimes be merged into one when interface requirements are minimally invasive as in the case of BMI (Peckham et al. 2013).

Laniak et al. (2013b) express a need for interoperability (Target 3) between different disciplinary models and between integrated environmental modeling frameworks that are implemented with different programming languages, compilers, and platforms (Matott et al. 2009). IPC techniques address this need for interoperability between models with varying architectural, platform, or license dependencies, but has previously required invasive approaches or required extensive programming expertise (Targets 1 and 2). Compiling multiple models together into one executable requires models be interoperable either directly, or at least utilize a language interoperability tool such as Babel (Dahlgren et al. 2012). In our experience with re-implementing the approach by Yuan et al. (2011) discussed in Section 5, interoperability of original model code was also compromised when compiling legacy models together because of conflicting compiler flags, and overlapping global variable names or file handles. Also, maintaining the state of the submodel between timestep advancements required additional debugging and refactoring. Baart et al. (2014) improved interoperability of models implementing the Basic Modeling Interface (BMI) through an IPC technique.

Although component-based modeling may be easier to understand and program, Target 4 with regard to linking closed-source models prohibits excessive refactoring of model code, which would need to be done by the model developer. Dozier (2012) showed that event constructs can be utilized to decouple model codes, maintain model individuality, and allow plug-and-play with different models, even closed-source models. Becker and Schuttrumpf (2011) improved interoperability (Target 3) of this approach by implementing the Open Modelling Interface (OpenMI) standard (Moore and Tindall 2005) for a closed-source model through event constructs and remote procedure calls. However, the extent to which a geophysical scientist is capable of programming IPC in a similar manner is extremely limited, consequently negatively impacting its potential acceptance in the broader modeling community.

Data structures need to be reconciled when compiling models together or performing inter-process communication, but are facilitated by input and output file formats when passing data via the hard drive (Target 5). Although exchanging data via subroutines is one of the most utilized approaches for fine-grained integration, legacy model developers do not often maintain support of model integration interfaces, thus downplaying advantages of plug-and-play model integration (Donatelli and Rizzoli 2008; Lloyd et al. 2011).

Performance overhead (Target 6) must be taken into consideration especially in cases when data must be passed between models at a fine-grained resolution in time or space relative to the number of computations performed by each model. Hard drives and networks communicate data between models more slowly than main memory, but overhead may be minimal when computations outweigh data exchange requirements.

3.3.2.4 A New Interface

A generic interface for decoupling computations and disciplinary models using IPC (to address interoperability, Target 3) without requiring extensive legacy code refactoring (Target 1, 2, and 4) or unacceptable performance overhead (Target 6) while generically allowing for data structure reconciliation (Target 5) still remains to be developed. MODPI is introduced here to address this need by attempting to satisfy each of the framework design targets through use of an event-based publish-subscribe system with a message broker (Salas 2012). Although there are still limitations to the use of MODPI and required work on the part of the modeler, MODPI represents a significant advancement towards satisfying each of the framework design targets. Figure 4 displays a schematic of the form of model integration presented by MODPI.

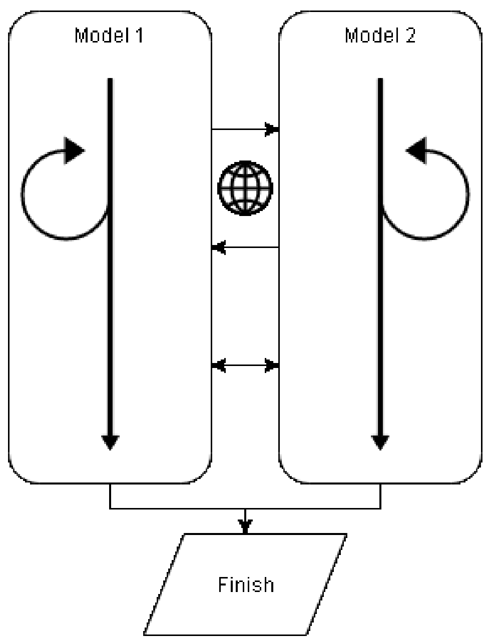


Figure 4: Selected implementation of MODPI links model coupling equations either implicitly or explicitly, and passes data through publisher-subscriber interactions across separate processes. Depending on the inter-process communication mechanism and machine setup, data can be passed through either hard disk, shared memory, or network communications.

Section 3 describes the interface, its components, requirements, and optional features. Section 4 describes the implementation of the MODPI integration platform and choice of IPC mechanism for interoperability purposes. Section 5 illustrates the use of MODPI with a case study application linking two legacy models, DayCent and HYDRUS. Section 6 summarizes the results of the case study by presenting measures of required code modifications and performance of the integrated modeling system. Section 7 presents discussions of benefits, limitations, advantages, and disadvantages of MODPI and its use for further different studies. Section 8 concludes with a discussion about the benefits of MODPI, its design considerations, and results of the case study application, while Section 9 presents potential future work to improve this study and future implementations of MODPI.

3.4 The Model Data Passing Interface

MODPI provides read and write access to any relevant variable by name within a legacy model during simulation without legacy code refactoring through use of event constructs and an automated IPC message broker. MODPI formalizes, adapts, and expands the approach used by (Becker and Schuttrumpf 2011) to generically and automatically apply IPC to any model, open-source or closed-source. A legacy model must implement the following elements to become MODPI-compatible:

1. Legacy model as a library with MODPI directives as code comments
2. Generated wrapper program with optional customization
3. XML linkage file

These essential elements of MODPI are discussed in the following three subsections and shown in Figure 5 for a sample model. The *MODPI integration platform* refers to a controller that automates code generation (for event constructs and wrapper programs) and runs the integrated modeling system. The component that exchanges data between models during simulation using IPC is called the *MODPI Broker*.

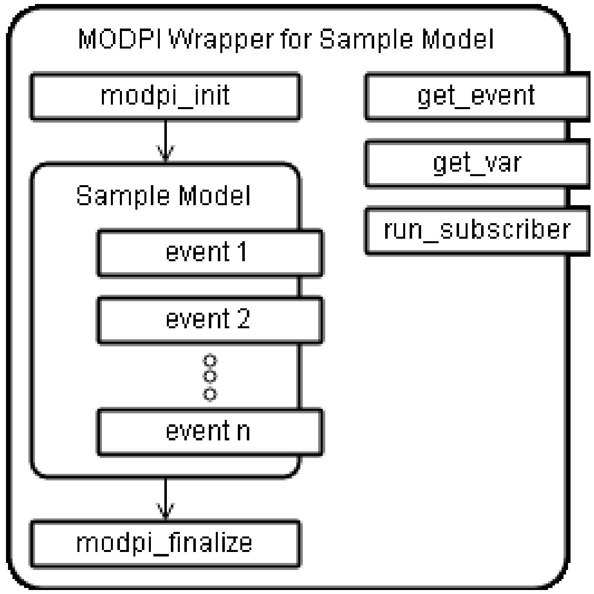


Figure 5: Schematic of a wrapper program for a sample model that implements the Model Data Passing Interface (MODPI) using its three interface functions get_event, get_var, and run_subscriber, and runs the MODPI-compatible sample model after initializing and before finalizing

3.4.1 Legacy Model as a Library with MODPI Directives

A legacy model that implements MODPI must be accessible to the MODPI integration platform as a library, and must contain MODPI directives. Prior to compilation, the MODPI integration platform requires MODPI directives to generate the event constructs, but during compilation and runtime, it requires the actual event constructs to access model data. Thus, MODPI allows for the capability of wrapping closed-source models when generated event constructs are kept within the pre-compiled libraries delivered to model users, after which MODPI directives are no longer required to stay in the source code. The requirements for MODPI compatibility are very minimal changes to a legacy model code base. The model does not need to be decomposed into initialization, body, and finalization subcomponents, but remains entirely intact. The hardest legacy models to refactor into multiple components are poorly modularized codes that utilize a lot of global data. These very common, yet poorly modularized models provide good use cases for MODPI since localized model data requires additional event data constructs where global data does not.

Although being able to access both local and global data within a model allows MODPI flexibility, the model developer (in the case of closed-source models) or the one integrating models (in either closed-source or open-source models) should still take care to encapsulate or hide data from the model integration interface that should remain "private" in accordance with good practice. Local data is hidden from MODPI by not providing it as event data. Global data is hidden at compilation by not exporting certain variables to the library.

Directives have the following syntax directly after a comment mark ("!" in FORTRAN or "//" in C) to add an import statement and to invoke an event, respectively:

```
!MODPI$ use
!MODPI$ event <event_name>(<type> <intent> <variable_name> [<size>] …)
```

MODPI directives are placed within the legacy model code as code comments to support automatic generation of event, or callback, constructs to allow any number of subscribers to access local or global data at various points during model execution. Automatic generation of event constructs from directives is a functional requirement for integration platforms implementing the Model Data Passing Interface to simplify programming responsibilities for the modeler, and to render MODPI less invasive. Automation is especially useful in low-level languages such as FORTRAN and C due to the lack of language-supported event constructs. Event constructs may remain in the model without affecting its normal execution either apart from or within MODPI linkages.

Using MODPI directives, the automated event generator determines where to place use or import statements, when to fire events, and the data to provide as event data. If all variables declared locally are to be added as event data, the keyword all locals is used in addition to any variable names used. Types are declared using either C or FORTRAN data type syntax (e.g., int and integer are interchangeable). If the event invocation lies within a C source file, the type should include an asterisk symbol ("*") when a variable is declared as a pointer within the surrounding context. Intent of event data is an optional parameter that is declared using the following FORTRAN syntax:

1. intent(in): variable is passed by value
2. intent(inout): variable is passed by reference (or as a pointer)
3. intent(out): variable is an output parameter only

Intent is used primarily to ensure that parameter types are passed by value when declared as a constant, instead of being passed as a pointer, the default in FORTRAN. If a variable is an array, its dimensions are specified using square brackets after the variable name similar to a C declaration, and includes constant numbers or other variable names. The modeler tasked with implementing MODPI for a model will want to ensure that data that is meant to be read-only should be passed as value with intent(in).

The entire MODPI-compatible model is called as a subroutine within the compiled library. The model must not exit in a nonstandard manner (e.g., through using the stop keyword in FORTRAN) because the IPC mechanism needs to be finalized. An optional consideration for making a model compatible with MODPI is to ensure that any redundant calculations are switched off. As in the case study in Section 5, a detailed, physically-based model replaces the soil-water submodel of the biogeochemical model, which is switched off to avoid calculations that are overridden anyways.

3.4.2 Generated Wrapper Program with Optional Customization

A wrapper program implements MODPI for a legacy model by using the legacy model as a library. The MODPI integration platform generates the wrapper program in addition to the event constructs given MODPI directives, the XML linkage file, and an optional custom, user-written module. Any custom actions written in the module are not overwritten when code generation is performed, but are rather subscribed to events in the model based on subscriptions within the XML linkage file. The wrapper program implements through interface functions, initializes and finalizes

MODPI, and runs the legacy model.[4] Figure 5 shows each component and control flow of a wrapper program.

When initializing, the MODPI Broker first obtains user-specified model connection information from the XML linkage file. Then, it subscribes event handlers to event constructs, and initializes the IPC mechanism. After executing the model, the MODPI Broker finalizes the IPC mechanism. The wrapper program informs the MODPI Broker when to initialize and finalize by performing the following three tasks consecutively:

1. Initialize MODPI by executing modpi_init
2. Run the model by executing its main subroutine
3. Finalize MODPI by executing modpi_finalize

The wrapper program also implements three interface functions:

1. get_event: retrieves events within the model
2. get_var: retrieves data within the model
3. run_subscriber: executes custom subscribers to the model

These three functions allow the MODPI Integration Platform to retrieve model events and data, and to run custom subscribers during runtime based on specifications within the XML linkage file described in the next section.

Custom subscribers perform any calculations necessary to convert and manipulate data for any connection with another model (or modeling system) without requiring code changes to the original legacy code base. During runtime, the MODPI Broker automatically subscribes any custom data converter to events specified by the XML linkage file, allowing the modeler to easily toggle specific data conversions. Additionally, custom subscribers are compiled into the wrapper program for a model, not into the model itself, thus decoupling model integration customization from the

[4] A detailed discussion of each interface function and other attributes of wrapper programs is found at https://bitbucket.org/adozier/fortmodpi/wiki/wrapper_detail

model to aid maintainability of the integrated modeling system with future updates to the model code base. Still, custom subscriber modules must be updated when there is a change in names or locations of events and event data in addition to when a data structure is altered. When custom subscribers are changed, the automated code generator needs to be executed again to generate a run_subscriber routine that runs new custom subscribers. Although custom data conversions might require more maintenance than if the MODPI Integration Platform performed generic data conversions, MODPI remains minimally invasive because it does not require certain data structures within MODPI-compatible model code bases. Since customized model integration actions are performed outside of the model library through events and event data, there are minimal maintenance requirements compared to approaches that add framework dependencies to the model code.

3.4.3 XML Linkage File

An XML file specifies data to exchange between MODPI-compatible models. Its structure provides the list of connected models, the data that is to be exchanged, the data conversions that are to take place, and the intermediate data required for data conversions. When building the XML file, a modeler must be able to understand that data can be passed from one model to another during its execution, but is not required to know how to program message passing into any code.

At runtime, the MODPI Broker requires the XML file to be named "modpi.xml" and found in the working directories for each of the models. Prior to runtime, the MODPI integration platform copies and renames the original XML file into each of the working directories automatically. The XML file path is not passed to MODPI as a command line argument so that some legacy models do not attempt parsing the file path incorrectly, as MODPI is designed to be minimally invasive. Examples and detailed descriptions of the XML file are found in the repository.[5]

[5] The XML file definition is found at https://bitbucket.org/adozier/fortmodpi/wiki/xml

3.5 The MODPI Integration Platform

This section describes the MODPI integration platform developed and used in this paper. Figure 6 displays the steps required to implement MODPI for any model, where preliminary model changes and MODPI directives allow a wrapper program to be generated. Linkage to another model is provided through the MODPI XML linkage file. MODPI is highly interoperable between programming languages and platforms, being tested in FORTRAN, C, and C++, and preliminarily tested in Java and MATLAB script on both Ubuntu and Windows operating systems. MODPI has also been tested to straddle different virtual machines, different physical machines, and Ubuntu and Windows operating systems, running one model in Ubuntu and the other in Windows.

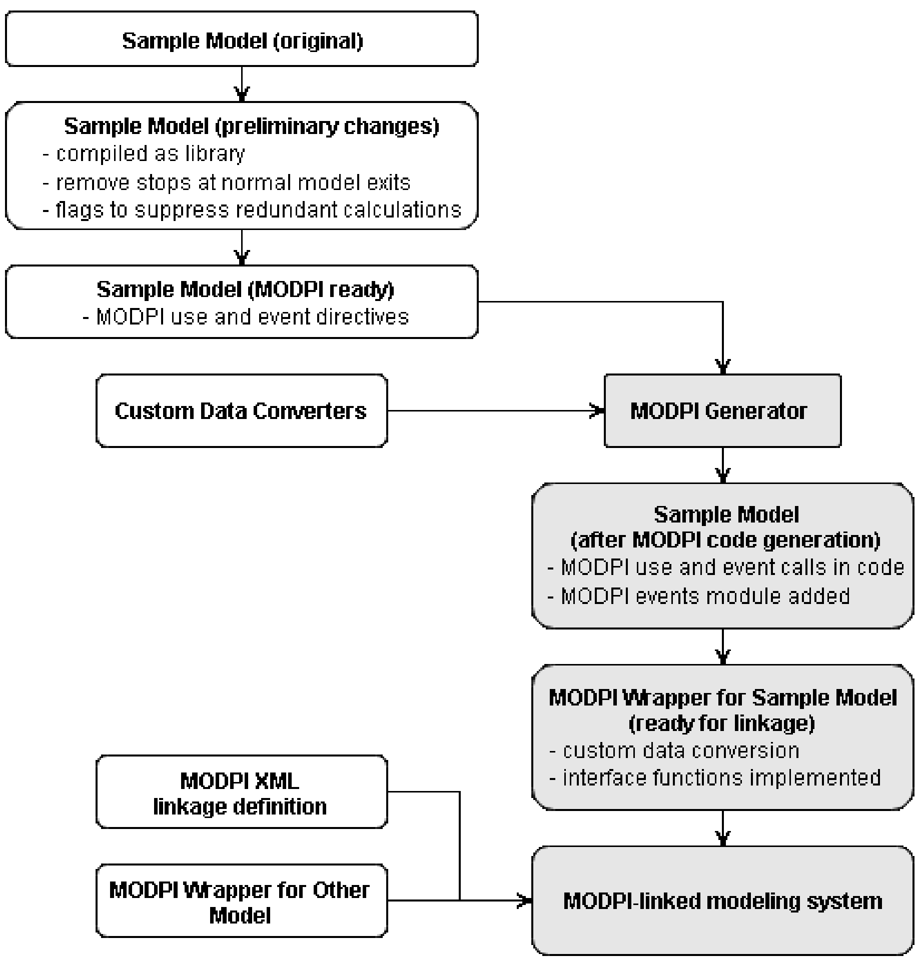


Figure 6: A flow chart displaying steps to implement MODPI for a generic model. A MODPI wrapper code generator within the MODPI integration platform called "modpi_generate.py"

automates the generation of events, event data, and MODPI interface functions. Gray elements highlight the generated components of the integrated modeling system.

The subsections below describe concepts and features of three components of the MODPI integration platform:

1. Event constructs
2. The MODPI Broker
3. The automated code generator

Two generic libraries, one for event constructs and one for the MODPI integration platform, are used within this paper to demonstrate implementation of MODPI. Concrete code references and detailed descriptions for the XML linkage file, event constructs, wrapper programs, automatic code generation and execution, and tutorials on using the MODPI integration platform can be found at the online MODPI repository.[6]

3.5.1 Event Constructs

The term "events" instead of "callbacks" is used here because the MODPI integration platform utilizes new object-oriented features of the Fortran 2003 standard. Events refer to a class of objects that run any number of subscribed subroutines to allow for customization without changing the control flow of the original code or adding many logic statements. Event invocations are placed in locations within the code of a model or component where something of interest happens or is about to happen.

Subscribers are subroutines that handle an event to perform customized calculations with model data at the location of the event during model execution. When invoked, an event executes each subscribing subroutine while passing data associated with the event as an argument. When no

[6] The open-source and publicly available repositories for the implementation of events and the MODPI integration platform is found at https://bitbucket.org/adozier/fortevents and https://bitbucket.org/adozier/fortmodpi, respectively.

subscribers exist, the firing method of the event simply exits, consequently leaving the original flow of the model unchanged.

Figure 7 illustrates events and subscribers for a sample model that adds the numbers one through ten. The wrapper subscribes to events within the sample model, and thus has access to local data that the event provides in addition to any globally exported variables within the library. In this sample case, the subscriber negates the calculations made by the sample model prior to the calculations being performed. If the sample model is executed by itself, it runs normally without needing recompilation.

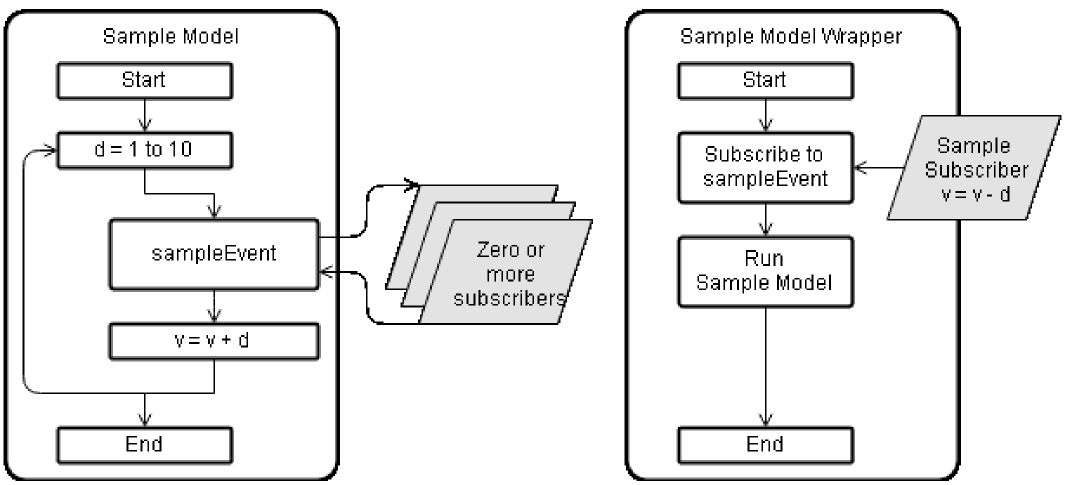


Figure 7: Schematic of a sample model that adds the numbers 1 through 10, and a wrapper that subscribes to the event within the data. This subscriber simply negates the addition within the sample model.

Events add value to MODPI by decoupling the model from the integration platform while still allowing access to model state, whether local or global, during execution. To be MODPI-compatible, a model needs to fire events during its simulation, and its source code remains closed if desired when the model is compiled as a library and appropriate variables are exported. The legacy model code base is executed and maintained separately from its support of any specific integration with another model and separate from the integration platform. Other approaches, such as compiling models together or implementing an invasive model integration framework, create two separate code bases that need to be individually maintained in order to keep the integration intact with future versions of the model, whereas MODPI allows merging these two branches of code into one, reducing maintenance requirements. We argue that the use of events in MODPI will result in a higher probability of framework adoption by the broader modeling community because events reduce framework invasiveness by preserving model control flow and individuality.

A user of MODPI is not required to manually implement events within the legacy model, because the interface only requires MODPI directives within the comments of the legacy model code base. The MODPI integration platform then automatically generates the event constructs within the legacy model, without loss of generality since the event constructs are very generic structures. However, so that the reader understands the event construct, this section defines events and subscribers to reinforce why they render MODPI less invasive.

3.5.2 The MODPI Broker

The MODPI integration platform performs data exchange between models through a construct called the MODPI Broker, which uses IPC to exchange data between MODPI-compatible models and also automatically subscribes custom data converters to events within the models. The modeler looking to implement MODPI for a legacy model does not need to build the MODPI Broker. Figure 6 displays steps required to implement MODPI for a generic model, and distinguishes automated steps. This section discusses the features, functionality, and dependencies of the various MODPI Broker components.

The MODPI Broker developed for use in this paper is implemented in FORTRAN, which is currently the most commonly used language for legacy geophysical models. This broker implementation effectively links models built in FORTRAN, C, or C++. It utilizes either the Message Passing Interface, MPI (The MPI Forum 1993), or ZeroMQ (Hintjens 2013) as the selected forms of IPC since they are well-developed standards, have widespread community support, and have proved to be very interoperable approaches. Interaction schemes implemented in this version of the broker are MPI_Send and MPI_Recv (and similar calls for ZeroMQ) with limited broadcasting support. Due to the dependency of the MODPI Broker on MPI, the number of times a variable is sent from one model must be matched with the number of times a variable is received in the other model, and vice versa. Thus, if timestep loops encompass events where MODPI exchanges data, the number of timesteps must be equivalent across models. Otherwise, execution will hang at the end of the simulation.

Figure 8 illustrates the connection between the MODPI Broker, a MODPI-compatible model, and the wrapper program. The MODPI Broker subscribes to events retrieved by get_event and performs message passing between other models running as separate processes to exchange data retrieved through the get_var subroutine. The broker automatically subscribes and executes custom data converters to events within the model using the user-supplied run_subscriber subroutine. The implementation and interfaces for these subroutines are discussed in more detail in the online repository.[7]

[7] See footnote 6

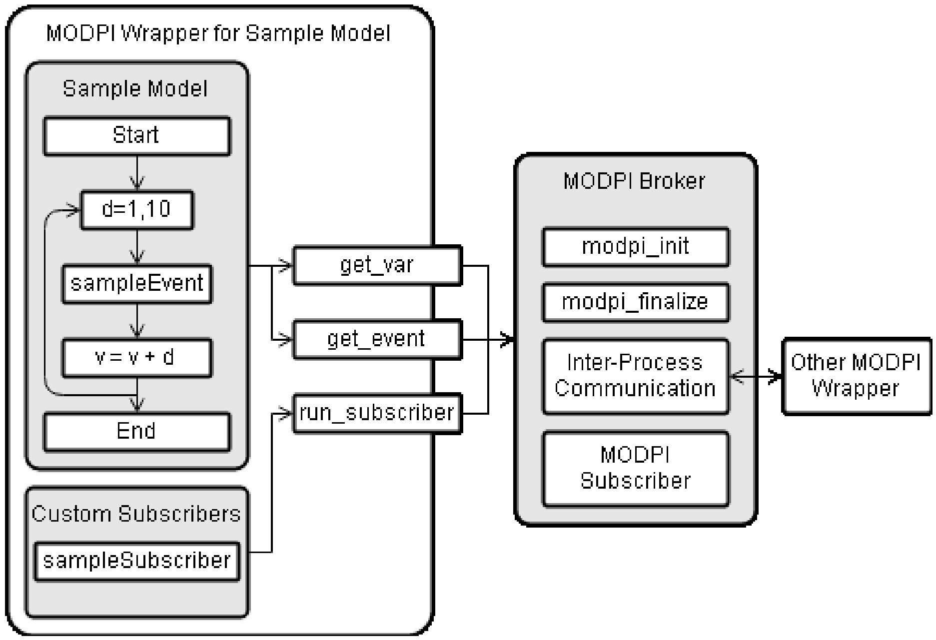
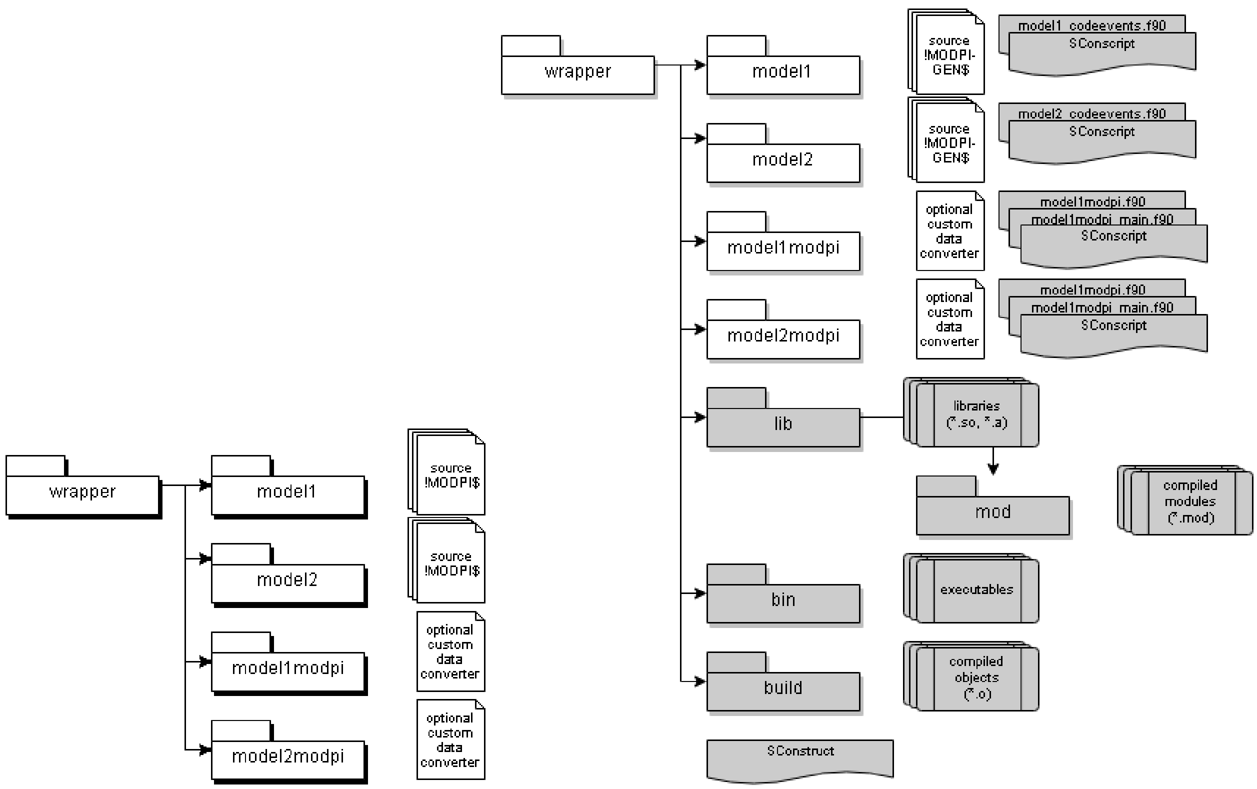


Figure 8: A MODPI wrapper for a sample model to illustrate how the MODPI Broker connects models through the use of the interface functions get_var, get_event, and run_subscriber and IPC.

3.5.3 Automated Code Generation, Compilation, and Execution

MODPI requires that events, event data, and necessary wrapper components be automatically generated from MODPI directives within the comments of the source code. Section 3.1 describes the syntax and usage of the MODPI directives, which render MODPI less invasive and potentially easier to use by novice programmers. To automatically implement MODPI for a MODPI-compatible model, the modeler places MODPI directives within comments of the original legacy model code, writes any necessary custom data converters, potentially creates an XML linkage file to declare intermediate variables, and runs the automatic generation tool. Code generation and automated compilation is performed for each model separately or for all models in the integrated modeling system simultaneously.

Automatic detection of model source files, custom data converters, and library directories is achieved through use of the recommended directory structure shown in Figure 9. After automated code generation, MODPI directives within the original model source code are replaced with import statements and calls to subroutines that fire events. A generated events module declares event constructs and associated event data, and is compiled into the original model source code. The generated wrapper program discussed in Section 3.2 includes the custom data converter and two other files that implement the three interface functions, initializes the MODPI Broker, runs the model, and finalizes the MODPI Broker.



a) Prior to code generation **b) After code generation**

Figure 9: Directory structure and naming conventions for automated MODPI wrapper generation. White elements are user-supplied, gray elements are generated.

Closed-source models are provided as a library, without original source files. If customization of the generated MODPI-compatible wrapper program is desired, the generated events module should be provided to users of the model. In the case study discussed in Section 5, DayCent acts as a closed-source model to demonstrate an implementation of MODPI for closed-source models.

The code generator automatically attempts to compile the generated wrapper program and associated model. Automated code compilation is meant for models and wrapper programs written in any combination of FORTRAN, C, or C++. Compiled libraries, modules, and executable files are automatically placed in their respective directory locations according to the directory structure shown in Figure 9.

Additional features of the code generator include options to remove all generated code, and perform automated execution of the integrated modeling system. Automated execution sets up and starts the MPI job in a fashion consistent with the model communication definitions found within the XML linkage file. The repository documentation discusses specific file locations, requirements and tools used for automatic code generation and execution of MODPI-compatible modeling systems.

3.6 Case Study Application Linking DayCent and HYDRUS-1D

To investigate invasiveness of MODPI, DayCent (Parton et al. 1998) and HYDRUS-1D (Simunek et al. 2008) are integrated using both MODPI and a previous approach where models were compiled into one executable and HYDRUS is called as a subroutine within DayCent (labeled the “subroutine approach” or “SUB”). DayCent provides daily simulation of biogeochemical fluxes using one-dimensional representation of vegetation, atmosphere, organic decomposition, and water movement through the soil (Parton et al. 2001). DayCent and HYDRUS-1D have been previously linked using the subroutine approach to analyze the added benefit of improved soil-water dynamics, because HYDRUS-1D provides necessary physically-based modeling of soil water content at fine time and spatial scales (Yuan et al. 2011). This linkage serves as a benchmark to compare the MODPI approach.

The subroutine approach is used to call the finite element solver within HYDRUS-1D as a subroutine within DayCent. Yuan et al. (2011) provided code for the implementation of the subroutine approach for DayCent-HYDRUS. Since DayCent and HYDRUS are compiled together, code bases of the integrated models are dependent on each other, and no longer stand as individual models. Additional changes to the code are difficult to separate from the integrated DayCent-HYDRUS modeling system. The original linkage combined an earlier version of DayCent with an earlier version of HYDRUS (Yuan et al. 2011). For our investigation, we utilized the current versions of DayCent and HYDRUS to integrate the models using the same approach and data conversion code. The updated linkage required nontrivial adaptation of the code to carefully preserve HYDRUS model state between daily timestep updates within DayCent. These characteristics and requirements demonstrate the difficulties of maintaining individual legacy model code to support integration with another model using the subroutine approach.

The second approach integrates the models using MODPI. DayCent and HYDRUS are minimally changed to compile as libraries. Original data conversion between DayCent and HYDRUS provided by Yuan et al. (2011) is preserved and supplied to the DayCent-HYDRUS model as a custom subscriber. By placing conversions within the wrapper program through custom subscribers, modifications to the DayCent library are avoided. MODPI directives are added to the original source files, and the MODPI wrapper code generator creates event constructs and event data within each model. The MODPI-compatible DayCent and HYDRUS executable files still execute independently, just as before MODPI integration. A wrapper program implements the MODPI interface for each model. The only dependency for MODPI-compatible DayCent and HYDRUS is the event library discussed in Section 4.1.

Figure 10 illustrates the evolution of the DayCent model code base to make it compatible with MODPI. HYDRUS underwent a similar process. A connection between DayCent and HYDRUS using MODPI is achieved through the following three steps:

1. Minimal code modifications include creating a new program entry point, removing nonstandard model exits using the keyword stop, and refactoring code specific to the

Windows operating system to compile and run HYDRUS on Linux using GNU compilers.[8] Two MODPI directives are added to DayCent, and five to HYDRUS, in locations where the most desirable model states for linkage are achieved.

2. A single XML linkage file is built to provide specific information on data exchanges between the models.
3. Model events and a wrapper program are generated using the automated code generator.

The XML linkage file, events, and wrapper program for the DayCent-HYDRUS integrated model are found in the MODPI open-source repository.[9] The link between DayCent and HYDRUS achieved through MODPI was intuitive because it provides access to model state at specific locations within the code. Unlike the subroutine approach, the MODPI-connected DayCent-HYDRUS did not require special consideration to preserve model state, because model state is internally preserved in HYDRUS when running as its own process without an adapted control flow.

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[8] Code for DayCent is available by email. Code for HYDRUS-1D is available in the repository https://bitbucket.org/adozier/fortmodpi.
[9] Ibid. 6

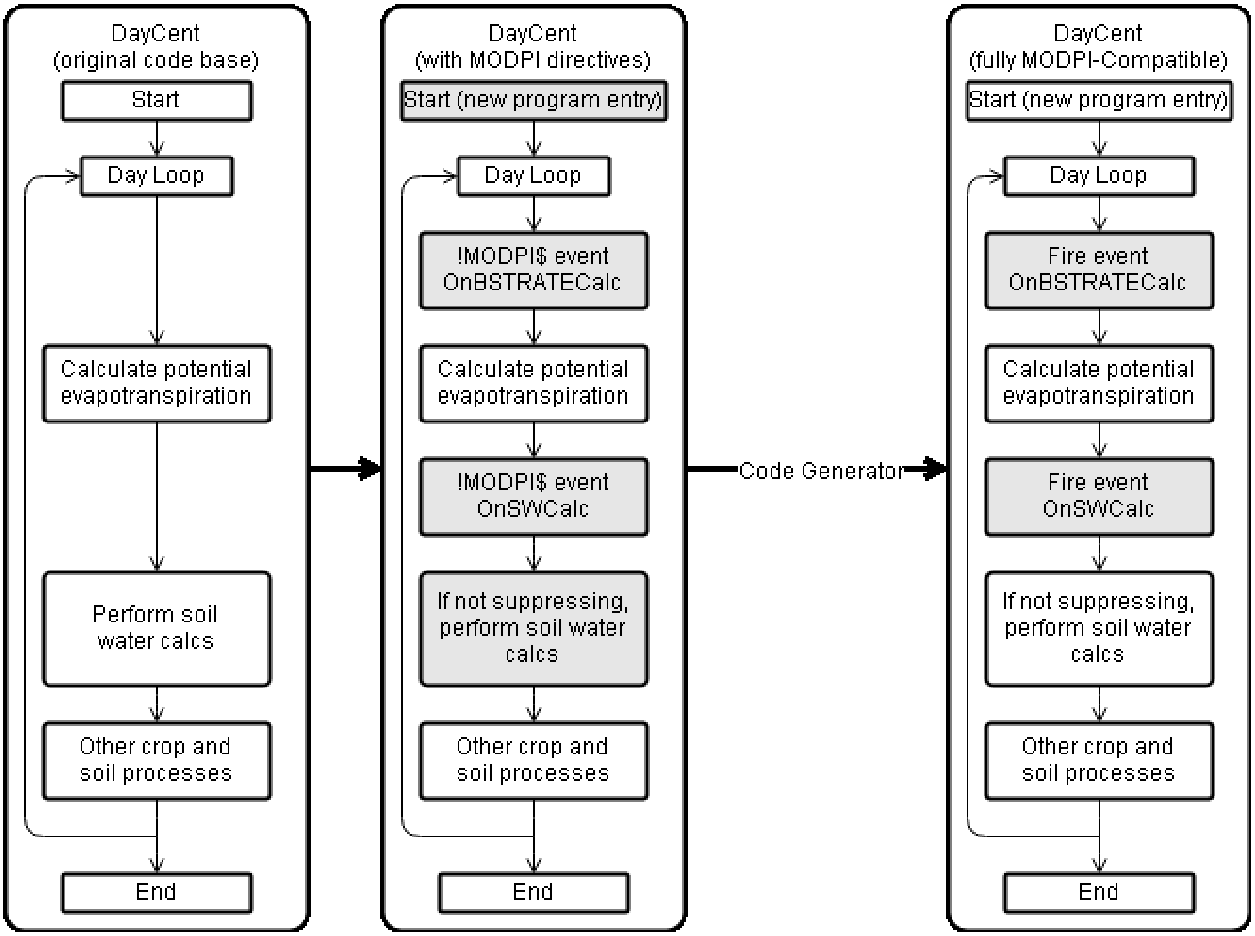


Figure 10: A flow chart displaying the evolution of DayCent from its original code base (left), to the MODPI-ready code (middle), to the full MODPI-compatible code (right). The MODPI integration platform generates events and event data that are placed into DayCent. Gray elements highlight incremental changes made within the legacy model code base.

Figure 11 displays the flow of data for the DayCent-HYDRUS connection and the events at which custom data converters are subscribed to each model. At runtime, the wrapper programs for DayCent and HYDRUS are started as two separate processes, running in parallel. MODPI enables the models to exchange data using MPI over the network, or shared memory if both processes are running on one machine.

Within a DayCent-HYDRUS simulation, MODPI sends precipitation (pptsoil), potential evaporation (bserate), potential transpiration (bstrate), and root depth (tadep) from DayCent to HYDRUS prior to calculating soil water flux within HYDRUS. Since HYDRUS has an adaptable timestep but DayCent has a daily timestep, output data from HYDRUS is summarized at a daily timestep within the subroutine OnOutput_handler, in which the event OnCumQdlyCalc fires every day. Within the XML linkage file, the summarized daily output data are sent back to DayCent from the OnCumQdlyCalc event, not directly from the OnOutput event, which fires at a sub-daily timestep. The number of layers n, the depth of each layer x, an array cumqdly containing actual evaporation, transpiration, drainage, and runoff data, flux of water between soil layers vnacc, and soil water content of each layer thnew are received by DayCent at the event OnSWCalc. After arriving, the variables are converted within the custom subscriber convert_SWCalcs and used to update model state of DayCent. Other custom subscribers set variables or flags that aid linkage between DayCent and HYDRUS to improve console output readability.

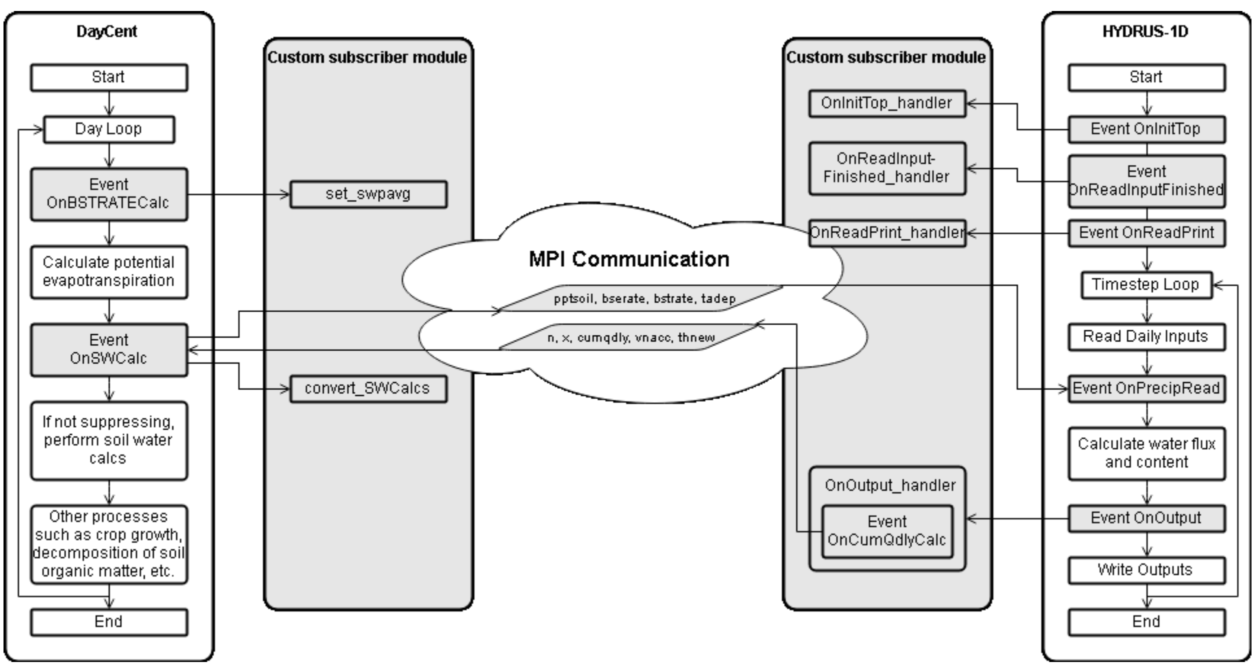


Figure 11: Data flow between MODPI-connected DayCent-HYDRUS. Links to and from events represent subscriptions that are automatically attained by the MODPI integration platform. Gray elements are essential for MODPI to perform linkage between DayCent and HYDRUS. Custom subscriber modules and the list of data to exchange between models found in the XML file are manually constructed, but events are automatically generated from MODPI directives within the code.

3.7 Results

DayCent-HYDRUS serves as a case study to benchmark the MODPI integration platform presented in this paper.[10] This section quantifies invasiveness and performance of MODPI in comparison with the subroutine (SUB) approach.

3.7.1 Code modifications

The goal for developing MODPI is to reduce invasiveness of model integration tasks, thus necessitating use of metrics. Here, we quantify invasiveness using five software metrics based on lines of code (LOC):

1. Code modifications within each model code base (IN-LOC)
2. Code additions outside of each model code base (OUT-LOC)
3. Directive additions within each model (DIR-LOC)
4. Generated lines of code within the model (GEN-IN-LOC)
5. Generated lines of code outside of the model (GEN-OUT-LOC)

The first (IN-LOC) attempts to quantify the amount of work performed within each model code base, and serves as a surrogate measure for the amount of effort that would be required to maintain the integrated modeling system with changing versions of the original code base. The rest of the measures are specific to the coupled modeling system implementing MODPI in the case study. The second (OUT-LOC) attempts to measure the amount of work required to maintain the integrated model only when events or variables within the original model code base are renamed or moved. The third (DIR-LOC) attempts to quantify the amount of work performed to implement syntactically correct MODPI directives within the model code base, although there is no dependency of MODPI within the model through the use of directives since the directives are placed within the comments and not in code.

[10] Case study model files for the DayCent-HYDRUS integrated model are found at the Environmental Risk Assessment Management System (eRAMS) Resource Center: https://erams.com/resources/Platform/MaaS/Model_Integration

Finally, the GEN-IN-LOC and GEN-OUT-LOC metrics attempt to identify the amount of generated code that benefits abstraction and interoperability of model integration through inter-process communication. GEN-IN-LOC quantifies the number of lines of code to invoke events within the model, and is equal to 1 when global data is retrieved at an event and greater than 1 when using local data, which populates the event data construct. GEN-OUT-LOC quantifies the lines of code generated for the model wrapper that implements the Model Data Passing Interface for the model, but is compiled separately from the model code base.

The first three measures are better when lower assuming the same level of difficult, elegant code writing between each model integration technique. The fourth and fifth measures depend on modeler preference because they add value to the integrated modeling system but are additional lines of code not readily understood by the modeler. Therefore, GEN-IN-LOC and GEN-OUT-LOC are provided here for evaluation by the reader.

IN-LOC and DIR-LOC are invasive according to the definition in the introduction, and OUT-LOC and GEN-OUT-LOC is not since they are code additions outside of the original model code base. Attribution of invasiveness to GEN-IN-LOC is more subjective since some work is performed by the modeler run the generator, which is a relatively cheap operation compared to manually writing the code. MODPI outperforms SUB for code changes within the model (IN-LOC plus DIR-LOC), but requires more changes outside of the model (OUT-LOC) in addition to generated lines of code (GEN-IN-LOC and GEN-OUT-LOC).

Understand 3.1 (Scientific Toolworks 2014) was used to quantify total LOC for each model, which do not include comments or blank lines. Code modifications within each model code base are identified as insertions and deletions in the Mercurial version control system.[11] For each changeset in the Mercurial repository, all blank and commented lines were removed except for MODPI

[11] Mercurial documentation and software is found at http://mercurial.selenic.com/.

directives to quantify DIR-LOC. Although utilizing insertions and deletions through a version control system captures changed lines of code as an additional work item not otherwise captured when counting total LOC, changed lines of code are represented by both an inserted and deleted line of code, and are thus double-counted.

Table 2 shows code modifications necessary to integrate DayCent and HYDRUS for each approach. DayCent contains 236 source files with 23,057 LOC, and the original HYDRUS code base contains 9,034 LOC in 10 source files. The baseline HYDRUS code base used in this analysis is a Linux-compatible version with 8,995 LOC. The SUB approach required 123 (and 562) LOC modifications to the DayCent model (and the HYDRUS-1D model, respectively) specific to the integrated modeling system. The MODPI approach required only 116 (and 204) LOC modifications within DayCent (and HYDRUS-1D), 11 (and 21) of which are manual modifications while the rest are generated. Total LOC modifications including the wrapper code to link DayCent (and HYDRUS-1D) using MODPI were 354 (and 515) LOC, while only a total of 87 (and 109) LOC were manually modified.

Table 2: Comparison of code modifications (insertions plus deletions) of lines of code (LOC) within DayCent and HYDRUS (Linux version) using the subroutine (SUB) and MODPI approaches to model integration.

Code Base	LOC	IN	OUT	DIR	GEN-IN	GEN-OUT	TOTAL
DayCent	23,057						
SUB	23,157	123	--	--	--	--	123
MODPI	23,399	11	74	2	103	164	354
HYDRUS-1D	8,995						
SUB	9,066	562	--	--	--	--	562
MODPI	9,455	21	78	10	173	233	515

Five MODPI event directives and five import directives (10 DIR-LOC total) are added to the HYDRUS code. Import directives are required in FORTRAN for utilizing event constructs and subroutines found in modules. However, the same requirement does not apply to events invoked through subroutines from C source files, and thus only two MODPI event directives and zero import directives (2 DIR-LOC total) are added to the DayCent source code.

Yuan et al. (2011) provided 82 LOC that perform data conversion between HYDRUS and DayCent for the SUB approach within the DayCent model code, and is reported within the IN-LOC measure for DayCent. These LOC were adapted slightly to convert data within the MODPI linkage using a custom subscriber, and are therefore reported as OUT-LOC for DayCent (74 LOC) because the changes remain outside the original model code base. MODPI-compatible HYDRUS-1D incorporated 78 lines of converter code.

Filling event constructs with data and invoking them consume 103 and 173 LOC while generated wrapper codes include 164 and 233 LOC for DayCent and HYDRUS-1D, respectively. These generated LOC represent 75% and 79% of the 354 and 515 LOC changes for DayCent and HYDRUS-1D, respectively. These LOC are provided to the modeler as value-added attributes of MODPI, but they also represent code that is not readily understood by the modeler.

Minimal IN-LOC modifications for MODPI-compatibility come from adding flags to suppress redundant calculations and creating a new entry program (main) routine that calls the original entry as a subroutine. Total LOC for HYDRUS is based on a Linux version derived from the original Windows version with minimal changes. IN-LOC modifications for HYDRUS-1D are slightly disproportionate to the LOC within the SUB linkage (562 LOC) because several hundred file handle constants were changed to be able to compile HYDRUS-1D directly with DayCent.

All 123 (and 562) LOC modifications for the SUB approach in DayCent (and HYDRUS-1D) are integration-specific and consequently invasive. The MODPI approach does not require any integration-specific code changes within a model rendering it less invasive. However, the modeler can parameterize the automatic code generator to insert integration-specific event data to support a specific desired interface without effecting normal model execution or control flow. To illustrate this, modifications to DayCent include 12 lines of generated code that declare and allocate intermediate event data. This can be avoided by placing an event within the custom data converter (i.e., convert_SWCalcs in Figure 11) that directly receives data from HYDRUS. To illustrate the minimally invasive potential for implementing MODPI, generated modifications to HYDRUS contain 0 integration-specific modifications.

3.7.2 Performance characteristics

Use of MPI in the MODPI integration platform provides an opportunity to perform parallel processing on different CPUs and storage facilities, to potentially speed up model execution. The DayCent-HYDRUS integrated model, however, does not contain overlapping computations beyond initialization and output file writing, leading to little potential for parallelization. Consequently, network communication overhead may be an issue leading to slow model execution. To address this issue, four different HYDRUS models with differing discretizations of soil layers (50, 100, 300, and 1000) are used to help diagnose performance issues from arbitrarily increasing the number of computations between MPI network access. Computational overhead for DayCent-HYDRUS is assessed by comparing runtimes between the MODPI-connected integrated modeling system with those of the baseline subroutine (SUB) approach. Although runtime combines both overhead due to MODPI (and network communication) and time reduction due to parallelization, it serves to compare the SUB and MODPI approaches, and is more readily reproducible.

Tests are performed on a single SUN Blade x6270 server running Ubuntu 12.04 with two quad-core 2.8 GHz Intel Xeon processors each with hyper-threading for a total of 16 logical cores. The servers offered 72 gigabytes of random access memory (RAM), and 145 gigabytes hard disk storage on a virtual local area network (VLAN) network connected with a 1 gigabit switch.

Table 3: Mean runtime (in seconds) for 200 DayCent-HYDRUS simulations when linked using both the subroutine (SUB) approach and MODPI. Four models were run with varying numbers of soil layers (50, 100, 300, and 1000) within HYDRUS to arbitrarily increase computation time between network access. Bold MODPI mean runtimes highlight statistically significant differences from the corresponding SUB mean runtime with a p-value < 0.01.

Integration Type	HYDRUS Layers			
	50	**100**	**300**	**1000**
SUB	2.37	5.79	43.8	75.5
MODPI	2.40	5.79	43.4	74.9

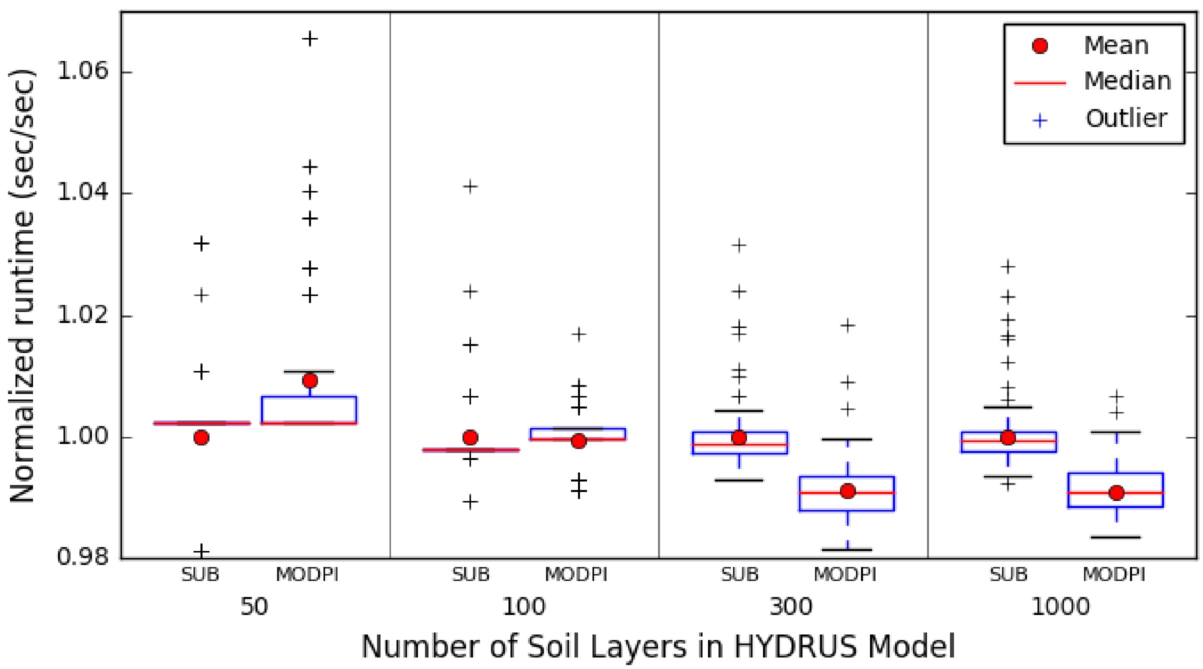


Figure 12: Normalized model runtimes of 200 identical simulations comparing the subroutine (SUB) approach with MODPI on a single machine with four different HYDRUS model setups to arbitrarily increase computations between network access. Runtime is normalized by the mean runtime of the SUB approach for each HYDRUS model setup. Outliers are runtimes that occur outside of the 95% confidence interval assuming a normal distribution.

Table 3 summarizes runtimes of 200 identical test runs for each computational scenario, and Figure 12 displays associated runtime variability. Overhead due to MPI network communication within MODPI-connected DayCent-HYDRUS is minimal and is outweighed by benefits of parallelization for more computationally expensive scenarios. Mean runtime for the MODPI-connected model deviated from that of the SUB-connected model by -0.9% to 0.9%. MODPI outperforms SUB for computationally expensive models with 300 and 1000 soil layers. Additional performance analyses for MODPI found in Appendix B demonstrate larger overhead in virtualized environments and across machines, except in cases where there is little network communication relative to the number of computations and when running in Amazon EC2 instances.

3.8 Discussion

Very few code modifications are required to implement MODPI for a model compared to other model integration framework requirements for fine-grained, multidirectional feedbacks that would generally require significant refactoring of the legacy model code base. For the case study, although code modifications remain very minimal for both the MODPI and SUB model integration approaches, MODPI is less invasive for the following reasons:

1. Code changes are not specific to the linkage between DayCent and HYDRUS
2. Code changes retain the control flow of the original code base
3. DayCent and HYDRUS are not compiled together, nor do they depend on each other or even on MODPI after integration
4. Fewer code changes are required within each model using MODPI than required by the SUB approach to model integration

By utilizing custom subscribers for external data manipulation and accessing variables and events by name, wrapper programs support a plug-and-play methodology for linking MODPI-compatible models or systems of models. Customized calculations can be turned on and off within the XML linkage file without having to recompile or generate model wrapper code again. Models using MODPI still retain model individuality and can be run individually or when connected to MODPI, and even run on separate operating systems and frameworks. These are benefits that could not be afforded even if the SUB approach was re-implemented with events to decouple the model code bases from the integrated modeling system as performed by (Wible 2014).

There are advantages and disadvantages to using any model integration framework. Many situations exist where MODPI is a preferable approach to fine-grained model integration as discussed through the paper. However, there are situations when MODPI is not the preferable approach. Here we list situations on both sides of the spectrum starting with situations where MODPI is a preferable approach:

1. Integrating closed-source models with hidden or difficult input file formats
2. Performance overhead of input-output exchange between model runs is unacceptable
3. Subprocess representation within a model needs to be modified or overridden without changing the original model code
4. Poorly modularized legacy models that are otherwise difficult to integrate
5. Integrating models across different operating systems or frameworks
6. Integrating models without a predetermined number of connections to other models

Legacy models that are poorly modularized or that otherwise use a lot of global variables, which is characteristic of arguably most legacy models, are good use cases for MODPI because global variables grant MODPI easier access to model data. In this case, MODPI minimizes required refactoring for integration as compared to component-based frameworks, although care must still be taken to incorporate the correct model data in the linkage, as expected when using any model integration framework. Model integration with MODPI can also be performed across operating systems and has been shown to effectively link models across an Ubuntu and Windows systems. Although the current implementation of MODPI, the MODPI Integration Platform presented in this paper, has only been preliminarily tested in higher-level languages such as MATLAB and Java, the concept of multilingual frameworks is a well-known contribution of inter-process communication approaches. The use of events allows MODPI to grant publish-subscribe type interactions to models so that any number of subscribers (i.e., other models, visualizations, or analysis packages) can listen to events being invoked within the publishing model.

MODPI is not always the preferable approach to model integration due to the specific use cases that MODPI was designed to address. The following situations should prompt consideration before attempting to implement MODPI:

1. There is no intention to maintain up-to-date versions of integrated models and model codes are already easily interoperable
2. There is no need for within-simulation data access and exchange, or it is desirable to implement an iterative approach to obtain implicit solutions to equations
3. There is little potential for parallel execution but computational speed is high priority
4. The framework, language, or operating system is known not to support the inter-process communication mechanism (the MODPI Integration Platform currently supports both MPI and ZeroMQ)

If high performance is top priority for short jobs (less than 10 seconds), MODPI can help speed computations through parallel processing when possible, especially in high performance computing environments with high-end network hardware and proper configurations. Optimized configuration of a virtual environment and of the selected form of inter-process communication can also significantly improve performance. If no or very little parallel execution is possible for a specific model integration task, compiling models together (when possible) or utilizing events to decouple the models (still within a single process) without overhead due to inter-process communication may be a preferable approach.

The MODPI integration platform potentially reduces the amount of programming work and the required level of programming expertise for specific model integration tasks through automated wrapper generation. However, there are a few tasks to be performed by the modeler that must be taken consideration. First, the modeler must conceptualize the model integration task correctly regarding both semantics and logistics as must be performed for integrating any model regardless of the framework or approach. Second, linkage locations within each model must be identified based on where certain data is available. Either events can be placed where the data is available, and custom subscribers can track references to the data, or data handling within the model is slightly refactored to provide certain data at a specific event. Third, the modeler must have knowledge of either event constructs, which is more probable with higher level languages, or the syntax of MODPI directives and rely on the MODPI code generation process to make a model compatible with MODPI. Fourth, nomenclature of the XML linkage files must be learned for specifying the data to be passed between models. Fifth, debugging a parallel application with automatically generated code may prove to be more difficult than sequential, manual approaches to model integration. Finally, custom data conversions will likely need to be performed (and maintained) by the modeler since MODPI does not currently require specific data structures within its interface. Aggregation and data conversion in space or time must currently be performed by the modeler, but this may change in future versions of MODPI. Benefits of custom data conversion includes flexibility, applicability to a broader set of model integration tasks, and computational speed addressed by removing potentially slower generic conversions.

One significant benefit is that MODPI can be used to integrate models with closed-source models in a fine-grained manner. The closed-source model developer must be willing to add events into the model, compile the model as a library with exported and relevant model data, and provide the names of events, event data, and other model data of interest to the modeler. In this manner, the model can still be used for integration with other models without having to share the source of the code or input file format. Closed-source model developers in the environmental sciences would benefit from this because they would not have to directly support interfaces of model integration platforms, but could still attract users that want to integrate the model with another. A finite set of interaction points within the closed-source model can be provided to users that would allow for varying degrees of granularity in integration and customization. This has been done in closed-source models like MODSIM (Dozier 2012; Labadie 2010) and FEFLOW (Becker and Schuttrumpf 2011), for instance.

Potential users of MODPI include interdisciplinary researchers interested in model integration for improving process representation in geophysical modeling. Model developers for either open-source or closed-source models would be interested in using event constructs because they decouple the model from customized actions, other models, and model integration frameworks. Using events, model developers can maintain one code base instead of different code branches that implement interfaces for external integrated modeling systems. Modelers and consultants that perform integrated analysis of biophysical systems may find MODPI a useful framework for minimizing programming time while allowing for fine-grained feedbacks between models.

3.9 Conclusions

The case study application demonstrates that minimal code modifications to a legacy model are required to implement MODPI for a model integration task. Only 11 and 21 lines of code were manually modified within legacy model code bases respectively, compared to 123 and 562 lines of manual code modifications for a baseline approach. At runtime, MODPI-compatible models incorporate 116 and 204 lines of code modifications, respectively, including generated code and MODPI directives found in the comments. Although the case study application required some user-written custom data converters and a bit of MODPI-generated wrapper code, MODPI requires less code changes in the original model code base than the baseline "subroutine" approach.

Performance tests demonstrate that MODPI not only has minimal overhead for the use case on a single machine, but provides speedup through parallel execution of linked models. Further evaluation of performance results as described in Appendix B highlights worsening overhead when running across two machines, except when little network communication is performed relative to computations or when running in virtual machines in Amazon EC2, depending on hardware, hypervisor, and virtual network setup. Mean runtime of MODPI-connected models varies between -0.9% to 0.9% when compared to that of the subroutine approach, representing a shift from minimal overhead to minimal speedup for a model integration scenario with few overlapping computations.

Inter-process communication provides MODPI a large degree of interoperability across languages, platforms, hardware, and license requirements, although only fully implemented and tested in Ubuntu and Windows with FORTRAN, C, and C++. Closed-source models can be linked with other models using MODPI given that they come precompiled as a library with events. Customization allows any data structure to be converted and manipulated outside of the original model code base through use of event subscribers.

The design of MODPI attempts to address each of the six framework design targets discussed in Section 2. MODPI performs fine-grained, multidirectional feedbacks while remaining less invasive than other approaches, enhancing the maintainability and reusability of MODPI-integrated models. MODPI does not require any framework component or integration-specific code modification within the original model code base other than directives within model code comments and event constructs at runtime.

The MODPI-compatible model contains event constructs that generically provide read and write access to relevant data for model integration while preserving original control flow. The MODPI integration platform delivers most of these benefits by automated means, and therefore reduces modeler programming time.

Maintenance is minimal, but MODPI still does require care in event locations and naming, data access encapsulation and naming, and correct data conversion logic both within the wrapper program and the XML linkage file. Although inter-process communication offers interoperability and speed up through parallel execution, debugging a parallel program with automatically generated code is potentially more difficult than sequential approaches.

3.10 Future Work

Future work and developments will improve implementation of the MODPI Integration Platform to be more interoperable, generic, and widely applicable. Full MODPI implementations in Java, MATLAB, Python, R, and .NET languages will improve its assertion of interoperability. Although MODPI has already been tested on Ubuntu and Windows operating systems (and across both operating systems with one model on Ubuntu and one on Windows), more cross-platform tests for other operating systems such as Mac, Debian, BSD, HP-UX, Solaris, CentOS, and RHEL will increase its broader applicability.

MODPI benefits technically from not specifying data structures in order to allow model data to remain in its current structure to achieve minimal invasiveness, but this complicates generic data transformations in space, time, and across various data structures. Future research will focus on implementing generic data transformations within the MODPI Integration Platform followed by further advancements up the levels of conceptual interoperability model (Wang et al. 2009). Other future work on MODPI can be to implement it as a proxy between the model and a more generic model integration standard such as OpenMI or BMI for example, which will have a much broader impact on integrated modeling through use of open standards.

Currently, MODPI does not detect potential deadlock situations, but could in the future. Since timesteps are a common feature of many legacy environmental models, MODPI could be improved to include a timestep-tracking feature that detects when time periods are out of sync so that models do not hang at the end of execution waiting for more IPC. Another area of future work is to utilize MODPI to link more than two models or models in more spatial dimensions, since the current case study performs analysis only in one spatial dimension. Use cases for models with significant amounts of computation to be run in parallel will improve analysis of potential speedup benefits of MODPI.

4 BIOPHYSICAL MODELING SYSTEM

A multifaceted biophysical modeling system applies the framework developed in this dissertation to a water-limited basin with rapid urbanization and declining agricultural ownership of water, the South Platte River Basin (SPRB). The SPRB extends from the continental divide in the state of Colorado to western Nebraska (Section 4.1). Streamflow in the SPRB is driven by snowmelt, naturally peaking in May and June. New water supply developments such as reservoirs and trans-basin conveyance systems have become very difficult to implement because i) many river systems are already over-allocated, ii) environmental impacts and regulations impede construction, and iii) other prohibitive costs such as land acquisition and rights-of-way make large projects infeasible. Therefore, growing cities in the region are rapidly purchasing South Platte River water from the remaining major sources of water: agricultural producers. As revealed in this study, water rights are being traded at a rapid pace, while a decline in agricultural cropland and production follows at a slower rate.

The biophysical modeling system characterizes i) supply of water and land, ii) population and land use, iii) agricultural demand, iv) municipal demand, and v) the water rights market. A partial equilibrium model embodies the water rights market in the SPRB by representing cities as consumers of water rights and agricultural producers as suppliers of water rights (Section 4.2). The model is parameterized separately for agricultural producers and municipalities (Section 4.3). Agricultural producers attempt to maximize their profit from both producing crops and selling water rights. A well-tested agro-ecosystem model DayCent (Parton et al. 1998) represents irrigation, tillage, crop growth, crop water use, and farming and management practices (Section 4.3.1). Cities attempt to minimize cost of water rights purchases to sustain projected population growth via raw water purchase requirements placed on land developers, modeled with an empirically-based statistical model (Section 4.3.2). Agents within the partial equilibrium model are informed with spatially-varying transaction costs and water supply reliability in various subregions of the SPRB (Section 4.3.3). Estimates of urban water end-use and impacts of various management practices were derived from the Integrated Urban Water Model (IUWM) as described in Sharvelle et al. (n.d.), which is granted special attention in this chapter (Section 4.4).

Indicators for vulnerability of water resources and sustainability of agriculture are limited in this work to agricultural profitability of crop production and water rights sales, cost of water acquisition to municipalities, and a probabilistic estimate of reliability of water supply delivery (Section 4.5). Indicators were used to assess and analyze targeted alternative management practices to sustain agriculture at lowest cost (Section 4.6).

4.1 Case Study Region

The South Platte River Basin (SPRB) in northeastern Colorado includes a vibrant agricultural sector consisting of approximately 760,000 acres of farmland. Prevailing crops in the regions are summarized in Table 4 for the survey year 1976, which is near the start of the analysis period of 1980-2050. Figure 13 shows a map of the South Platte River Basin and five subregions that were used in the study overlaid on land use and land cover. The study region encompasses seventeen Colorado counties that are located within the South Platte River Basin. These counties were aggregated into 5 subregions for analysis purposes to capture the topological overlay of the surface water system and the special variety of sectors within each subregion. Counties within each subregion are summarized in Table 5.

Table 4: Acreage of prevailing crops in each subregion within the SPRB in 1976[12]

Crop	North	North Central	Central	South Metro	East	Total
Corn	153,729	96,374	23,956	6	83,066	357,131
Sugar Beets	47,334	5,921	4,467	0	9,971	67,693
Winter Wheat*	16,105	1,604	8,715	867	3,026	30,317
Alfalfa**	202,662	49,637	58,538	48,244	50,032	409,113
Others	22,101	3,065	4,637	0	1,756	31,559
Total	441,931	156,602	100,314	49,117	147,850	895,813

* Includes other small grains
** Includes irrigated grass and pasture

Table 5: Counties assigned to each subregion

Subregion	**County**
North	Boulder Broomfield Larimer
North Central	Weld
Central	Adams Arapahoe Clear Creek Denver Gilpin Jefferson
South Metro	Douglas Elbert Park
East	Logan Morgan Sedgwick Washington

A large majority of surface water supply to the snowmelt-driven SPRB comes from the three regions on the west side of the basin (North, Central, and South Metro) that touch the continental divide to the west. Surface water hydrology downstream of mountainous canyons is very difficult to characterize due to the unusually high amount of surface water diversions for agricultural, municipal, industrial, and environmental uses. Groundwater recharges surface water allowing recycling of water throughout the basin, as evidenced by the fact that surface water diversions for uses is about 3.9 million acre-feet (MAF) annually, or about 2.8 times the amount of water that

[12] Ibid. 40

supplied by both mountainous headwater streams and trans-basin water conveyance via the Colorado Big Thompson (CBT) project (1.4 MAF, not including groundwater supply). The CBT project is jointly operated by Northern Water Conservancy District (NCWCD) and the U.S. Bureau of Reclamation. District boundaries for NCWCD restrict allocation of CBT water to the "North," "North Central," and "East" regions, where the majority of surface water irrigated agricultural land resides.

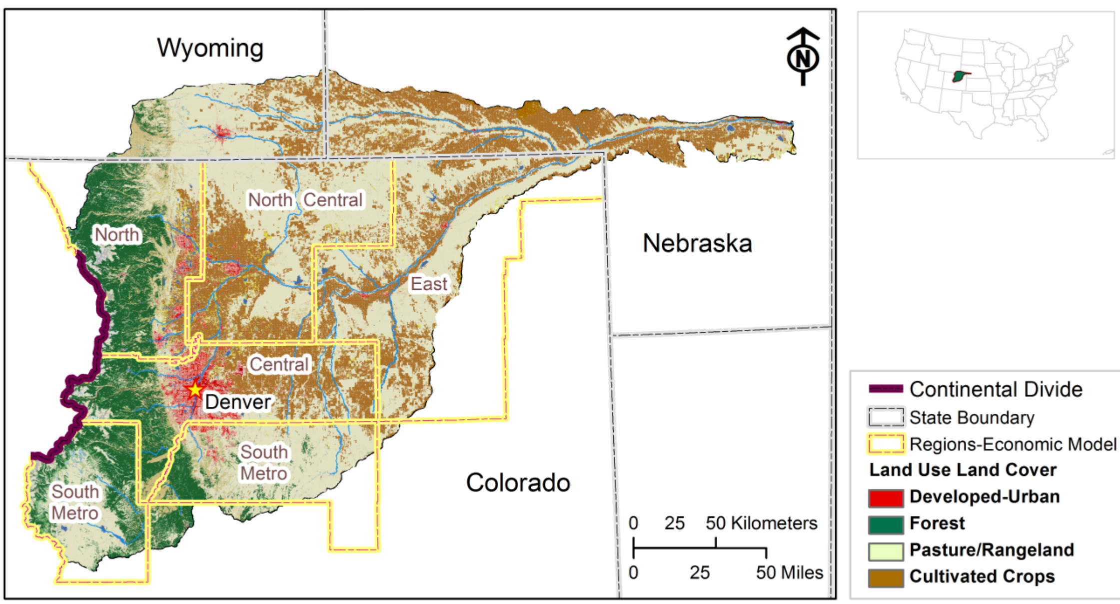


Figure 13: Map of modeled region and subregions overlaid on land use and land cover

4.2 Modeling the Water Rights Market

A model representation of the water allocation institution, the prior appropriation doctrine in the case of the SPRB, was developed. A partial equilibrium model with spatially diverse regions and agents represents this system where municipalities minimize total purchase cost of water rights required to sustain a growing population from agricultural producers while producers attempt to maximize profit from crop production and sale of water rights. Transaction costs are incurred with each water rights purchase both due to physical constraints and legal requirements. The following subsections define the structure and solution procedure of the water rights model.

4.2.1 Mathematical representation of the permanent water supply market

Central to the approach used in this study is a mathematical representation of a multi-agent water rights market with transaction costs and multiple equilibrium constraints including a market clearing constraint. Two types of agents, municipalities and agricultural producers, are represented in this model. For each subregion, the model assumes one representative municipality and four agricultural producers for the four primary crops shown in Table 4. The goal of each individual municipality m in subregion r is to minimize the cost of water rights purchases across all pools:

$$\min_{B_{m,r,d}} \sum_{d \in D} \left(P_d^{\text{water}} \cdot B_{m,r,d} + c_{r,d}^{\text{tran}} \cdot B_{m,r,d} + \frac{b^{\text{tran}}}{\sum_{p,r} u_{p,r,d}^{\text{endow}}} \cdot B_{m,r,d}^2 \cdot [d = r] \right) \tag{1}$$

where P_d^{water} denotes price of water (\$/AF) in pool d within the set of all pools D, $c_{r,d}^{\text{tran}}$ represents transaction costs (\$/AF) for an agent in subregion r purchasing water rights from pool d, and $B_{m,r,d}$ is municipal decision on the amount of water rights (AF) to buy pool d. To account for spatial heterogeneity within a subregion, a quadratic term is added with a calibrated coefficient b^{tran} and scaled by the total water right endowment of agricultural producers (the endowment for producer p in subregion r from pool of water p is $u_{p,r,d}^{\text{endow}}$). Parameterization and calibration procedures for transactions costs $c_{r,d}^{\text{tran}}$ and b^{tran} are described in Section 4.3. The expression $[d = r]$ utilizes Iverson brackets to evaluate to 1 when the expression is true ($d = r$), and zero when false ($d \neq r$), thus introducing the quadratic term only when the municipality is buying from within its own subregion. Municipalities require land developers to purchase firm water, a water supply considered to have almost 100% reliability, to meet raw water requirements (RWR) for each acreage of land developed. This RWR drives the purchase and transfer of water to municipalities in the model according to the following equation:

$$g_{m,r}^{\text{rwr}} = \sum_{d \in D} \left[k_d^{\text{rel}} \cdot B_{m,r,d} \right] - q_r^{\text{rwr}} \cdot a_{m,r,t}^{\text{devel}} \geq 0 \tag{2}$$

$$B_{m,r,d} \geq 0$$

where q_r^{rwr} is the firm raw water requirement for water (AF/acre) purchased from pool d, $a_{m,r,t}^{\text{devel}}$ is the amount of newly developed land (in acres) that requires water rights purchases. A reliability factor ($0 < k_d^{\text{rel}} < 1$) represents the fraction of purchased water considered "firm" yield, delivered even during the worst drought year on record. Restrictions on the speed of CBT water acquisition by municipalities as determined by NCWCD[13] constrain the model as follows:

$$g_{m,r}^{\text{cbt}} = 2 \cdot \left(q_r^{\text{rwr}} \cdot a_{m,r,t}^{\text{devel}} - \sum_{d \in D_n} k_d^{\text{rel}} \cdot B_{m,r,d} \right) - B_{m,r,cbt} \geq 0 \quad (3)$$

$$g_{m,r}^{\text{cbt,2}} = 2 \cdot q_r^{\text{rwr}} \cdot a_{m,r,t}^{\text{devel}} - \sum_{d \in D_n} B_{m,r,d} - B_{m,r,cbt} \geq 0 \quad (4)$$

where purchases from native pools of water rights D_n are distinguished from CBT purchases, $B_{m,r,cbt}$. The set of six pools of water rights D consists of five regions with native water rights markets $d \in D_n$ (simulating a combination of direct flow and storage rights) while the sixth pool $d = cbt$ represents water from the CBT project.

The goal of each individual agricultural producer is to maximize the expected value of the net present value (NPV) of annual profit from sale of produced crop and water rights to municipalities. For agricultural producer p in subregion r, the model represents this process with the following objective function:

$$\max_{V_{p,r}, A_{p,r}, S_{p,r,d}} k^{\text{NPV}} \left(p^{\text{crop}} \cdot f_{p,r}(V_{p,r}, A_{p,r}) - C_{p,r}^{\text{water}}(V_{p,r}, \eta_{p,r}^{a}) - C_{p,r}^{\text{land}}(A_{p,r}) \right) + \sum_{d \in D} (PW_d \cdot S_{p,r,d}) \quad (5)$$

where $V_{p,r}$, $A_{p,r}$, and $S_{p,r,d}$ are the decision variables for agricultural producers, representing irrigation volume (AF), land in production (acres), and amount of water sold (AF), respectively. A factor k^{NPV} is provided for calculating the net present value of an annual profit over 40 years

[13] Ibid 44

assuming a 3% discount rate. The crop production function $f_{p,r}$ (tons of production per year), cost of irrigation $C_{p,r}^{\text{water}}$ (\$), and cost of using farmland $C_{p,r}^{\text{land}}$ (\$) are defined as follows:

$$f_{p,r}(V_{p,r}, A_{p,r}) = k_p \cdot p_{0,p,r} \cdot \left[p_{1,p,r} \cdot A_{p,r}^{p_{2,p,r}} + (1 - p_{1,p,r}) \cdot V_{p,r}^{p_{2,p,r}}\right]^{\frac{p_{3,p,r}}{p_{2,p,r}}} \tag{6}$$

$$C_{p,r}^{\text{water}}(V_{p,r}, A_{p,r}) = \left(c_{p,r}^{\text{water}} - b_{p,r}^{\text{water}}\right) \cdot V_{p,r} \cdot \eta_{p,r}^{\text{a}} \tag{7}$$

$$f_{p,r}^{A}(A_{p,r}) = \left(c_{p,r}^{\text{land}} - b_{p,r}^{\text{land}}\right) \cdot A_{p,r} \tag{8}$$

where $p_{i,p,r}\ \forall\ i \in \{0,1,2,3\}$ are parameters of a constant elasticity function that varies by producer and subregion, and were calibrated to output of an agro-ecosystem model described in Section 4.3, which simulates both deficit irrigated crops and dryland production. Cost parameters $c_{p,r}^{\text{water}}$ (\$/AF) and $c_{p,r}^{\text{land}}$ (\$/acre) are estimated from reports of Colorado State University Extension[14], and "intrinsic benefit" parameters $b_{p,r}^{\text{water}}$ (\$/AF) and $b_{p,r}^{\text{land}}$ (\$/acre) are calibrated to match historically diverted amount of water for agriculture. A factor k_p converts crop production in dry mass to wet mass (in tons) while crop output price data are presented to the model in units of \$/ton. An application inefficiency factor accounts for losses in the on-field irrigation system and is represented in the model as $\eta_{p,r}^{\text{a}} > 1$. Prior to the on-field irrigation system, a conveyance system efficiency value, $0 \le \eta_r^{\text{c}} \le 1$, models channel and evaporation losses prior to diverting to the field. Agricultural producers are constrained by (9) to use less water ($\frac{V_{p,r}}{\eta_r^{\text{c}}} \cdot \eta_{p,r}^{\text{a}}$ is the amount of water diverted) than is owned after the market clears ($\sum_{d\in D}(u_{p,r,d}^{\text{endow}} - S_{p,r,d})$), and by (10) to sell land ($a_{p,r} - A_{p,r}$) alongside its consumptive use of water ($v_{p,r} - V_{p,r}$) except in the case of CBT water and alternative institutional scenarios:

$$g_{p,r}^{\text{supply}} = \sum_{d\in D}\left(u_{p,r,d}^{\text{endow}} - S_{p,r,d}\right) - \frac{V_{p,r}}{\eta_r^{\text{c}}} \cdot \eta_{p,r}^{\text{a}} \ge 0 \tag{9}$$

[14] Costs for irrigation and use of farmland were estimated from Crop Enterprise Budgets from the agricultural extension service of Colorado State University: http://www.coopext.colostate.edu/abm/cropbudgets.htm

$$g_{p,r}^{\mathrm{B\&D}} = k^{\mathrm{B\&D}} \cdot \left(v_{p,r} - V_{p,r}\right) - \left(a_{p,r} - A_{p,r}\right) \cdot I_{p,r}^{\mathrm{NIR}} = 0 \ (\geq 0 \text{ if relaxing buy and dry constraint}) \quad (10)$$

$$V_{p,r}, A_{p,r}, B_{p,r,d}, S_{p,r,d} \geq 0$$

where the endowment of water rights in year 1980 $u_{p,r,d}^{\mathrm{endow}}$ act as an upper bound on the annual amount agricultural producers can sell or use. The annual average net irrigation requirement $I_{p,r}^{\mathrm{NIR}}$ of crop p represents the amount of water farmers in subregion r should irrigate to meet the remaining water demand of the crop after precipitation (i.e., consumptive use minus effective precipitation). Initial values (those in 1980) of acreage $a_{p,r}$ and irrigation volume $v_{p,r}$ are also upper bounds for the decision variables of acreage and irrigation volume. Thus, the buy and dry constraint (10) simulates court decisions to require an amount of land to be taken out of production proportional to the water rights sold. A factor $k^{\mathrm{B\&D}}$ is added to (10) to simulate any relaxation to full buy and dry (e.g., allowing deficit irrigation, rotational fallowing, lease fallowing, interruptible supply agreements, etc.).

Endowments of water rights are fixed throughout the modeling time period because water rights native to the SPRB have reached a threshold beyond which no significantly new water rights have been attained. Also, because the model solves at an annual timescale, direct flow rights (a daily maximum flow rate) cannot simply be summed to an annual amount, combined with storage rights, and used as the endowment for an agent. Instead, the historical average annual diversions are used to set a water right "endowment" for agricultural producers in the model, which allows for consistency with the reliability indicators that rely on changes in mean annual supply and demand. Individual crops within each subregion are assigned a portion of the regional endowment in proportion to crop distributions in 1980. M&I endowment of water is set so as to have the same proportion of the total endowment as water rights, assuming half of endowment comes from direct flow rights and half from storage rights.

Equilibrium constraints are equations that link multiple agents that are independently making decisions, and force the model to follow a more reasonable solution path rather than the intractable "social planner" problem. The market clearing conditions force the solver to choose the price of water right in each pool d that clears each regional water right market such that the total amount sold equals the total amount bought, as follows:

$$\sum_{p\in P,r\in R} S_{p,r,d} - \sum_{m\in M,r\in R} B_{m,r,d} = 0 \tag{11}$$

Another equilibrium constrain includes a cap on regional ownership of water rights by municipalities within each pool d, as follows:

$$g_d^{CAP} = k_d^{\mathrm{mcap}} \cdot \sum_{p\in P,r\in R} \left(u_{p,r,d}^{\mathrm{endow}} + B_{p,r,d} - S_{p,r,d}\right) - \left(1 - k_d^{\mathrm{mcap}}\right) \cdot \sum_{m\in M,r\in R} \left(u_{m,r,d}^{\mathrm{endow}} + B_{m,r,d}\right) \geq 0 \tag{12}$$

where the additional parameter k_d^{mcap} specifies the fraction of each regional pool of water that municipalities can own. P is the set of all producers (crops), R is the set of all regions, and M is the set of all municipalities.

4.2.2 Optimization solver

The General Algebraic Modeling System (GAMS)[15] was used to solve these multiple optimization problems with equilibrium constraints (MOPEC) formulated to solve as a mixed complementarity problem (MCP) for a single snapshot of time. To project into the future, time dependent variables such as newly developed urban area $a_{m,r,t}^{\mathrm{devel}}$ were updated and GAMS would solve the problem again. This optimization problem is hard to solve because of the large number of constraints and would sometimes not converge, so different initial values were assigned to decision variables systematically until the problem was solved. A python program was created that automatically ran the entire workflow including all time periods and all scenarios, and also ran

[15] GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 24.2.1. Washington, DC, USA, 2013

subsequent analysis for purposes of rapid development, calibration, testing, and evaluation of the model.

4.2.3 Model limitations and future work

As in all modeling applications, models imperfectly represent reality given the assumptions on which they rely, limiting application of the model to its intended contexts and purposes, and motivating further development of the model. The modeling framework presented in this paper represents long-term trends of water rights transfers, and therefore does not incorporate other features of the water system that have little or unknown consequences on the permanent water supply market. Average historical data was used to drive the model, rather than year-to-year variation in water supply, demand, costs, or prices.

After model solution, net present value of agricultural users is determined assuming that cities were rented out all unused water, but during solution agricultural producers did not account for additional potential profit from utilizing rented water. It is unknown how extensively farmers will incorporate production from rented water into decisions about sell their water rights, but the effect is likely small because sale of the water right provides so much revenue compared with the profit from continuing in production, especially when paying more for the water. Similarly, risk of other severe agricultural losses due to natural disasters, including extreme drought, were also not modeled, but rather a surrogate probabilistic approach defining water supply reliability was used (Section 4.5). Livestock production within the SPRB may influence a regional price of alfalfa, but instead of incorporating this endogenously, we change the price of alfalfa exogenously over time according to a regression model trained on historical alfalfa prices (Section 4.3).

Groundwater recharge is incorporated partly because water rights endowments are determined by historical diversion volumes that include whatever groundwater existed in the stream, but future work could focus on better representation of groundwater as a backup water supply that could allow farmers to plan for continued production with groundwater. Other future work and improvements could be made to determine optimal (nondominated) solutions that both maximize agricultural profit and minimize the cost of water to municipalities by optimizing levels of efficient irrigation technology, water storage supply, and specific urban conservation retrofits.

4.3 Model parameterization

In the SPRB, drivers of municipal acquisition of water rights were identified as firm yield requirements for raw water based on the amount of urban land developed in cities. As more land development occurs, cities will pay a large price to ensure "firm" annual supply, that is, an amount of water that is viewed with guaranteed availability. Agricultural production is motivated not only by profit from production and sale of crops but also presumably enjoyment of the lifestyle. Characterization and parameterization of the agricultural sector, the municipal and industrial (M&I) sector, and transactions costs are provided in the following section.

4.3.1 Parameterization of agricultural producers

A recent version of the DayCent agro-ecosystem model (Parton et al. 1998; Zhang 2016) that has been calibrated and tested for limited irrigation of crops in semi-arid regions was used to parameterize the crop production functions in (6). Figure 14 displays calibrated yield compared to county-level yield estimates.[16] Most input parameters were obtained from previous studies (Zhang 2016).[17] The parameter of radiation use efficiency for total biomass was slightly adjusted to reflect the yields obtained by farmers in Weld County. Yield of farmers are usually lower than those well-managed experimental sites mainly due to suboptimal management and factors that were not

[16] County-level yield data in Weld County with representative management and soil type was obtained from National Agricultural Statistics Service, U.S. Department of Agriculture for the period between 1981 and 2012.

[17] "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014", Report No. EPA 430-R-16-002, U.S. Environmental Protection Agency, 2015. Available on https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014

simulated such as disease, pest, and hail damage (Grassini et al. 2011). Calibrated parameters were then applied to the whole SPRB.

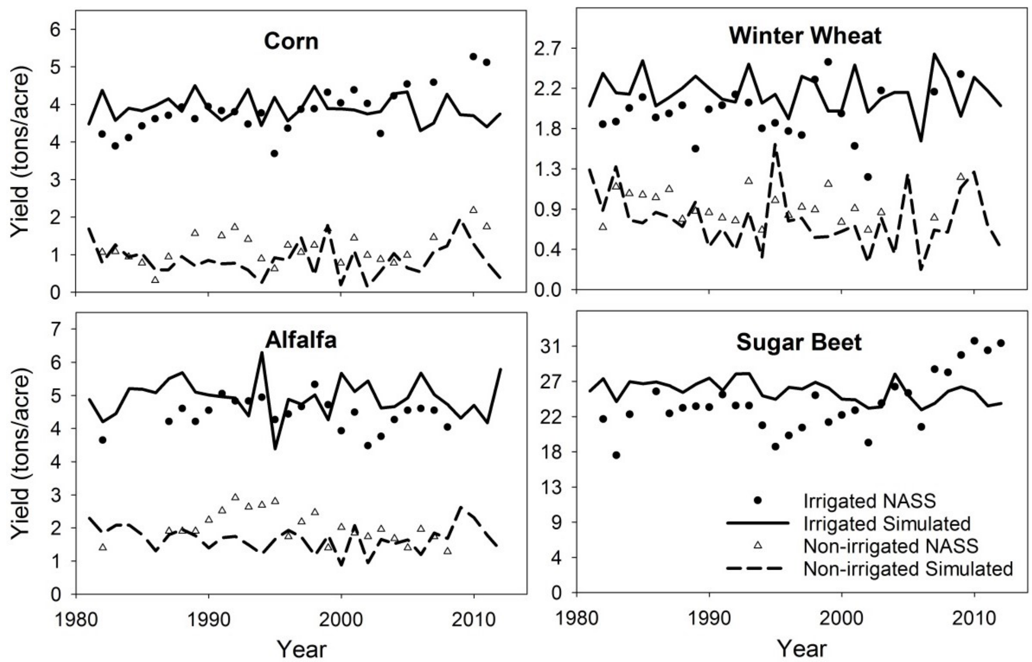


Figure 14: Crop yield calibration results for each crop, both non-irrigated and fully-irrigated. Observed data (1981-2012) is from county-level yield estimates in Weld County collected by the National Agricultural Statistics Service of the U.S. Department of Agriculture.

To construct crop production functions (factors of acreage and irrigation volume in AF) for each subregion and crop, yearly water budget and production (total wet mass of produced crop in tons) output from DayCent were combined with field acreage sorted by productivity. Figure 15-Figure 19 illustrate simulated output from DayCent used for characterization of crop production functions for all five subregions and associated four primary cropping systems: corn, sugar beets, winter wheat, and alfalfa. Each point on the curve represents a single year of DayCent output. Parameters of the CES function were fit to production output curves from DayCent and are listed in Table 6 in addition to error statistics and plot bounds.

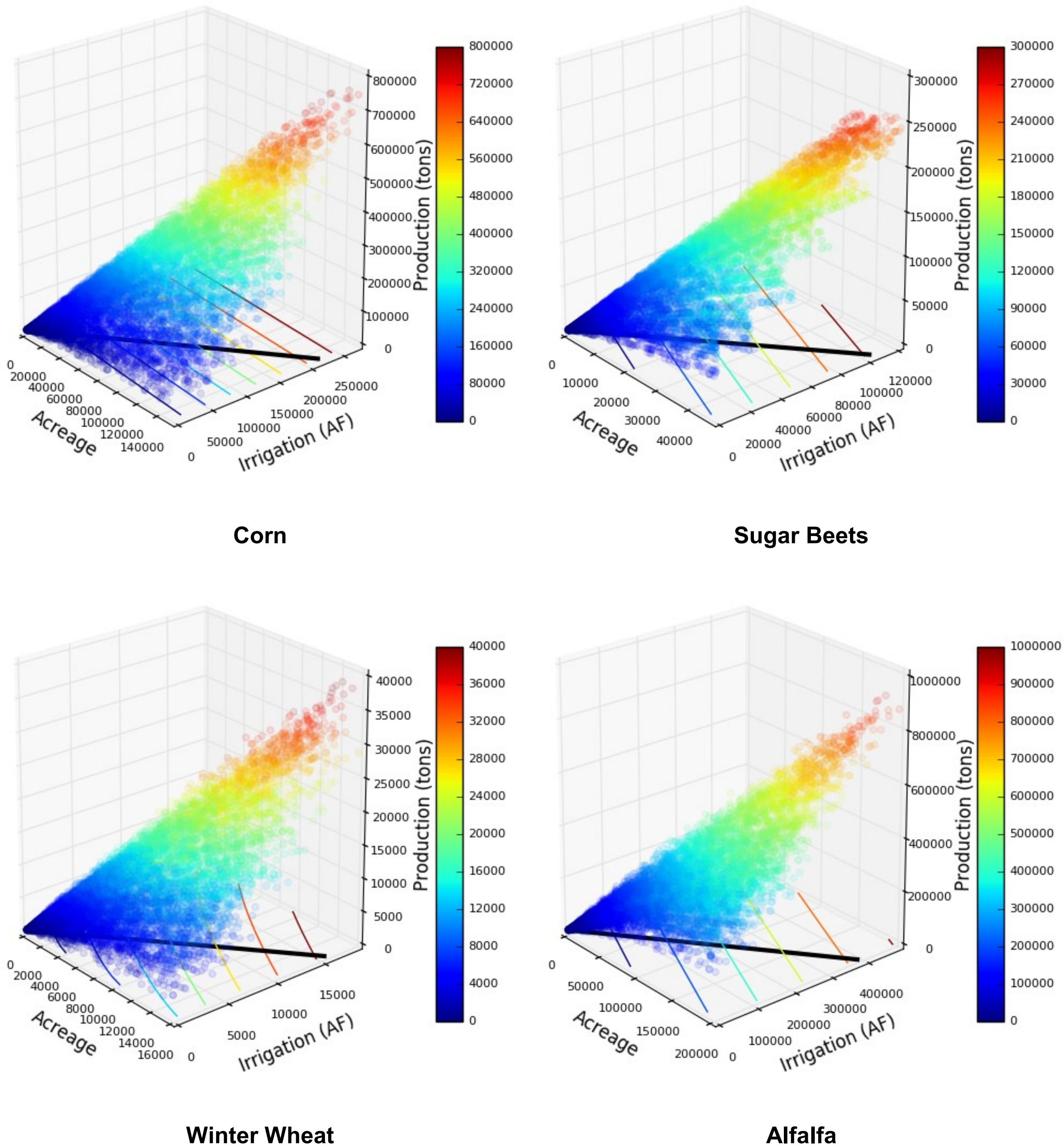


Figure 15: Simulated crop production functions for the North subregion as a function of cropland acreage in production and irrigated depth (ft) from no irrigation to consumptive use requirements of crops. Contours on the x-y plane are built using the fitted Constant Elasticity of Substitution (CES) functions.

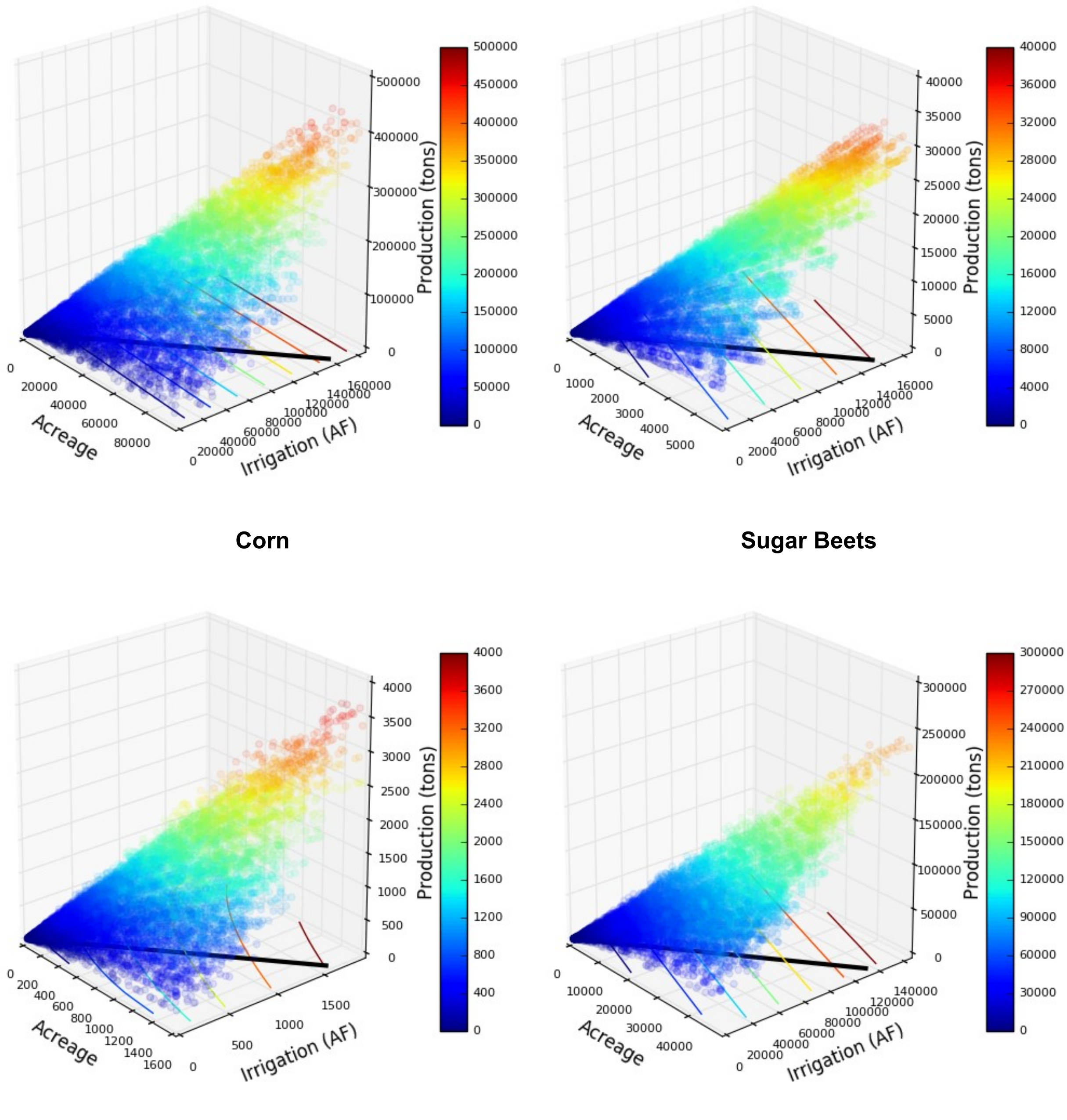
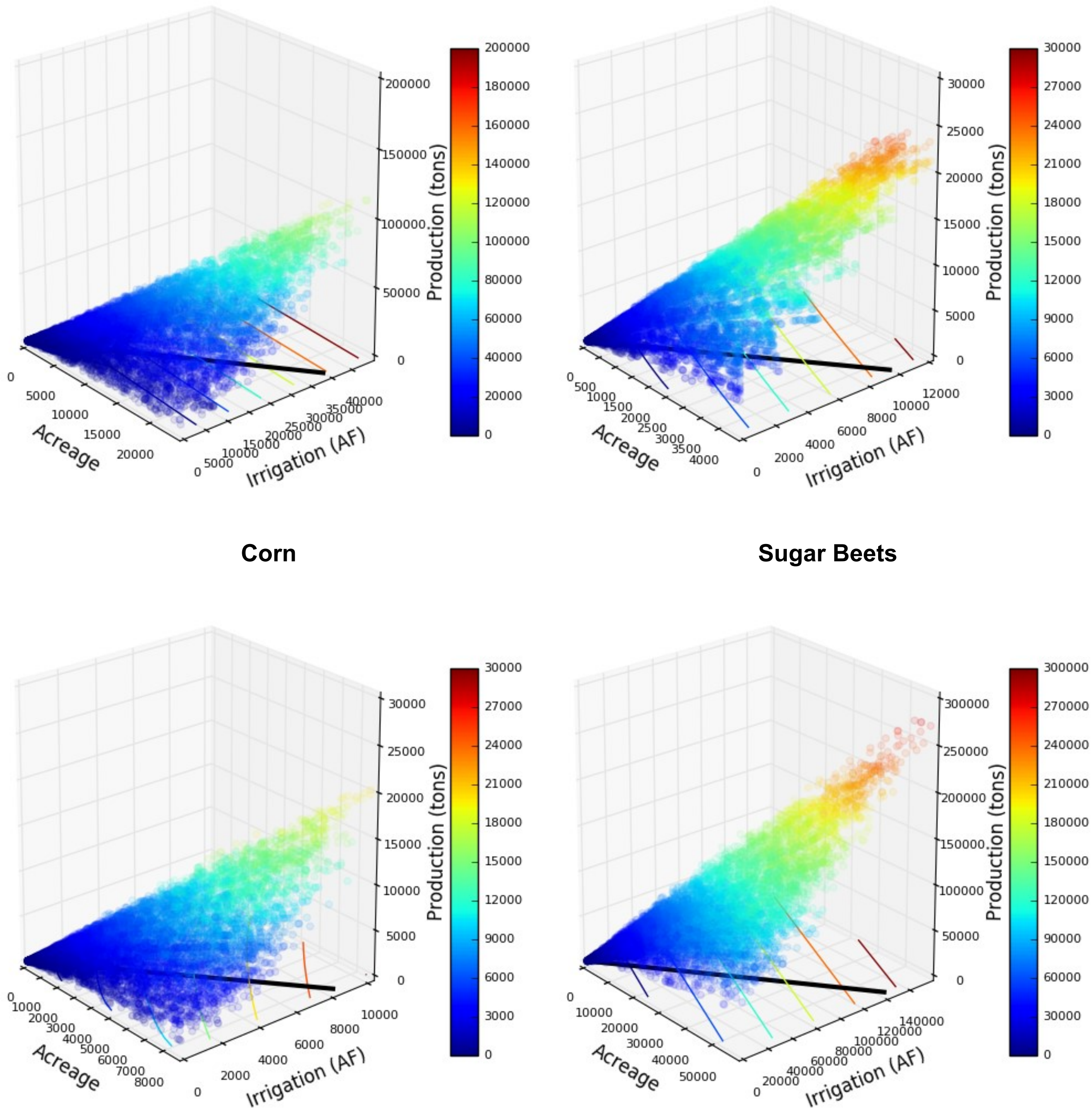


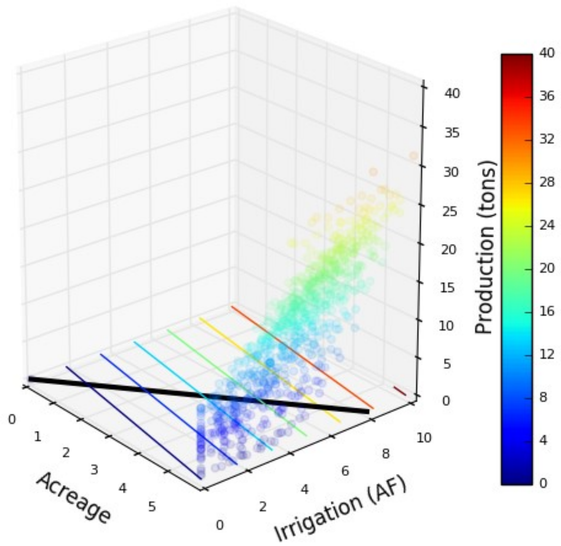
Figure 16: Simulated crop production functions for the North Central subregion as a function of cropland acreage in production and irrigated depth (ft) from no irrigation to consumptive use requirements of crops. Contours on the x-y plane are built using the fitted Constant Elasticity of Substitution (CES) functions.



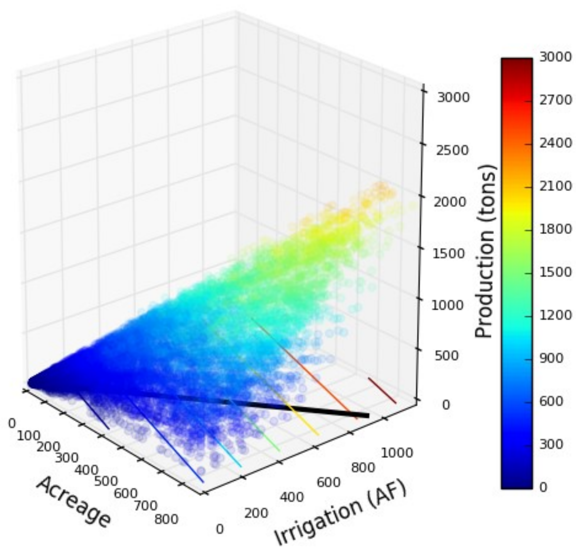
Corn **Sugar Beets**

Winter Wheat **Alfalfa**

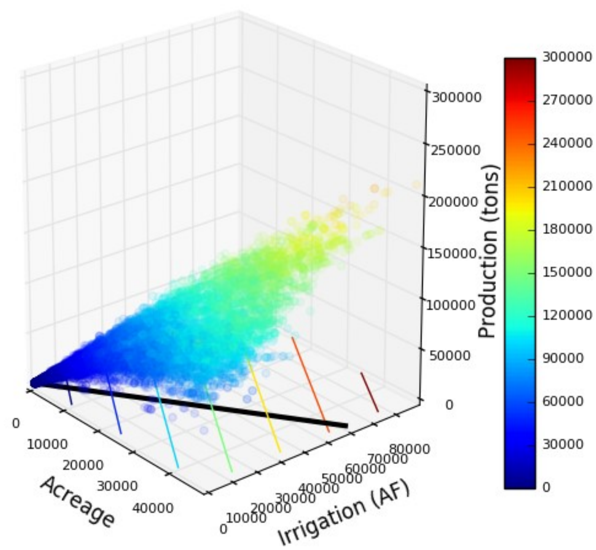
Figure 17: Simulated crop production functions for the Central subregion as a function of cropland acreage in production and irrigated depth (ft) from no irrigation to consumptive use requirements of crops. Contours on the x-y plane are built using the fitted Constant Elasticity of Substitution (CES) functions.



Corn



Winter Wheat



Alfalfa

Figure 18: Simulated crop production functions for the South Metro subregion as a function of cropland acreage in production and irrigated depth (ft) from no irrigation to consumptive use requirements of crops. Contours on the x-y plane are built using the fitted Constant Elasticity of Substitution (CES) functions. Very little acreage of corn and winter wheat were irrigated in 1976 within the South Metro subregion, while no sugar beets were irrigated.

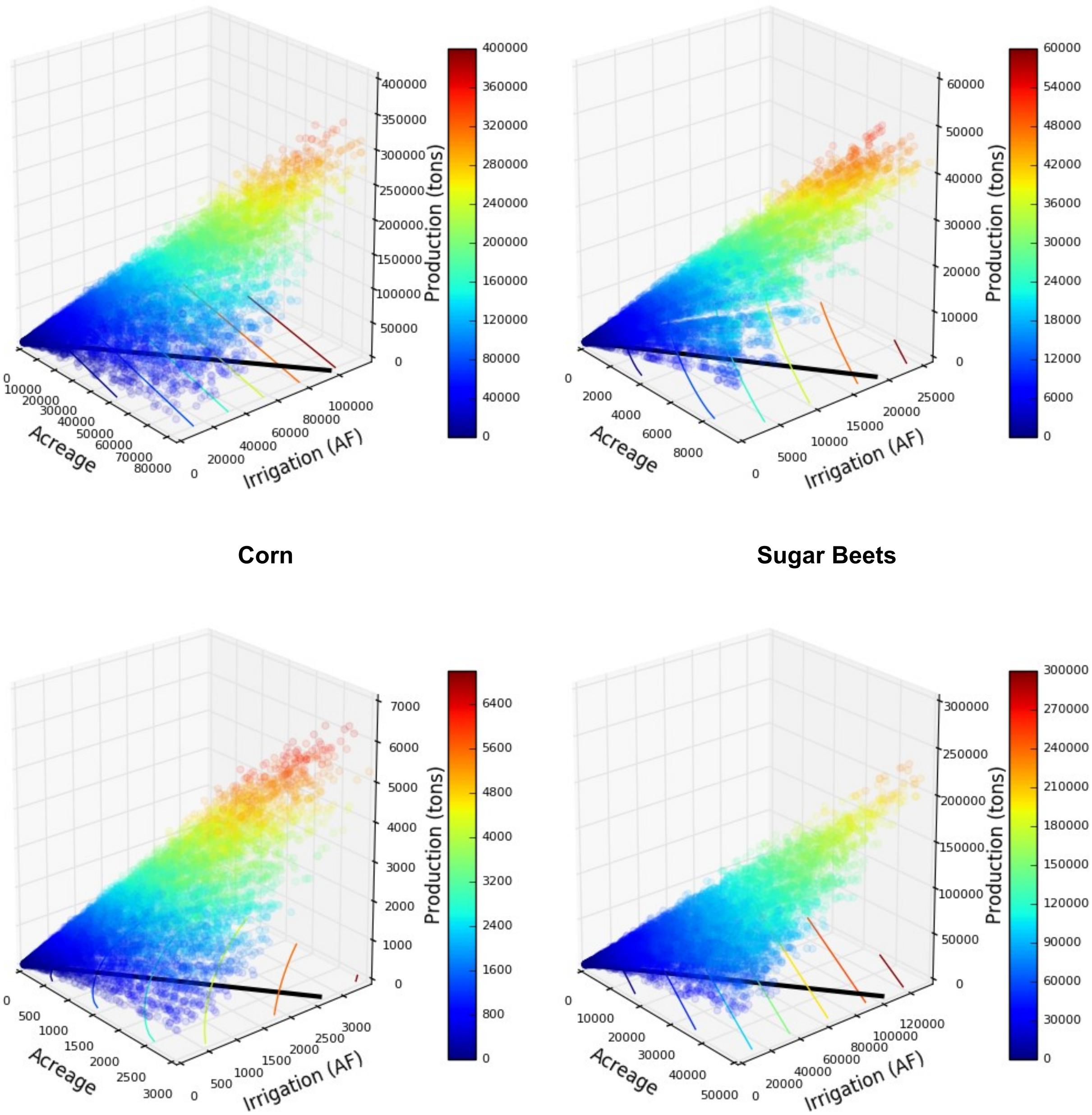


Figure 19: Simulated crop production functions for the East subregion as a function of cropland acreage in production and irrigated depth (ft) from no irrigation to consumptive use requirements of crops. Contours on the x-y plane are built using the fitted Constant Elasticity of Substitution (CES) functions.

Table 6: Fitted crop production parameters from 1976 data and error statistics including the coefficient of determination (r^2), mean relative error (MRE) and root mean squared error (RMSE). Initial baseline acreage $a_{p,r}$ and maximum simulated irrigation $I_{p,r}^{\text{NIR}}$ (ft) and production (tons) are also shown. No sugar beets were irrigated in 1976 in the South Metro subregion.

Crop	Subregion	p_0	p_1	p_2	p_3	r^2	MRE	RMSE	$a_{p,r}$	$I_{p,r}^{\text{NIR}}$	Production
Corn	North	7.9	0.12	1.00	0.92	87%	-10%	58,200	154,000	1.40	781,000
	N. Central	8.2	0.11	1.00	0.91	85%	-12%	36,900	96,400	1.40	470,000
	Central	5.7	0.12	1.00	0.94	85%	-12%	9,580	24,000	1.40	122,000
	S. Metro	3.1	0.22	1.00	1.00	64%	-30%	4	6	1.34	31
	East	11.3	0.25	0.98	0.89	84%	-12%	30,100	83,100	1.14	374,000
Sugar Beets	North	6.1	0.49	0.98	0.94	94%	-4%	15,900	47,300	2.13	280,000
	N. Central	5.0	0.48	1.00	0.95	93%	-4%	2,120	5,920	2.26	34,800
	Central	5.6	0.49	0.93	0.93	92%	-5%	1,590	4,470	2.14	25,500
	East	10.6	0.57	0.87	0.87	91%	-13%	3,700	9,970	1.86	53,500
Winter Wheat	North	10.0	0.38	0.82	0.82	77%	-26%	3,840	16,100	0.96	39,900
	N. Central	19.1	0.37	0.66	0.66	74%	-50%	390	1,600	0.97	3,830
	Central	10.1	0.48	0.79	0.79	72%	-43%	2,160	8,720	0.95	20,700
	S. Metro	4.4	0.28	1.00	0.89	82%	-14%	210	867	1.05	2,210
	East	11.8	0.58	0.75	0.75	73%	-37%	736	3,030	0.86	6,900
Alfalfa	North	9.3	0.52	1.00	0.90	94%	-3%	43,300	203,000	1.86	972,000
	N. Central	6.9	0.50	1.00	0.91	93%	-3%	12,100	49,600	2.23	253,000
	Central	8.2	0.53	1.00	0.90	93%	-3%	13,300	58,500	2.06	285,000
	S. Metro	20.6	0.53	1.00	0.84	93%	-9%	12,100	48,200	1.20	222,000
	East	7.8	0.55	1.00	0.90	92%	-4%	12,200	50,000	1.99	242,000

Input data required by the DayCent model are daily maximum or minimum temperature and precipitation, soil properties, and management strategies for irrigation and tillage. Historical weather data from 1981-2014 was used in the analysis were extracted from the 4 km by 4 km gridded PRISM dataset (PRISM Climate Group 2004). Soil properties data were derived from SSURGO[18] and the pedotransfer function (Saxton et al. 1986) was used to estimate soil hydraulic parameters. Every unique combination of soil, 32 kilometer climate region defined by the North American Regional Reanalysis (NARR)[19] grid cells, and crop type was simulated assuming they respond hydrologically similar to one another as hydrologic response units (HRUs), reducing the number of individual spatial units to simulate from 25,200 to 4,500. These runs resulted in one terabyte of output consisting of daily water budget and yearly biogeochemical fluxes, which were

[18] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. Available online at https://sdmdataaccess.sc.egov.usda.gov

[19] NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/

stored in a privately managed MongoDB[20] datastore wrapped with a web-service to extract DayCent model outputs in a reproducible manner.

Common practices for management of each crop in the study region were used in our simulations. Automatic fertilization option of the model was used to eliminate nutrient stress. Tillage was assumed to be conventional practice. For each HRU, various levels of the net irrigation requirement (NIR) and maximum allowable depletion (MAD) were simulated to quantify crop yield responses to deficit irrigation. These levels were applied separately to non-critical and critical irrigation periods according to approximated phenology stages (reproductive period of the crop) to approximate an optimal irrigation management strategy. Dominated output yield (higher irrigation depth and acreage that produce a lower yield than another strategy) of enumerated levels of NIR and MAD were removed from the crop production function assuming farmers will tend toward more optimal irrigation strategies and ensure to irrigate at critical periods of plant growth, although imperfectly.

Calibration of the two "intrinsic benefit" parameters $b_{p,r}^{\text{water}}$ (benefit to producer to irrigate just as much as historically) and $b_{p,r}^{\text{land}}$ (benefit to producer to farm just as much land as historically) ensured that agricultural production of the baseline institution matches observed yield data. Calibrated values of these parameters are shown in Table 7. Prior to this calibration, most parameterized irrigation costs were higher than the real or perceived cost to farmers, and most land costs were lower than the real or perceived cost to farmers as evidenced by the sign of $b_{p,r}^{\text{water}}$ and $b_{p,r}^{\text{land}}$ (Table 7).

[20] MongoDB is a distributed document datastore that allows for distributed aggregation of queries across very large datasets. It can be obtained online at https://www.mongodb.com/

Table 7: Calibrated "intrinsic benefits" $b_{p,r}^{\text{water}}$ and $b_{p,r}^{\text{land}}$ to irrigating historical observed amount and farming historically observed amount, respectively. Positive values indicate that parameterized costs ($c_{p,r}^{\text{water}}$ and $c_{p,r}^{\text{land}}$) are too high or farmers find some benefit from using more inputs than optimal. Negative values indicate parameterized costs are too low, or farmers find some benefit from using less inputs than optimal.

Crop, p	Subregion, r	$b_{p,r}^{\text{water}}$	$b_{p,r}^{\text{land}}$
Corn	North	-87	291
	North Central	-91	215
	Central	-91	207
	South Metro	-193	176
	East	-67	147
Sugar Beets	North	-67	361
	North Central	-78	302
	Central	-64	289
	South Metro	-482	-363
	East	-47	242
Winter Wheat	North	2	201
	North Central	-13	140
	Central	-12	116
	South Metro	-33	72
	East	-4	77
Alfalfa	North	-12	171
	North Central	-40	106
	Central	-32	96
	South Metro	-35	58
	East	-33	60

Crop production functions estimate dry biomass in tons and are converted to wet biomass in tons. Crop prices for each year were scaled to 1980 dollars and temporal trends were determined since 1980. Prices for corn and winter wheat were originally in dollars per bushel (a volume),[21] and were converted to dollars per ton for this analysis. Data for prices of sugar beets and alfalfa was in dollars per ton already. Assumptions for conversion of dry mass to wet mass and volumetric bushels from mass in tons is shown in Table 8, where k_p is the wet-to-dry ratio unit conversion factor in (6).

[21] Data obtained from Quick Stats 2.0, National Agricultural Statistics Service, U.S. Department of Agriculture, USDA-NASS, Available online at https://www.nass.usda.gov/Quick_Stats/index.php

Table 8: Wet-to-dry ratio k_p with assumed moisture content and mass to volume ratio

Crop	Moisture Content	lbs/bu	k_p
Corn	0.155	56	1.18
Sugar_Beets	0.8	--	5.00
Wheat_Fall	0.135	60	1.16
Alfalfa	0.2	--	1.25

Crop price trends were added to the model to inform changes over time in crop prices according to regression results found in Table 9. Regression analysis was performed on inflation-adjusted crop prices years within the period (1980-2014) consistent with the time period of DayCent model runs. Although prices are increasing from year-to-year, inflation-adjusted trends show a negative price change from year to year of corn, sugar beets, and winter wheat, while a positive change in alfalfa prices. That is, only the price of alfalfa is rising more rapidly than inflation because it is a heavy, regional commodity subject to regional price swings. All prices since 2000, though, have a positive price trends. Because of these properties, price trends were only applied to alfalfa.

Table 9: Inflation-adjusted crop price trends in 1980 dollars per ton obtained from regression analysis[22]

Parameter	Corn	Sugar Beets	Winter Wheat	Alfalfa
Estimated price in 1980	$62.36	$26.30	$73.21	$43.05
Price change per year	-$0.72**	-$0.42**	-$0.72**	$0.20**

$^{**}p \leq 0.01$

Historical yield (averaged across all counties in the SPRB) has significantly improved since 1980 for all crops except alfalfa (Table 10). A trend for alfalfa was not statistically significant. Therefore, yield improvement trends for only corn, sugar beets, and winter wheat were included in the model.

[22] Ibid. 21

Table 10: Crop yield trends in tons per acre obtained from regression analysis[23]

Parameter	Corn	Sugar Beets	Winter Wheat	Alfalfa
Estimated yield in 1980	3.6	18.2	1.6	4.4
Yield change per year	0.034**	0.273**	0.014**	-0.010

$^{**}p \leq 0.01$

Application efficiencies refer to the percentage of irrigation water actually used by the crop. For flood irrigated fields, application efficiencies were set to 60%, and for sprinkler irrigated fields to 80% (Howell 2003; Leonard Rice Engineers 2010). For each subregion, aggregated application efficiencies $\hat{\eta}_r^a$ were estimated from DayCent output by dividing the regional net irrigation requirement from the regional gross irrigation requirement. An annual average depth of net irrigation requirement $\hat{I}_{p,r}^{\text{NIR}}$was also estimated from DayCent output. For each crop and subregion, the average application efficiency $\eta_{p,r}^a$ and surface water net irrigation requirement $I_{p,r}^{\text{NIR}}$ were calibrated such that:

$$\eta_{p,r}^a = \max\left(\hat{\eta}_r^a, \sum_d \left(u_{p,r,d}^{\text{endow}}\right) \cdot \frac{\eta_{p,r}^c}{A_{p,r} \cdot I_{p,r}^{\text{NIR}}}\right) \tag{13}$$

$$I_{p,r}^{\text{NIR}} = \min\left(\hat{I}_{p,r}^{\text{NIR}}, \sum_d \left(u_{p,r,d}^{\text{endow}}\right) \cdot \frac{\eta_{p,r}^c}{A_{p,r} \cdot \eta_{p,r}^a}\right) \tag{14}$$

This calibration ensures that no more than the gross irrigation requirement is met, and assumes if the net irrigation requirement cannot be met with surface water, groundwater services the rest. When simulating historical decades (1980 through 2010), application efficiencies were updated to historically observed efficiencies. The Colorado Decision Support System dataset[24] indicates that in 1956, 100% of irrigated lands used flood irrigation. About 10% of lands used sprinkler systems by 1980, and by 2010, about 36% of lands used sprinkler. Although the prior appropriation doctrine governing water rights does not incentivize more efficient irrigation,

[23] Ibid. 21
[24] Ibid. 40

farmers still adopted sprinkler irrigation historically. For future simulations after 2010, the rate of irrigation technology adoption and subsequent improvement to application efficiency was set to continue the average historical trend as determined by the average percent change from 1980 to 2010. The conveyance efficiency parameter η_r^c is assumed to be 80% as estimated from a similar neighboring river basin (Gates et al. 2002; Triana et al. 2010b).

4.3.2 Parameterization of municipal consumers

Population within the SPRB has doubled since 1975 to about 3.4-3.5 million in 2010, and is projected to increase to between 5.8-6.6 million by 2050 (Camp Dresser & McKee and Harvey Economics 2010). As land development occurs, water utility providers require purchase of firm annual yield, ranging from 1-1.6 AF per acre of developed land. This raw water purchase requirement is the driving factor behind municipal acquisition of water rights and shares of CBT water and is explicitly modeled in this study.

Municipal ownership of water rights within the SPRB continues to grow as population grows. In 1976 when no significant amount of new water rights were obtained, agricultural water direct flow right ownership reached a maximum of about 113,000 cfs absolute decreed rate (including alternate point and exchange rights), and in 1981 agricultural storage rights reached a maximum of about 1.01 MAF. Since then, municipal water ownership continues to steadily increase as agricultural ownership decreases.

The primary driver for municipal water right purchases in the model is developed land, or new urban area $a_{m,r,t}^{\text{devel}}$, projected out to 2050. Autoregressive models were developed to estimate developed land as a function of population both forward in time (15) and backward in time (16):

$$a_{t,std}^{\text{devel}} = \alpha \cdot pop_{t,std} + \beta \cdot a_{t-1,std}^{\text{devel}} + \epsilon \qquad (15)$$

$$a_{t-1,std}^{\text{devel}} = \alpha \cdot pop_{t-1,std} + \beta \cdot a_{t,std}^{\text{devel}} + \epsilon \qquad (16)$$

where $a_{t,std}^{\text{devel}}$ is the standardized historical amount of urbanized area (acres) at the county level, $pop_{t,std}$ is county population. Historical land use data for years 2001 and 2011 from the National Land Cover Dataset (Homer et al. 2015) were combined with county-level population estimates from the U.S. Census 2000 and 2010, respectively, to provide training data for time periods $t-1$ and t, respectively. Population and land-use drivers are summarized for the entire SPRB in Table 11. The equation is defined for each municipality m in subregion r at time t (parameterized from 2011 for urban area and 2010 for population) and $t-1$ (2001 for urban area and 2000 for population). Each variable is standardized (subscript std). Estimated regression parameters α and β are shown in Table 12.

Table 11: Drivers of municipal growth for the entire South Platte region

Year	Population	Urban Area (acres)
2010	3,448,565	899,263
2020	4,264,600	996,997
2030	4,920,000	1,108,591
2040	5,470,364	1,232,669
2050	6,014,600	1,369,488

Table 12: Urban area parameters, error, and regression model statistics for both forward and backward projecting models

Statistic	Forward	Backward
α	0.0169	-0.0116
β	1.029	0.95
r^2	99.4%	99.2%
Adj. r^2	99.3%	99.2%
MRE	1.8%	3.0%
RMSE	2373	2469
Mean of Error	-220	468
Std. Dev. of Error	2363	2425
Skewness of Error	0.44	-1.28
$\mu_{ua_{t,std}}$	29,496	29,496
$\sigma_{ua_{t,std}}$	29,573	29,573
$\mu_{ua_{t-1,std}}$	27,599	27,599
$\sigma_{ua_{t-1,std}}$	26,362	26,362
μ_{pop}	78,581	67,207
σ_pop	155,796	136,689

Raw water requirements for CBT water that drive municipalities along the Front Range to purchase water based on urbanized land developed (Table 13). Water rights native to each individual subregion typically require a larger water purchase except for municipalities in the East region (Table 14). Two key parameters that capture the drivers behind municipal purchases of water rights are the reliability factor of each pool d of water rights k_d^{rel} and a firm water requirement (q_r^{rwr} in Section 4.2). Reliability factors for each subregion were estimated as the diversion volume with a 75-year return period q_{75} divided by the average annual diversion volume $\bar{q}$:

$$k_d^{\text{rel}} = \frac{q_{75}}{\bar{q}} \tag{17}$$

Diversion data between 1980 and 2014 were used to estimate q_{75} and $\bar{q}$, and the return period length was calibrated based on sensitivity of modeled acreage in 2010 with respect to observed acreage in 2010. Gross water purchase requirements from two cities in the SPRB are 2 AF of water rights purchases per acre of developed land for the City of Longmont,[25] and 2-3 AF per acre of developed land (depending on number and density of units) for the City of Fort Collins.[26] The native water reliability factor for Longmont was estimated to be the reliability factor from the North subregion $k_{north}^{\text{rel}} = 50\%$, and Fort Collins to be $52\% = \frac{1}{1.92}$, where 1.92 is the "water supply factor" that the city uses in determining a raw water requirement for residential land development. Sample CBT water reliability factors from 10 different cities ranged from 50% to 100% and

[25] Direct flow water right policy from Longmont obtained from the Raw Water Requirement Policy within the city ordinance of the City of Longmont, Colorado. Available at: https://www.municode.com/library/co/longmont/codes/code_of_ordinances?nodeId=PTIICOOR_TIT14PUSE_CH14.05RAWAREPO

[26] A document named "Water Supply and Demand Management Policy Report" (2012) by the City of Fort Collins outlines their raw water requirements for developers. Available at http://www.fcgov.com/utilities/img/site_specific/uploads/Final_Fort_Collins_Policy_Report_April_2014_w_Appendices.pdf

averaged 78.1% of volume per CBT unit (Table 13).[27] Average annual yield, though, from CBT is about 70% (the most common value in Table 13), so this is used as the reliability factor.[28] The firm water requirement q_r^{rwr} is estimated by multiplying the gross water requirement by the reliability factor k_d^{rel} for native water rights for both Longmont and Fort Collins, and CBT water (using the average of the two gross water requirements for Longmont and Fort Collins, 2.5 AF per acre of developed land). The average of the resulting firm water requirements for Longmont, Fort Collins, and CBT (1 AF/acre, 1.56 AF/acre, and 1.75 AF/acre, respectively) was used as a constant across all regions so that $q_r^{\mathrm{rwr}} = 1.44$ AF/acre for all regions.

Table 13: Reliability factors (in AF per CBT unit) or cash in lieu per acre-foot (both up-front and annualized) for various cities within the South Platte River Basin obtained from the City of Loveland[29]

City	Reliability Factor (AF/unit)	Cash in Lieu ($/AF)	Cash in Lieu ($/AF-year)
Loveland	1	$ 26,250	$ 1,136
Longmont	0.76	$ 14,210	$ 615
Greeley	0.75	$ 16,800	$ 727
Fort Collins	1	$ 6,500	$ 281
Windsor	0.7	$ 30,714	$ 1,329
FCLWD	1	$ 23,500	$ 1,017
Little Thompson	0.5	$ 18,200	$ 787
Left Hand	0.7	$ 26,500	$ 1,146
North Weld County	0.7	$ 20,000	$ 865
East Larimer County	0.7	$ 23,000	$ 995
Average	0.781	$ 20,567	$ 890

Table 14: Firm raw water requirements (RWR) for each pool of water

Pool	Firm RWR (AF/ac)	Reliability
North	1.44	0.50
North Central	1.44	0.63
Central	1.44	0.37
South Metro	1.44	0.48
East	1.44	0.71
CBT	1.44	0.70

[27] The City of Loveland listed 10 different water provider CBT water purchase requirements in "Northern Colorado Cities' Raw Water Requirements or Credits Comparison" (2014). Available at http://www.ci.loveland.co.us/home/showdocument?id=22497
[28] Average yield
[29] Ibid. 27

4.3.3 *Parameterization of transactions costs*

Model parameterization was performed primarily through the use of literature values and historical data. While many parameters were fixed and remained unchanged throughout the analysis, some were used as calibration parameters to more accurately represent historical trends. Most calibration parameters were calibrated manually, except for $b_{p,r}^{\text{water}}$ and $b_{p,r}^{\text{land}}$ which utilized the GAMS MCP solver to find an initial solution that set the baseline marginal value of agricultural profit to \$0 (see previous section on parameterization of agricultural producers for further details and calibrated values).

Transactions cost data is very sparse and variable depending on location and type of water right, yet have significant impact on the price of water because of opportunity afforded by local sellers when buyers have to decide between purchasing more expensive water nearby with a relatively low infrastructure cost and cheaper water farther away with a relatively high infrastructure cost (Bauman et al. 2015). That is, local sellers can then raise their price yet still be competitive. Because of the importance of transactions costs, and yet very apparent lack of data, some of the remaining degrees of freedom were used to calibrate transactions costs to be able to more adequately reproduce expected behavior of water rights price trends (Figure 20).

Water rights purchases incur a transaction cost $c_{r,d}^{\text{tran}}$ that simulates legal costs plus physical infrastructure costs per acre-foot of water purchased by an agent in subregion r from pool d. In the most general form, we set

$$c_{r,d}^{\text{tran}} = \frac{c_{r,d}^{\text{legal}} + c_{r,d}^{\text{infra}}}{\prod_{t=1980}^{2014} k_t^{\text{inflation}}} \tag{18}$$

where $c_{r,d}^{\text{legal}}$ represents legal transactions costs and $c_{r,d}^{\text{infra}}$ represents infrastructure costs. No legal costs $c_{r,d}^{\text{legal}}$ are associated with CBT shares since they are trans-basin waters free of native water right restrictions on change of use or ownership through water court. Legal costs were set to about \$4,000 for purchases within each subregion r with an additional $0.25 \cdot 4000 x_{r,d}$ for each pool d that was $x_{r,d}$ distance away from subregion r.[30]

$$c_{r,d}^{\text{legal}} = \$4{,}000 \cdot \left(1 + b^{\text{legal}} \cdot |x_{r,d}|\right) \quad (19)$$

where $x_{r,d}$ is a heuristic, "fuzzy" surrogate for distance from subregion r to pool d, the water source. The additional legal cost of transferring water rights over a distance is $b^{\text{legal}} = 0.25 \cdot \$4{,}000 = \$1{,}000$. Purchasing from the same subregion does not incur the additional distance cost (i.e., $x_{r,r} = 0$). Larger infrastructure costs $c_{r,d}^{\text{infra}}$ are also assumed for regions farther away or at lower elevations:

$$c_{r,d}^{\text{infra}} = c^{\text{infra}} \cdot \left(1 + b^{\text{infra}} \cdot x_{r,d} \cdot [x_{r,d} > 0]\right) \quad (20)$$

where $c^{\text{infra}} = \$10{,}000$ is the calibrated cost of infrastructure for a nearby or upstream water right purchase (i.e., $x_{r,d} \leq 0$), and $b^{\text{infra}} = \$12{,}500$ is the calibrated additional cost for infrastructure incurred from a downstream or lower elevation water right purchase corroborated with data obtained from an interview with Kelly DiNatale and a news article on the Thornton pipeline project.[31] Parameterization according to (20) ensures that the lowest infrastructure costs are incurred from purchases within the same subregion or from upstream regions.

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[30] The assumption and usage of a \$4,000 per AF cost to trading within the same region, and an additional 25% legal cost for outside tributary purchases was obtained from an interview on Nov. 3, 2015 with Kelly DiNatale who works in the SPRB on developing and transferring water rights http://dinatalewater.com/about/

[31] These calibration terms are estimated based on infrastructure costs being 50% to 67% of water projects that cost \$25,000 to \$30,000 per AF plus or minus \$2,500. These values came from an interview on Nov. 3, 2015 with Kelly DiNatale who works in the SPRB on developing and transferring water rights http://dinatalewater.com/about/. The Thornton (in the Central region of the model) pipeline project importing water from the Cache La Poudre river (in the North region of the model) was estimated to cost about \$28,600 / AF (Duggan, K. "Thornton plans pipeline to tap into Poudre water," *Coloradoan*, Oct. 19, 2015. Available on http://www.coloradoan.com/story/news/2015/10/19/thornton-plans-pipeline-poudre-river-water/74247032/). This was used as a target for transactions cost $c_{3,1}^{\text{tran}}$ where agents in the Central region (Region 3) incur a transaction cost when buying from the North region (Region 1).

The distance parameter $x_{r,d}$ (Table 15) was utilized as a calibration parameter to indirectly calibrate total transactions costs $c_{r,d}^{\text{tran}}$ (Table 16) with a simple heuristic rule that set most of its values:

1. $x_{r,d} = 0$ for purchases within the same subregion,
2. Add one for each distance downstream (e.g., add one for purchases from the North Central subregion by agents in the North subregion, and add two for purchases from the East subregion by agents in the North subregion),
3. Subtract one for each distance upstream, and
4. Add 0.5 for each decrease in elevation

Transactions costs due to sales of water from the North Central subregion (a largely agricultural subregion with some rapidly growing towns and small cities) to the Central subregion (the most heavily populated subregion) played a key role in water rights transactions between Central, North, and North Central. Instead of the original value of 1.5, $x_{3,2}$ was set to 1.6667 to improve modeled agricultural acreage dry up regionally (Figure 28).

Table 15: Calibrated surrogate distance $x_{r,d}$ from pool d of seller to subregion r of buyer

Subregion $\boldsymbol{r}$ of Buyer	Pool $\boldsymbol{d}$ of Seller					
	North	North Central	Central	South Metro	East	CBT
North	0	1.5	1.5	2.5	2.5	0
North Central	-1	0	-1	-1	2.5	-1
Central	1	1.6667	0	-1	2.5	10
South Metro	1.5	2.5	1.5	0	2.5	10
East	-1	-1	-1	-1	0	-1

Table 16: Calibrated transactions costs $c_{r,d}^{\mathrm{tran}}$ (in 2014 dollars) from pool d of seller to subregion r of buyer. To obtain this matrix in 1980 dollars, each value was divided by 3.25 (except for CBT water transactions costs in Central and South Metro regions).

Subregion $\boldsymbol{r}$ of Buyer	Pool $\boldsymbol{d}$ of Seller					
	North	North Central	Central	South Metro	East	CBT
North	\$14,000	\$34,250	\$34,250	\$47,750	\$47,750	\$10,000
North Central	\$15,000	\$14,000	\$15,000	\$15,000	\$47,750	\$10,000
Central	\$27,500	\$36,500	\$14,000	\$15,000	\$47,750	\$1,000,000
South Metro	\$34,250	\$47,750	\$34,250	\$14,000	\$47,750	\$1,000,000
East	\$15,000	\$15,000	\$15,000	\$15,000	\$14,000	\$10,000

Another model parameter that was indirectly calibrated to affect location of transfers from other regions in addition to increasing modeled water price to historical levels was the quadratic transaction cost term b^{tran}. The term simulates an additional cost to water rights acquisition when purchasing from within the same subregion to account for heterogeneity of purchases within each subregion. For an agent in subregion r, purchasing water rights from the same subregion $d = r$:

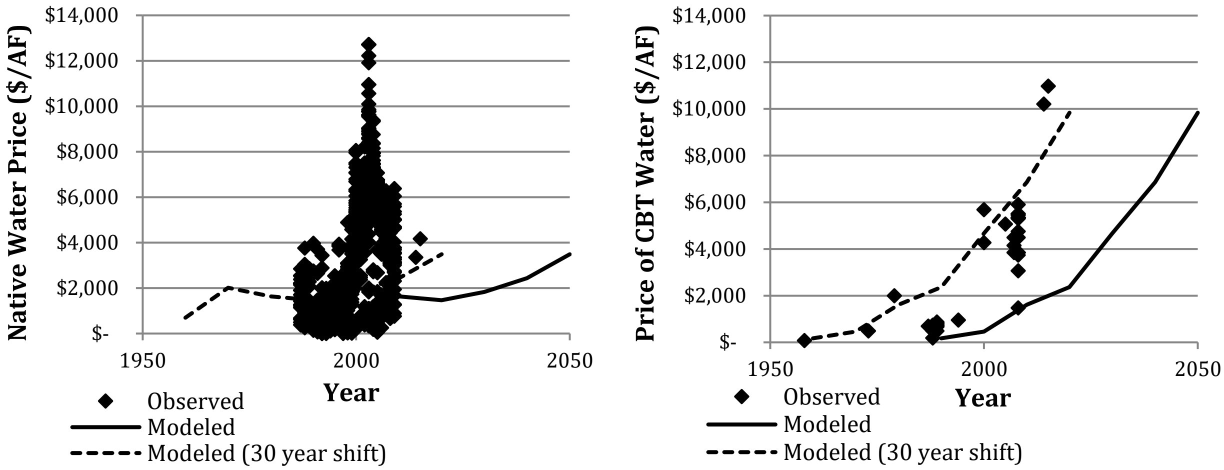
$$b^{\mathrm{tran}} = \frac{k^{\mathrm{tran}}}{\prod_{t=1980}^{2013} k_t^{\mathrm{CPI}}} \left(b^{\mathrm{legal}} + b^{\mathrm{infra}}\right) \tag{21}$$

where $b^{\mathrm{infra}} = \$12{,}500$ and $b^{\mathrm{legal}} = \$1{,}000$ as described above. The factor k^{tran} is a calibration constant that scales the cost of retrieving some of the last remaining water rights within the same subregion above the cost of retrieving rights from a neighboring subregion (when greater than 1). This constant k^{tran} was calibrated to 1.5. Estimates for b^{legal} and b^{infra} are based on the year 2014 while b^{tran} needs to be in 1980 dollar amounts, so the product of consumer price indices k_t^{CPI} from 1980 to 2014 (excluding 2014 itself) accounts for inflation between those two years.

Trends of total regional acreage are captured by the model (Figure 28b), but trends by crop are not as well represented as historically irrigated acres of corn decrease much faster than alfalfa when the model predicts the opposite (Figure 28c). The total percent of acreage in 1980 still being used in production in 2010 is almost identical at the full basin scale. Observed is 82% and modeled is 80%. Regional distribution of cropland acreage is generally matched, including the trend of sustained agricultural production in the East subregion, likely because the subregion is both downstream and at a lower elevation than most cities in the SPRB, making water purchases from the subregion more difficult. Discrepancies in acreage by individual crop may be explained by benefits to farming alfalfa that were not modeled such as a lower risk of revenue loss in the case of drought, or externalities such as a large livestock population that depends on alfalfa feed. There has also been a decreasing inflation-adjusted price trend since 1980 for corn, sugar beets and alfalfa, but these trends have not been included in the model because they have reversed since year 2000.

Modeled water rights prices capture long-term trends fairly well (Figure 20). Price in any individual subregion always increases as time progresses, but since prices vary by subregion, purchases from cheaper native sources drop the total average price in 2020 relative to 2010. Several cities in the SPRB purchase water rights between 10-40 years in advance of project finish (and resulting water usage), and therefore can drive up the price of water long before actual shifts in beneficial uses are made. Evidence of this long planning period are found in news articles of water rights purchases by the city of Thornton[32] and of large conditional water rights lingering around still from the 1960s.[33] Thus, a 30-year shift in modeled price is shown to demonstrate how this foresight can affect (and has likely affected) the price of water. Observed water rights prices have such large variance because they include monopolization, individual expectations on prices, and other market inefficiencies that are not modeled.

[32] Duggan, K. "Thornton plans pipeline to tap into Poudre water," *Coloradoan*, Oct. 19, 2015. Available on http://www.coloradoan.com/story/news/2015/10/19/thornton-plans-pipeline-poudre-river-water/74247032/
[33] Ibid. 40



a) Native water rights price **b) CBT water price**

Figure 20: Modeled water price (lines) with respect to historically observed water rights transactions prices (black diamonds) for a) native water rights, and b) CBT water shares. Developers, cities, and speculators (in the case of CBT shares) can purchase water long before the transfer of use and location happens, so a 30-year shift in modeled price data is shown to display how foresight and planned water projects can affect price long before water is put to municipal and domestic uses. Some "observed data" in the native water rights figure might belong in the CBT water shares figure, but due to incomplete datasets, the assignment to CBT was indistinguishable in many cases.[34]

All financial inputs to the model such as costs of water and acreage, crop prices, and transactions costs were scaled back to 1980 dollar amounts so as to keep analysis consistently in the same dollar value. Parameterization for every individual value in the above model is not listed

[34] Observed water rights price data came primarily from the "California Water Transfer Records" compiled by the Bren School of Environmental Science & Management on http://www.bren.ucsb.edu/news/water_transfers.htm. Native water rights and CBT water rights were split using "buyer" and "seller" names which were incompletely filled out, so many of the observed water transfers within the graph of "native" water rights might actually be CBT shares. Other minor sources of water rights price information came from 1) "Colorado's South Platte Basin Water Rights Market," *Water Market Insider* (2016) publication of WestWater Research LLC on http://www.waterexchange.com/wp-content/uploads/2016/02/16-0217-Q1-2016-WWInsider-LO-singles.pdf. 2) Nichols, P.D., Murphy, M.K., and Kenney, D.S. (2001). "Water and Growth in Colorado: A review of legal and policy issues," Natural Resources Law Center, University of Colorado School of Law, Boulder, CO. Available on http://www.colorado.edu/geography/geomorph/envs_5810/Water_and_Growth.pdf. 3) Plunkett, C. (2005). "Fortunes flow from water sales," The Denver Post. Available on http://www.denverpost.com/2005/12/16/fortunes-flow-from-water-sales/. 4) A water right clearinghouse called "Water Colorado: Buying South Platte River Basin Water Rights" operated by Water Colorado on http://www.watercolorado.com/buy-water/district1.shtml. 5) Another water right clearinghouse operated by Selling Colorado Water on http://sellingcoloradowater.com/buysellwater/.

here for the sake of brevity. For more detailed data values, all input tables for each decade of analysis and policy scenario can be found in supplementary data for Dozier et al. (n.d.).

4.4 Integrated Urban Water Model[35]

To characterize urban water use and management strategies and opportunities, the Integrated Urban Water Model (IUWM) was developed. IUWM applies an end-use, mass balance approach on a daily time step for projecting urban water demand and savings for assessing urban water management strategies (Figure 21). The model simulates water demands and savings through use of demographic, land cover, and climate data readily available via publically accessible databases (Figure 22). IUWM includes explicit options for evaluating the effects of specific urban water conservation strategies on water use, utility costs, and rates. These strategies include: indoor conservation, irrigation conservation and use of alternative water sources including treated wastewater, graywater and stormwater. Each alternative water source can be used to meet commercial, industrial, and institutional (CII) demand, CII and residential irrigation demand, residential toilet or potable demand, or some specific combinations. Once service areas are specified by the user, various scenarios can be created and compared with different parameters and practices.

[35] Sharvelle, S., Dozier, A. Q., Arabi, M., and Reichel, B. I. (under review). "A geospatially-enabled web tool for urban water demand forecasting and assessment of alternative urban water management strategies." *Environmental Modelling & Software*, Elsevier B.V.

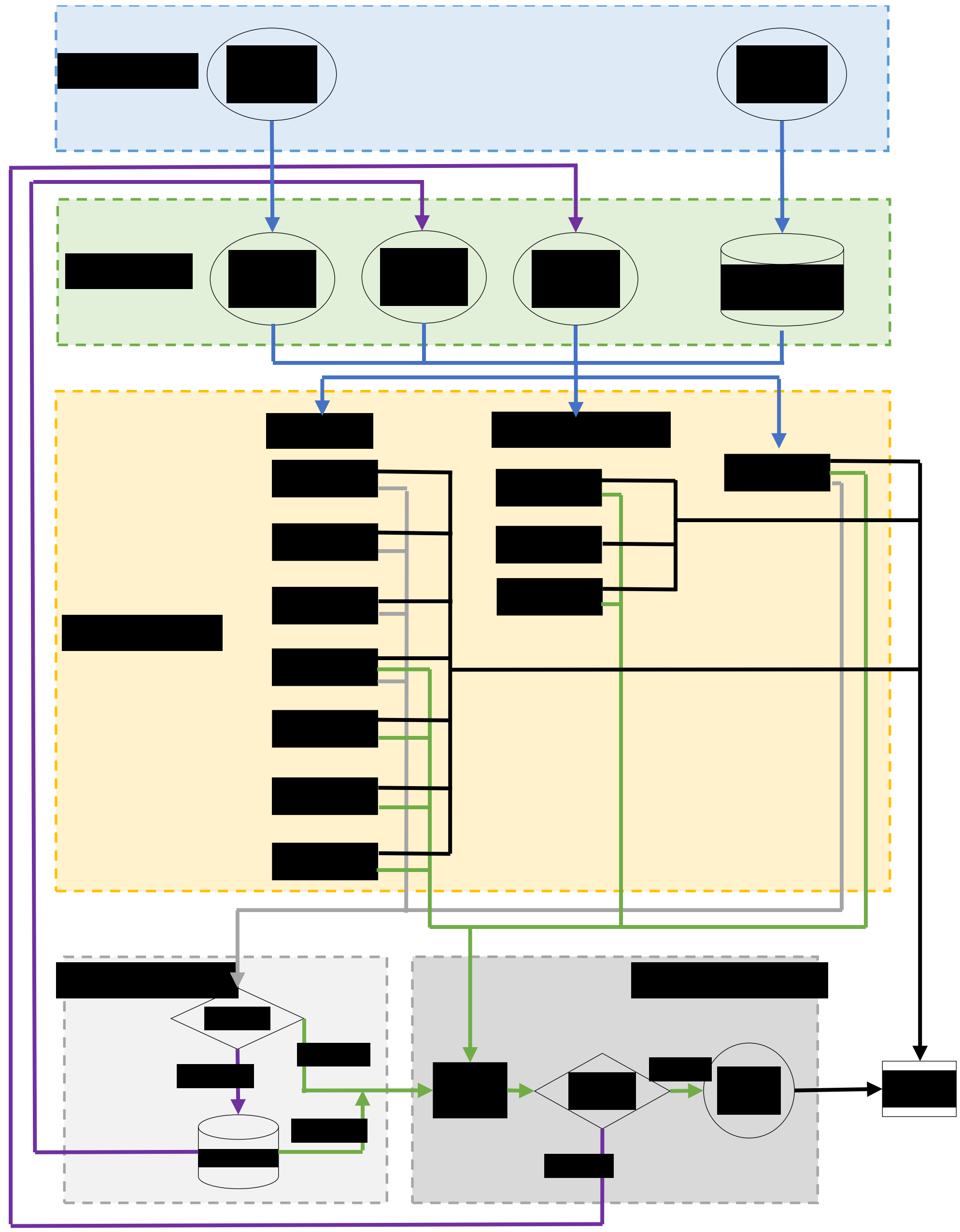


Figure 21: Mass balance flow chart for the Integrated Urban Water Model (IUWM).

The core simulation model for IUWM is written in Python, while a web-based interface is developed in HTML and JavaScript. IUWM is available as a tool within the environmental Resources

Assessment and Management System (eRAMS) cloud computing infrastructure.[36] An advantage of deployment of analysis tools in eRAMS is integration with the eRAMS geographical information system (GIS), which enables access to geoprocessing, mapping, and visualization tools.[37]

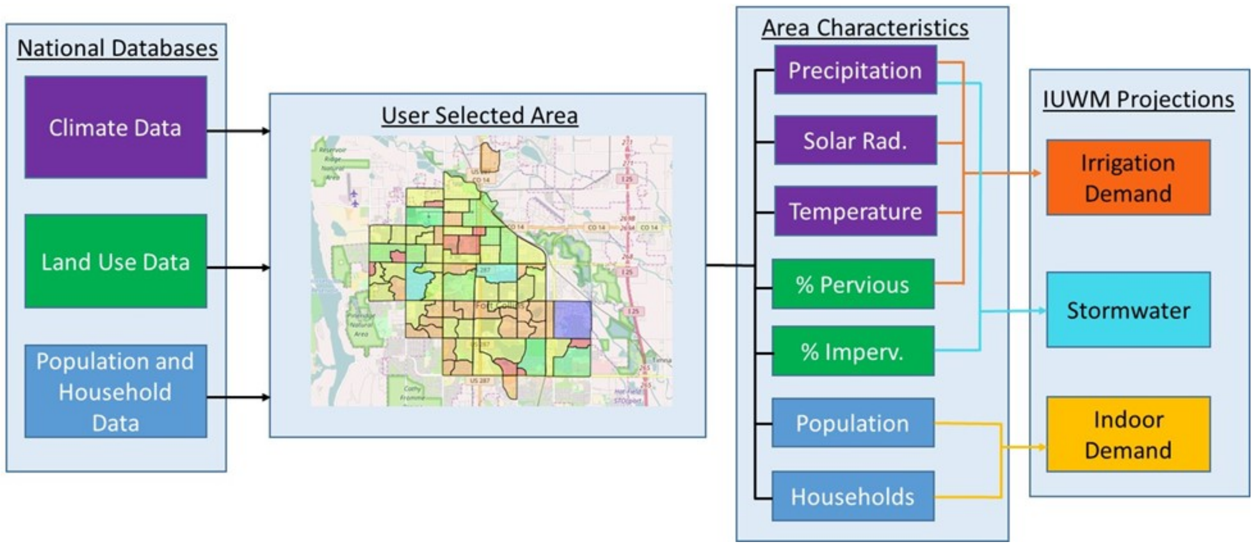


Figure 22: Schematic of the IUWM input data, area characteristics for projection of indoor, demand, outdoor demand, and stormwater

4.4.1 Spatial Discretization and Data Requirements

The IUWM modeling service area is divided into spatial subunits that are assumed to have homogeneous characteristics. Users can specify polygon features that define the geographic boundary of computational subunits. Model parameters are fully distributed and may be defined or estimated for each subunit. The smallest subunit that may be defined is the building level. Within the IUWM GIS interface, service areas and spatial subunits may be created by heads-up digitizing, or using known boundaries (e.g., incorporated areas, political boundaries, demographic regions, or watersheds) or user uploaded geospatial features (i.e., polygon shapefiles).

[36] www.erams.com/iuwm
[37] www.erams.com/documentation

The required input data for creating an IUWM model are: service area boundary; computational subunit boundaries; land cover, imperviousness, population, households, and daily climate (Figure 22). Users can upload the input data for the service area. This ensures the general applicability of the model for all regions.

To lower data collection and preparation barriers, for regions within the U.S., the required spatial and time series data can be automatically extracted from readily available U.S. databases (Figure 23). Land use, land cover and imperviousness are extracted from the National Land Cover Dataset, NLCD (Homer et al. 2015). NLCD is derived from Landsat satellite imagery at a 30-meter resolution published by the Multi-Resolution Land Characteristics (MRLC) Consortium. The database has been published in its current format since 2001 and has been updated every five years. The dataset includes 16 land cover classes but only the four urban development categories are used by IUWM as follows (NLCD class number in parentheses): open-space (21), low-density (22), medium-density (23), and high-density (24). Population and household information are obtained from the U.S. Census Bureau (2011). Climate data for daily precipitation and temperature are retrieved from the historically interpolated PRISM dataset at 4-kilometer spatial grid resolution (PRISM Climate Group 2004). City, state, county, track, block group and block boundaries are obtained from U.S. Census TIGER/Line® Shapefiles database (U.S. Census Bureau 2016).

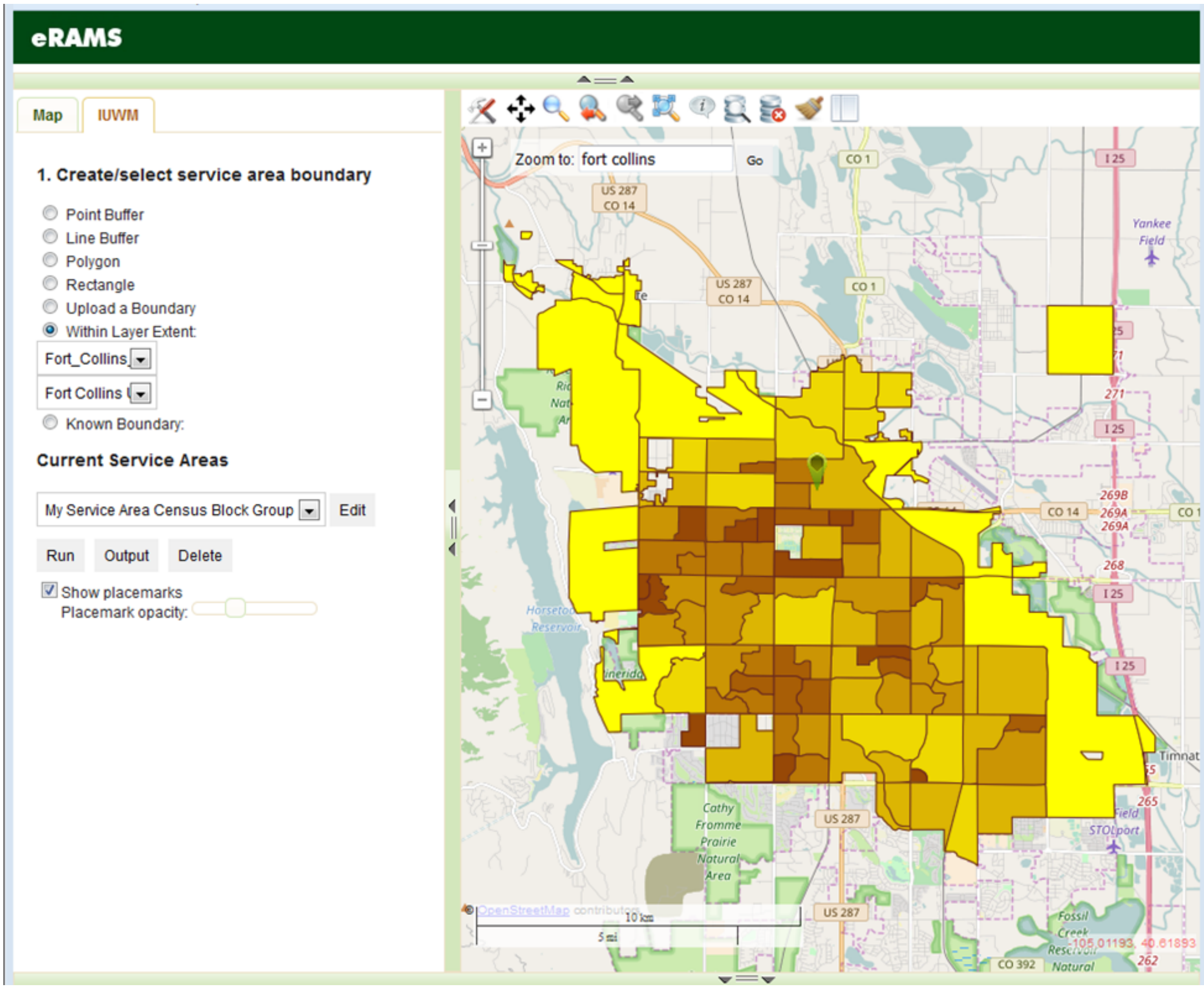


Figure 23: IUWM interface for selection of service area and data sources. The map shows Census Block Groups with 2010 population density in person per square kilometer for the Fort Collins Utility Service Area.

4.4.2 Water Use Characterization

4.4.2.1 Indoor Residential Water Use

Indoor residential water use in IUWM is estimated using demand profiles that relate household size to average daily household indoor water use (DeOreo and Mayer, 2012). Total daily indoor use $q_{i,f}^{\mathrm{res.in}}$ for spatial subunit i (e.g., census block or county) with demand profile function f is represented as a power function of household size s_i with parameters $\alpha_{i,f}$ and $\beta_{i,f}$ that remains constant throughout time:

$$\mathrm{q}_{i,f}^{\mathrm{res,in}} = \alpha_{i,f} \cdot {s_i}^{\beta_{i,f}} \cdot n_i^{\mathrm{hsd}} \tag{22}$$

Household size s_i represents an average number of people per household across spatial subunit i with population n_i^{pop} and number of household units n_i^{hsd}:

$$s_i = \frac{n_i^{\mathrm{pop}}}{n_i^{\mathrm{hsd}}} \tag{23}$$

Household units and population for this study can be supplied by the user, or otherwise automatically extracted from U.S. Census with no distinction between single-family and multi-family residences. Total indoor use for each spatial subunit is the sum across a specified fraction of homes $k_{i,f}$ from each demand profile f:

$$q_i^{\mathrm{res,in}} = \sum_{f \in F} k_{i,f} q_{i,f}^{\mathrm{res,in}} \tag{24}$$

where F is the set of household profile functions including user-defined profiles. IUWM users specify $\alpha_{i,\mathrm{user}}$ and $\beta_{i,\mathrm{user}}$ for each spatial subunit i, or specify a fraction of homes $k_{i,f}$ using pre-defined demand profiles from results of published end-use studies. Three pre-defined household profile functions are included in IUWM (Table 17), the Residential End Uses of Water Study (REUWS 1999; Mayer et al. 1999), the REUWS version 2 (REUWS 2016; DeOreo et al. 2016) and High Efficiency New Homes (HENH; DeOreo 2011). The REUWS monitored water use from over 1,000 homes across North America to build empirical relationships between household size and water use (DeOreo et al. 2016; Mayer et al. 1999). These empirical demand profile functions for 1999, 2016, and HENH are used as default pre-defined demand profiles for IUWM (Table 17). Average household water use has decreased from 1999 to 2016 by approximately 22.6%, and high efficiency homes have reduced indoor water use by an additional 18.5%. Indoor conservation can be modeled by modifying $k_{i,f}$ or by adapting $\alpha_{i,f}$ and $\beta_{i,f}$.

Table 17: Average indoor household water use $\overline{q}_f$ (and standard deviation) in gphd and power function factors. Data obtained directly from DeOreo (2011), DeOreo et al. (2016), and Mayer et al. (1999).

Study	$\overline{q}_f\left(SD(q_f)\right)$	α_f	β_f
REUWS 1999	177.6 (96.9)	87.4	0.69
REUWS 2016	137.5 (79.7)	67.3	0.65
HENH	112.0 (59.6)	59.6	0.53

Indoor end-use $q_{i,e}^{\text{res,in}}$ is estimated by splitting total indoor water use by fraction $k_{i,f,e}$ for each spatial unit i, household demand profile f, and end-use e as follows:

$$q_{i,e}^{\text{res,in}} = \sum_{f \in F} k_{i,f,e} \cdot q_{i,f}^{\text{res,in}} \tag{25}$$

End-use percentages can be specified by the user or will default to empirical values from REUWS using monitored readings in highly instrumented houses (Table 18).

Table 18: Percent of total household use by end-use from REUWS used by default. Data obtained directly from DeOreo (2011), DeOreo et al. (2016), and Mayer et al. (1999).

Demand	REUWS 1999	REUS 2016	HENH
Bath	3	3	6
Clothes Washer	22	17	19
Dish Washer	2	1	2
Faucet	15	19	19
Leaks	12	12	10
Other	4	4	1
Shower	17	20	24
Toilet	25	24	19

4.4.2.2 Outdoor Water Use

IUWM estimates total outdoor water use including both residential and CII end-uses. Water used for irrigation is assumed to comprise total "outdoor" water uses, so the approach used by IUWM is to base outdoor demand off of gross irrigation requirement for an estimated irrigated area. For each daily time step t and each spatial subunit i, a gross irrigation depth $q_{i,t}^{\text{irr}}$ is calculated:

$$q_{\text{i,t}}^{\text{irr}} = \frac{k_i^{met} \cdot k_i^{pf} \cdot e_{i,t}^{pot} - k_i^{pcp} \cdot r_{i,t}^{pcp}}{k_i^{eff}} \tag{26}$$

where $e_{i,t}^{\text{pot}}$ estimates potential evapotranspiration (ET) depth (units of length) while $r_{i,t}^{\text{pcp}}$ represents depth of precipitation (units of length). Potential ET is estimated according to energy balance as approximated by Hargreaves and Samani (1982), parameterized using weather extracted from a specified data source, defaulting to historically interpolated weather from PRISM (PRISM Climate Group 2004).

Impacts of conservation practices on outdoor water use can be simulated using the various parameters provided in (26). A mixture of technology and behavioral parameters are provided to be able to distinguish effects of technology updates from behavioral patterns. Plant factors k_i^{pf} can be provided for each spatial subunit i to estimate actual ET from different landscape categories, defaulting to 0.8 for cool season grass (Pittenger et al. 2001). A technology parameter k_i^{eff} characterizes irrigation application efficiency that specifies the fraction of water that is actually received and used by the plant. IUWM models residential users that meet only a fraction of ET (either by choice or by ignorance) through the behavioral parameter k_i^{met}. Another behavioral parameter k_i^{pcp} can be used to simulate the fraction of precipitation to which irrigators respond. For each spatial subunit i, the estimated irrigation depth is applied over a fraction $k_{i,c}$ of total area $A_{i,c}$ with land use c to estimate total volume of water used for outdoor purposes $q_{i,t}^{\text{out}}$:

$$q_{i,t}^{\text{out}} = \begin{cases} \max\left\{ 0 \ , \ q_{\text{i,t}}^{\text{irr}} \cdot \sum_{c \in C} k_{i,c} \cdot A_{i,c} \right\} & \text{if } T_{i,t} \geq T^{\text{irr}} \\ 0 & \text{otherwise} \end{cases} \quad (27)$$

To simulate the irrigation season, outdoor demand is assumed to be zero when the daily average temperature $T_{i,t}$ drops below a threshold temperature parameter T^{irr} (default is 12 °C). The set of all land use categories C is defined by urban development categories with default characterization obtained from the National Land Cover Database, NLCD (Homer et al. 2015). NLCD is derived from Landsat at a 30 square meter resolution published by the Multi-Resolution Land Characteristics (MRLC) Consortium. The database has been published in its current format since

2001 and has been updated every five years. It includes 16 land cover classes, but only the four urban development categories are used by IUWM as follows (NLCD class number in parentheses): open-space (21), low-density (22), medium-density (23), and high-density (24).

4.4.2.3 Indoor CII Water Use

Although difficult to generalize (Morales et al. 2009), a reasonable estimate of indoor commercial, industrial, and institutional (CII) demand $q_i^{\text{cii,in}}$ for individual utilities within each spatial subunit i can be obtained through estimating CII demand per household. The following equation is calculated at the beginning of an IUWM simulation:

$$q_i^{\text{cii,in}} = k_i^{\text{cii,in}} n_i^{\text{hsd}} \tag{28}$$

where $k_i^{\text{cii,in}}$ is a user-specified amount of indoor CII demand per household given n_i^{hsd} for each spatial subunit. Using this formulation, CII demand remains constant for each day of analysis.

4.4.2.4 Produced Water

Both residential and CII indoor uses produce wastewater from backwater and graywater. First, for residential purposes, IUWM splits total indoor use into consumed $q_i^{\text{res,cons}}$ and non-consumed water $q_i^{\text{res,ncons}}$ using a user-specified fraction $k_i^{\text{res,cons}}$:

$$q_i^{\text{res,cons}} = k_i^{\text{res,cons}} \cdot q_i^{\text{res,in}} \tag{29}$$

$$q_i^{\text{res,ncons}} = \left(1 - k_i^{\text{res,cons}}\right) \cdot q_i^{\text{res,in}} = q_i^{\text{res,black}} + q_i^{\text{res,gray}} \tag{30}$$

where produced blackwater $q_i^{\text{res,black}}$ and graywater $q_i^{\text{res,gray}}$represent fractions of the estimated water use for each residential indoor end-use e, $k_{i,e}^{black}$ and $k_{i,e}^{gray}$ respectively:

$$q_i^{\text{res,black}} = \sum_{e \in E_B} k_{i,e}^{\text{black}} \cdot q_{i,e}^{\text{res,in}} \tag{31}$$

$$q_i^{\text{res,gray}} = \sum_{e \in E_G} k_{i,e}^{\text{gray}} \cdot q_{i,e}^{\text{res,in}} \tag{32}$$

Default consumed percentage $k_i^{\text{res,cons}}$ is 10% of total indoor use (Metcalf and Eddy, 2003). Baths, clothes washers, showers, and non-kitchen faucets are in the subset of end-uses E_G assumed to produce graywater. Dish washers, toilets, leaks, kitchen faucets, and "other" end-uses are in the subset of end-uses E_B assumed to produce blackwater. Separate input parameters are allowed to specify percent blackwater produced for faucet and "leak" end-uses, defaulting to 66.7% and 50% respectively (assumed values). This provides flexibility in modeling kitchen faucets that produce blackwater separately from other faucets that produce graywater. It also allows some leaks to produce blackwater resulting in waste effluent from each spatial subunit. Due to these separate input parameters, consumed fractions of other individual end-uses $k_{i,e}^{\text{cons}}$ are shifted to ensure that each the following constraints are met:

$$\sum_{e \in E} k_{i,e}^{\text{cons}} \cdot q_{i,e}^{\text{res,in}} = k_i^{\text{res,cons}} \cdot q_i^{\text{res,in}} \tag{33}$$

$$k_{i,e}^{\text{black}} + k_{i,e}^{\text{gray}} + k_{\text{i,e}}^{\text{cons}} = 1 \tag{34}$$

Fractions of blackwater $k_i^{\text{cii,black}}$ and graywater $k_i^{\text{cii,gray}}$ produced from CII indoor usage are direct input parameters to IUWM. CII blackwater $q_{i,t}^{\text{cii,black}}$ and graywater $q_{i,t}^{\text{cii,gray}}$ produced are calculated as fractions of total CII indoor usage:

$$q_{i,t}^{\text{cii,black}} = k_i^{\text{cii,black}} q_{i,t}^{\text{cii,in}} \tag{35}$$

$$q_{i,t}^{\text{cii,gray}} = k_i^{\text{cii,gray}} q_{i,t}^{\text{cii,in}} \tag{36}$$

Remaining CII indoor demands are consumed $q_{i,t}^{\text{cii,cons}}$:

$$q_{i,t}^{\text{cii,cons}} = q_{i,t}^{\text{cii}} - q_{i,t}^{\text{cii,gray}} - q_{i,t}^{\text{cii,black}} \tag{37}$$

Thus, for each spatial subunit and timestep, total water consumed ($q_{i,t}^{\text{cons}}$) and wastewater produced ($q_{i,t}^{\text{black}}$ and $q_{i,t}^{\text{gray}}$) for each spatial subunit are summed across CII and residential uses:

$$q_{i,t}^{\text{cons}} = q_i^{\text{res,cons}} + q_{i,t}^{\text{cii,cons}} \tag{38}$$

$$q_{i,t}^{\text{black}} = q_i^{\text{res,black}} + q_{i,t}^{\text{cii,black}} \tag{39}$$

$$q_{i,t}^{\text{gray}} = q_i^{\text{res,gray}} + q_{i,t}^{\text{cii,gray}} \tag{40}$$

4.4.2.5 Stormwater Estimation

Policy makers and legislators in semi-arid regions of the U.S. are increasingly considering stormwater as a viable source of water (National Acadamies Press 2016). As a policy evaluation tool, IUWM estimates both the amount of stormwater available and its impact on demand for potable water. Stormwater runoff available for capture and reuse is estimated according to Schueler (1987) as shown in (41) for the total area A_i of the spatial subunit i.

$$q_{i,t}^{\text{storm}} = k_i^{\text{coeff}} \cdot k_i^{\text{runoff}} \cdot r_{i,t}^{\text{pcp}} \cdot A_i \tag{41}$$

k_i^{runoff} is the fraction of precipitation that produces runoff, and k_i^{coeff} is the runoff coefficient representing the fraction of area that can produce runoff according to the following empirical relationship (Schueler 1987):

$$k_i^{\text{coeff}} = \left(0.05 + 0.9 \cdot k_i^{\text{imperv}}\right) \tag{42}$$

where k_i^{imperv} is the fraction of total land area that is impervious, which is estimated based on NLCD.

4.4.2.6 Use of Alternative Water Sources

User specification of adoption rates and supply availability parameters enables IUWM to simulate potential impact of use of alternative water sources on demands from specific indoor, outdoor, and CII end uses. Each water source (treated raw water, reused graywater, reused wastewater, and stormwater) can be used to meet the following potable and non-potable demands referred to as "reuse purposes" ($p \in P$) in order: (1) CII demand; (2) Toilet flushing; (3) All potable uses; (4) Irrigation; (5) Both toilet flushing and irrigation; and (6) Both potable and irrigation.

Recycle "bins", or simulated water storage containers, track water sources that can be used in any particular day. To activate a graywater, stormwater, or wastewater use system s, a fraction of households or CII entities must "adopt" the practice specifying the use purpose p within the set of reuse purposes P. P^{res} is the subset for residential purposes $\{p \mid p \neq 1\}$ and P^{cii} is the subset for CII purposes $\{p \mid p = 1\}$. For each recycle bin with storage volume $S_{i,s,p,t}$, mass balance is employed to select the amount of water reused $q_{i,s,p,t}^{\text{reused}}$ and consequently the amount of water spilled $q_{i,s,p,t}^{\text{spill}}$ given the following dynamics:

$$\frac{dS_{i,s,p}(t)}{dt} \cong \frac{\Delta S_{i,s,p,t}}{\Delta t} = S_{i,s,p,t+1} - S_{i,s,p,t} = q_{i,s,p,t}^{\text{avail}} - q_{i,s,p,t}^{\text{reused}} - q_{i,s,p,t}^{\text{spill}} \tag{43}$$

For each timestep t and spatial subunit i, storage of water $S_{i,s,p,t}$ (with upper bound $S_{i,s,p}^{\text{cap}}$) from source s for purpose p gains water from available supply $q_{i,s,p,t}^{\text{avail}}$ while concurrently releasing water for reuse purposes $q_{i,s,p,t}^{\text{reused}}$. When storage is full, spill $q_{i,s,p,t}^{\text{spill}}$occurs. Water made available for reuse $q_{i,s,p,t}^{\text{avail}}$ is a fraction of the total supply $q_{i,s,t}^{\text{supply}}$ given the fraction of households $k_{i,s,p}^{\text{adopt}}$ that adopted the system for purpose p and the fraction of water available $k_{i,s}^{\text{avail}}$ from water source s.

$$q_{i,s,p,t}^{\text{avail}} = k_{i,s,p}^{\text{adopt}} \cdot k_{i,s}^{\text{avail}} \cdot q_{i,s,t}^{\text{supply}} \tag{44}$$

Water can be reused up to the total amount of water used by a fraction of households $k_{i,s,p}^{\text{adopt}}$ that adopted the reuse system with water use $q_{i,p,t}^{\text{use}}$.

$$q_{i,s,p,t}^{\text{reused}} \leq k_{i,s,p}^{\text{adopt}} \cdot q_{i,p,t}^{\text{use}} \tag{45}$$

Constraints apply to $k_{i,s,p}^{\text{adopt}}$ and $S_{i,s,p,t}$ as follows:

$$\sum_{p \in P^{\text{res}}} k_{i,s,p}^{\text{adopt}} \leq 1 \tag{46}$$

$$\sum_{p \in P^{\text{cii}}} k_{i,s,p}^{\text{adopt}} \leq 1 \tag{47}$$

$$0 \leq S_{i,s,p,t} \leq S_{i,s,p}^{\text{cap}} \tag{48}$$

To model policy requirements and water quality standards associated with meeting potable demand with alternative water sources, a user-specified fraction $k_{i,p}^{\text{mix}}$ of water use $q_{i,p,t}^{\text{use}}$ must be met with treated raw water $q_{i,p,t}^{\text{demand}}$ while remaining water use can be met with reused water:

$$k_{i,p}^{\text{mix}} \cdot q_{\text{i,p,t}}^{\text{use}} \leq q_{i,p,t}^{\text{demand}} \leq q_{i,p,t}^{\text{use}} \tag{49}$$

Three supply sources are used as alternatives to treated raw water: graywater ("gray"), blackwater ("black"), and stormwater ("storm"):

$$q_{i,s,t}^{\text{supply}} = \begin{cases} q_{i,t}^{\text{gray}} & \text{if } s = \text{gray} \\ q_{i,t}^{\text{black}} & \text{if } s = \text{black} \\ q_{i,t}^{\text{storm}} & \text{if } s = \text{storm} \end{cases} \tag{50}$$

Each source can be used to meet any combination of the six reuse purposes:

$$q_{i,p,t}^{\text{use}} = \begin{cases} q_{i,t}^{\text{cii,in}} & \text{if } p = 1 \\ q_{i}^{\text{flush}} & \text{if } p = 2 \\ q_{i}^{\text{res,in}} & \text{if } p = 3 \\ q_{i,t}^{\text{out}} & \text{if } p = 4 \\ q_{i}^{\text{flush}} + q_{i,t}^{\text{out}} & \text{if } p = 5 \\ q_{i}^{\text{res,in}} + q_{i,t}^{\text{out}} & \text{if } p = 6 \end{cases} \tag{51}$$

When applying a given source of water, available water that is spilt from one reuse system is available for use by other reuse systems in the same order given above in the list of reuse purposes. A distinction in the notation is made between "use" of water representing a volume of water used for a particular purpose, and "demand" of water representing the remaining amount of potable water supply (treated raw water) required to meet the estimated use. When accounting for the amount of reused water, demand for treated raw water $q_{i,p,t}^{\text{demand}}$ drops according to:

$$q_{i,p,t}^{\text{demand}} = q_{i,p,t}^{\text{use}} - \sum_{s \in W} q_{i,s,p,t}^{\text{reused}} \tag{52}$$

4.4.3 Input Parameters

The web-based interface for IUWM is designed to provide reasonable estimates of indoor water use, outdoor water use and stormwater production with very little to no user input. Within the interface, IUWM retrieves data from nationally available data bases to characterize a user selected service area. Based on the automatically retrieved data (i.e. PRISM, NLCD and US Census) and default parameters (Table 19), an estimate of water use is provided. The user can modify the parameters listed in Table 19 to improve the estimate of water use for their selected area. For the Fort Collins case study presented in this paper, 14 years of data were used to calibrate the parameters as described below (see Application of IUWM at the Municipal Scale).

Table 19: Parameters Applied for Estimation of Indoor Water Use, Outdoor Water Use and Stormwater Produced Including IUWM Default Values

Parameter[a]	Realistic Range	Default Value	Calibrated Value 2000 – 2009	Calibrated Value 2010 - 2014
Indoor Demand:				
$\boldsymbol{\alpha}$	45 – 90	67.3	71.1	66.0
$\boldsymbol{\beta}$	0.50 – 0.80	0.65	0.76	0.76
$k_i^{\mathrm{cii,in}}$	0 - 20	0	151[b]	122[b]
Outdoor Demand:				
k_i^{met}	0 – 1.5	0.45	0.32[c]	0.32[c]
k_i^{eff} **(%)**	30 - 99	71[c]	71[c]	71[c]
k_i^{pcp} **(%)**	0 – 100	1	24.7	69.2
T^{irr} **(°C)**	0 – 20	14	12.6	13.1
$A_{i,c}$ **Open Space (%)**	50 – 100	80	80	80
$A_{i,c}$ **Low Density (%)**	50 – 80	70	70	70
$A_{i,c}$ **Medium Density (%)**	20 – 50	40	40	40
$A_{i,c}$ **High Density (%)**	0 – 20	5	5	5
k_i^{pf}	0.3 – 1.0	0.8	0.93	0.88
Stormwater Produced:				
k_i^{runoff}	0.3 – 1.0	0.90[d]	0.90[d]	0.90[d]

[a] The same values were applied to the parameters across all spatial subunits $\boldsymbol{i}$
[b] Values in the calibrated model actually vary by spatial subunit $\boldsymbol{i}$
[c] DeOreo et al (2016)
[d] Runoff coefficient taken from Schueler (1987)

IUWM includes options to evaluate alternate climate scenarios (Figure 24). The user can specify both a temperature and precipitation offset to be applied to the historical climate dataset or can upload a file of projected climate. Precipitation and temperature is increased or decreased according to the same offset percentage across all timesteps of analysis. Files uploaded to the IUWM interface during the model creation stage must be comma delimited and have columns "date", "tmpmax (C)", "tmpmin (C)", "tmpavg (C)", "apcp (in)", and an optional column named "dswrf (langley)".

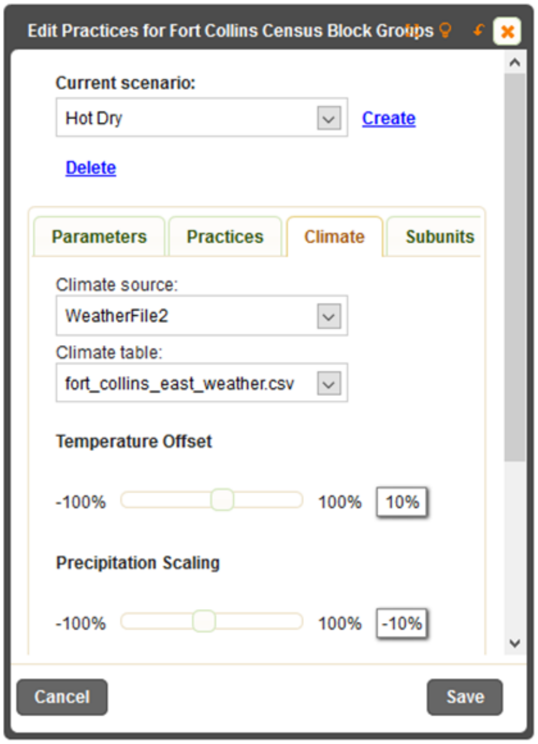


Figure 24: IUWM interface for climate scenarios

Important for a tool that informs long term water planning is the ability to run scenarios of population growth and land use change. IUWM has two options for running such scenarios. The first option is the ability to select projections within the interface for changes as a percentage increase or decrease in population, number of household, and land use (i.e. percentage change in area that is open space, low density, medium density and high density). This enables a user to apply a change that occurs evenly throughout their service area and evaluate impact to water use. Another option that enables running of scenarios of population growth and land use change specific to subunits (e.g. blocks, block groups or tract) is to upload projected values for population, number of households and land use type into the subunit table. This enables data associated with any specific subunit to be uploaded into a table based on the geographical identification for that subunit so that scenarios of population and land use changes in each subunit can be run.

4.4.4 Application of IUWM at the Municipal Scale

The City of Fort Collins in northern Colorado was selected for calibration and verification of IUWM with a case study application considering scenarios of water conservation and reuse as well as scenarios of climate change and population growth including land use change. Fort Collins was deemed suitable for model demonstration as a small city with mostly low to medium density development (Table 20) and adequate data was available to support calibration and verification. City of Fort Collins Utilities provided monthly water demand data for years 2000-2014 at the block group level used to calibrate and verify the model.

Table 20: Characteristics for Fort Collins, CO Water Service Area. Data extracted from US Census 2010 and NLCD 2011.

Service Area Characteristic	Value for the Water Service Area
Area (km^2)	52.3
Population (cap)	97,145
Households	40,810
Open Space Area (%)	23
Low Density Area (%)	50
Medium Density Area (%)	21
High Density Area (%)	6

4.4.4.1 Parameter Estimation

While IUWM default parameter values (Table 19) can be applied to estimate water demand, parameters were estimated for the City of Fort Collins via built-in calibration routines (not available in the interface) to provide an improved estimate of baseline demand. Some of these values were estimated based on literature (i.e. k_i^{met}, k_i^{eff} and k_i^{runoff}), while others were estimated via calibration with realistic ranges (Table 19). Total monthly water deliveries to residential and CII customers were reported separately at the block group level, from which indoor and irrigation demands were derived based on average non-irrigation demand months of January, February, March, November, and December. To account for data dropped due to personally identifiable information in block groups with fewer than 2 customers, these observations were scaled by a factor to match a separate dataset obtained from the City of Fort Collins containing total monthly water use from 2010-2014 for the entire city.

The water use dataset aggregated at block groups and obtained from the city of Fort Collins was split into two periods (2000-2009 and 2010-2014). A separate calibration was performed for each period for indoor residential, indoor CII, and total outdoor water use. The Sobol' Global Sensitivity Analysis technique (Saltelli et al. 2000; Sobol 1993, 2001) was used to perform global sensitivity analysis on model performance metrics and consequently calibration of model parameters through generation of thousands of parameter samples and evaluation by IUWM. Separate analyses of 3,000 and 8,000 parameter samples were performed for residential indoor (parameters α, β) and outdoor (parameters T_i^{irr}, $A_{i,c}$, k_i^{pf}, and k_i^{pcp}) uses, respectively. Because some parameters such as β and $A_{i,c}$were very similar across calibration periods, expected not to notably change over time, and had interactive effects on other parameters, those parameters were held constant over the two time periods of calibration. The selected parameter values for $A_{i,c}$ from the 2000-2009 calibration were rounded to the nearest 5% and held constant for the 2010-2014 calibration. CII indoor demand (parameter $k_i^{\text{cii,in}}$) was estimated by taking average observed indoor CII demand (determined during winter months) divided by the number of household units (from 2010 U.S. Census) for each census block group corresponding to spatial subunit i.

Three error statistics; mean relative error (MRE), bias fraction (BIAS), and Nash-Sutcliffe Coefficient of Efficiency (NSCE) were used to evaluate model performance. Parameter sets that maximized performance of both residential indoor and total outdoor water use were selected as calibrated (i.e. optimal) parameter values. The MRE statistic is the average ratio of model error to observed measurement where model error is observed minus modeled. BIAS is the sum of model errors divided by the sum of observed measurements. NSCE is commonly used for calibration and parameter estimation of hydrologic and water quality models. NSCE values can range from $-\infty$ to 1. A value of 1 indicates a perfect fit, a value of 0 indicates that the model explains variability as well as the mean of observations, and negative values indicate the model performs worse than the mean. A NSCE value between 0.7 and 1 is deemed "very good" (Moriasi et al., 2007). For indoor calibration, only parameter sets that produced MRE and BIAS between −5% and +5% were considered. The NSCE statistic is not appropriate for assessing the model performance for indoor demand predictions since indoor values show very little month to month variability (DeOreo, 2016). Outdoor calibration included the same criteria for MRE and BIAS, but also restricted NSCE to be above 0.9.

4.4.4.2 Scenario Analysis

The parameter set identified as the best fit to the 2010 – 2014 observed data (Table 19) was applied as baseline conditions to a case study of scenario analyses for the City of Fort Collins. Most current available data including unaltered 2010 census data, 2011 NLCD data, and climate data from the "Fort Collins East" weather station numbered 101 were applied (Northern Colorado Water Conservancy District 2016). Projections for average monthly water demand were determined using IUWM based on 15 years of weather data (2000 – 2014) to include variability temperature and precipitation in projections. Simulations included various water conservation and reuse strategies applied in the residential sector (i.e. not commercial) including indoor conservation, graywater reuse, use of roof runoff, stormwater use, treated effluent reuse, and irrigation conservation. The level of adoption and parameters specific to these scenarios are summarized in Table 21, including the processing time for each scenario. Scenarios were selected to represent aggressive adoption of practices to evaluate the potential of each scenario and develop benchmarks for comparison. Scenarios were also run for climate change and growth including increased population and change from low density to medium and high density land use (Table 21).

Table 21: Scenarios Evaluated for the City of Fort Collins and Associated Processing Time (Block Group Subunits)

Scenario	Parameter Selection	Run and Processing Time (seconds)
Indoor Cons.: Adoption of High Efficiency Fixtures	α = 60, β = 0.5	162
Graywater: Graywater Use for Irrigation and Toilet Flushing	$k_{i,s,p}^{adopt}$ = 80%, $S_{i,s,p,t}$ = 130 gallons	165
Roof Runoff: Roof Runoff for Irrigation and Toilet Flushing	$k_{i,s,p}^{adopt}$ = 80%, $k_{i,s}^{avail}$ = 30%, $S_{i,s,p,t}$ = 300 gallons	164
Stormwater Use: Stormwater Use for Irrigation and Toilet Flushing	$k_{i,s,p}^{adopt}$ = 80%, $k_{i,s}^{avail}$ = 80%, $S_{i,s,p,t}$ = 3000 gallons	146
Effluent Reuse: Treated Effluent Use for Irrigation and Toilet Flushing	$k_{i,s,p}^{adopt}$ = 80%, $k_{i,s}^{avail}$ = 80%	137
Irrigation Cons.: Use of Xeriscape and efficient irrigation systems	k_{i}^{pf} = 0.3, k_{i}^{eff} = 95%	133
Hot Dry: Change to Hot Dry Climate	Temperature Offset = +10%, Precipitation Scaling = -10%	10
Growth: Population Growth with Land Use Change	Population = +20%, Households = +20%, Low Density Area = -40%, Medium Density Area = +25%, High Density Area = +15%	10

4.4.4.3 Calibration and Testing Results

IUWM was calibrated against observed water use data for 2000 through 2009 as well as 2010 through 2014 using realistic ranges for the parameters to identify a best fit parameter set for each time period (Table 19). A unique nondominated parameter set (a parameter set that is not outperformed by another in all three performance metrics) was identified for outdoor use. Parameters for indoor use had a Pareto optimal front with multiple parameter sets with nondominated performance characteristics, so the parameter set that minimized the squared difference between MRE and BIAS was selected, effectively weighting both metrics equally. The NSCE for outdoor water use was greater than 0.9 for both calibration periods (Table 22), indicating a "very good" fit (Moriasi et al., 2007). In addition, the magnitude of MRE and BIAS were below 5% for both indoor and outdoor water use, and within $\pm$2% for CII indoor demand (Table 22).

Two years of IUWM simulation results and observed data are included in Figure 25 to demonstrate IUWM performance. Simulation results were sometimes higher and sometimes lower than observed values for water use for these years, with no consistent trend for over or underestimation of water use. Of note is that simulated outdoor water use shows similar trends, i.e. when simulated water use increases so does observed use, and vice versa. Results from the calibration effort demonstrate that parameters can be reliably estimated to provide a good fit between simulated and observed data for residential and CII indoor, outdoor and total water use.

The calibrated parameter set from the 2000 through 2009 period (Table 19) was applied for testing IUWM from 2010 through 2014. Negative MRE and BIAS for the testing period (Table 22) indicate that use of the 2000 through 2009 parameter set to predict water use during 2010 through 2014 results in a notable overestimation of both indoor and outdoor water use (Table 21). This is indicative of a trend toward indoor water fixtures that conserve water and reduction in outdoor demand due to either behavior changes or conversion to drought tolerant landscape, consistent with trends observed in the literature for residential use of water (DeOreo et al., 2016).

In addition to overprediction of water use in the 2010 through 2014 testing period using calibrated parameters from 2000 through 2009 period, parameters that represent behavioral patterns for water use changed for the two calibration periods (Table 19). For example, α decreased for the 2010 through 2014 calibration period compared to the 2000 through 2009 period, indicating use of water conserving fixtures (DeOreo et al., 2016). In addition, k_i^{pcp} increased and k_i^{pf} decreased for the 2010-2014 calibration period compared to the 2000-2009 period, consistent with changes in irrigation behavior and conversion to lower water use landscape.

Overestimation of water use for the 2010-2014 testing period based on calibrated values for the 2000-2009 period (Table 21) in addition to changes in parameter estimates for the calibration periods (Table 19) indicate the importance of selection of a dataset that is representative of the desired modeling period. For the City of Fort Collins scenario analysis conducted here, the parameter set identified from the 2010 through 2014 calibration was used to represent baseline conditions. This parameter set resulted in a good fit with observed data in 2014 (Figure 25).

Table 22: Model performance for residential indoor and outdoor, CII indoor, and total water use during a calibration (training) period and testing period.

Use	Calibration 2000 - 2009			Calibration 2010 - 2014			Testing 2010 - 2014		
	NSCE	MRE	BIAS	NSCE	MRE	BIAS	NSCE	MRE	BIAS
Res. Indoor	--	-0.20%	0.10%	--	1.60%	2.00%	--	-8.00%	-7.60%
Outdoor	0.90	-2.60%	4.60%	0.91	-2.60%	2.30%	0.87	-12.80%	-12.20%
CII Indoor	--	-1.40%	0.00%	--	-1.30%	-0.20%	--	-25.50%	-24.10%
Total	0.88	0.60%	1.50%	0.89	0.80%	1.40%	0.73	-15.60%	-14.50%

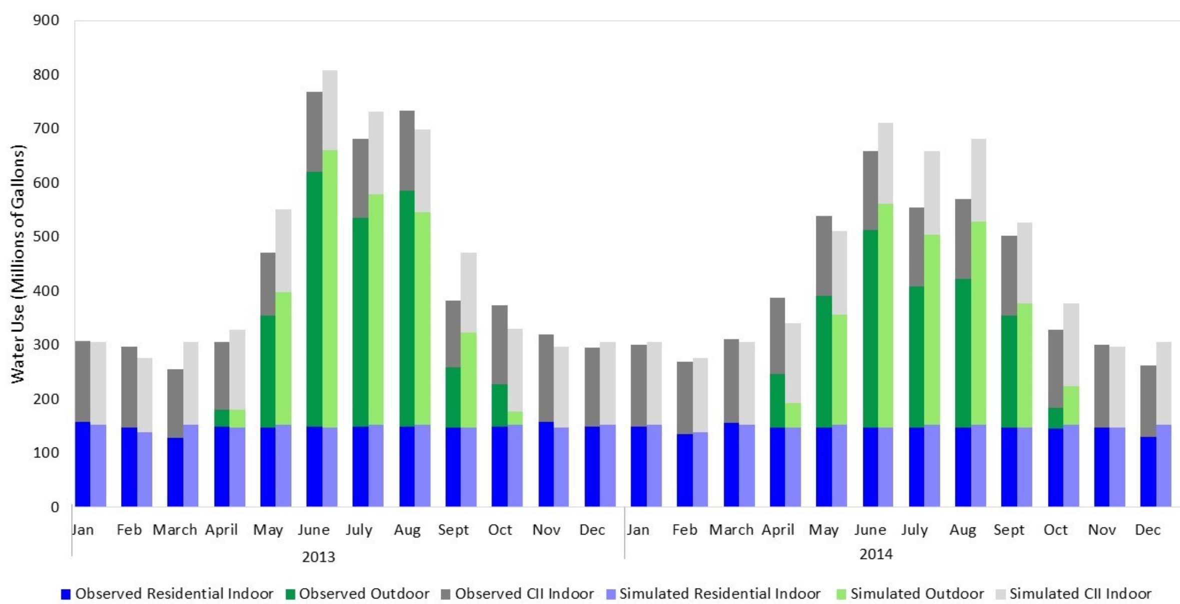


Figure 25: Comparison of residential indoor, outdoor and CII indoor simulated and observed values using the 2010 – 2014 calibrated values for parameters.

In addition to the municipal scale calibration, IUWM was calibrated for each block group individually (Figure 26). For a large majority of block groups in the Fort Collins Water Service area, a very good fit was achieved. The NSCE for a few areas was not acceptable, indicated in red on Figure 26. The area with an unacceptable fit on the north side of the service area (Figure 26) is

Colorado State University, where raw water is used for irrigation rather than municipally supplied water. Thus, there is a substantial area with irrigation demand that does not result in demand for municipal water. The other area with an unacceptable NSCE was on the south edge of the Fort Collins Service Area, in an area mixed commercial, multi-residential and single residence development. This block group includes a large fitness facility with an outdoor pool that may result in substantial outdoor water use, but is not impervious area and thus does not result in a projection for outdoor water use. A user could readily modify $A_{i,c}$ in each of these block groups to improve fit between observed and simulated water use through editing of the subunit table in the IUWM interface. The purpose of the calibration effort conducted here was to evaluate the capacity to quickly calibrate IUWM based on typical ranges of parameter values. Results from the block group calibration demonstrate that the distributed parameters of IUWM can be estimated at the block group level.

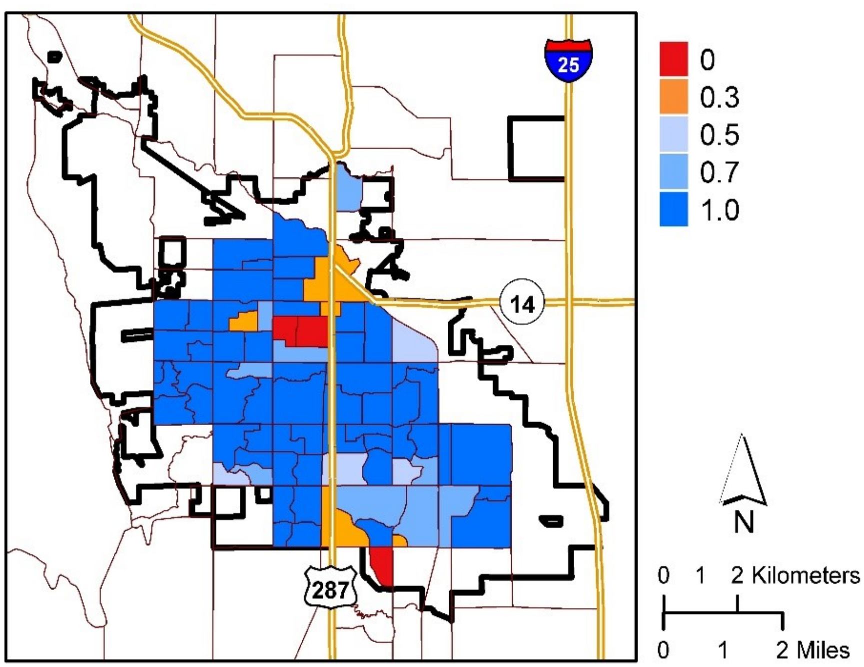


Figure 26: NSCE for each block group when IUWM was calibrated for each block group separately to estimate indoor residential and outdoor demand.

Overall, results from the calibration and testing effort indicate that data extracted through the GIS framework and subsequent parameter estimation can provide a very good fit between simulated and observed data from the block group to municipal scale. In addition, temporal changes in both indoor and outdoor water should be considered for calibration. If parameter selection is to be conducted based on calibration, an appropriate time period of water use data should be collected to be representative of the time period to be modeled.

Urban water use for each county in the South Platte River Basin was modeled using the same parameters that resulted from calibration to the City of Fort Collins water use (billing) data. This county model informed the percentage of household water use from toilet flushing and from irrigating lawns (for parameterization of management solutions in Chapter 7).

4.5 Selection and definition of sustainability indicators

The assessment framework is applied here to the SPRB, but the framework can be scaled to other regions. First, we conceptualize sustainable water management as an approach to cope with vulnerability in a socioeconomically viable manner that fosters system resilience, i.e., "*management to sustain the functional properties of [water] systems that are important to society under conditions where the system itself is constantly changing*" (Chapin et al. 2011). To evaluate impacts of different institutional or management scenarios on water supply vulnerability for desirable outcomes of interest to the region, a set of five indicators were selected that highlight different advantages and disadvantages for municipal rate payers, the agricultural economy, reliability of supply, and price of water. These indicators are as follows:

- Water rights cost to municipal and industrial water users ($ per person)
- Net present value of agricultural profit from crop production ($)
- Net present value of total agricultural profit including revenue from sale of water rights ($)
- Price of water right ($ per AF)

- Reliability of water supply (%)

Cost to municipal and industrial (M&I) water users is defined as the total cost of water rights acquirement, normalized by the number of people in the new incoming population, assuming that municipalities pass the costs to only new developments. Viability of the agricultural community is shown by three different indicators. The first is the profit due directly to sale of produced crops. The second is the revenue from sale of water rights added to the net present value of all profits from sale of produced crops over a 40 year planning horizon. The third represents the value of an agricultural water right, which has historically been treated as property and an appreciating asset in Colorado.

Water managers and decision-makers in municipalities, water districts, and governing bodies often consider reliability as a key indicator of avoiding the potential negative health and infrastructure consequences of water shortages (Howe et al. 1994). Thus, to capture indicators of value to decision-makers, reliability was utilized in this study and was defined as the probability of meeting full consumptive use of the crops with available surface water supply, or the probability that surface water surplus (supply s_r minus demand d_r in each subregion r) is positive. This defines reliability only of water supply to agriculture, assuming that municipalities will always secure sufficient water supply. Reliability of agricultural surface water supply for each subregion r, $R_{A,r}$, is therefore mathematically defined as follows:

$$R_{A,r} = \Pr(s_r - d_r \geq 0)$$

Reliability was analyzed historically by setting supply s_r to historical diversion records and demand d_r to DayCent simulated gross irrigation requirements, then subsequently estimating a probability of supply being greater than demand both empirically and parametrically assuming a normal distribution, an assumption that could only be rejected by one test of normality in the South Metro subregion, which uses very little water relative to other regions. When both supply and demand are normal, surplus z is normally distributed with mean $\mu_{z_r} = \mu_{s_r} - \mu_{d_r}$ and standard deviation $\sigma_{z_r} = \sqrt{\sigma_{s_r}^2 + \sigma_{d_r}^2 - 2cov(s_r, d_r)}$.

$$R_{A,r} = \Phi\left(\frac{-\mu_{z,r}}{\sigma_{z,r}}\right)$$

where Φ is the cumulative distribution function of the standard normal distribution. Table 23 displays sample mean and standard deviation of demand $(\mu_{d_r}, \sigma_{d_r})$ and supply $(\mu_{s_r}, \sigma_{s_r})$ for each subregion and estimated reliability $R_{A,r}$.

Table 23: Regional statistics and reliability estimates, both empirical ($\hat{R}_{A,r}$) and parametric ($R_{A,r}$)

Subregion r	μ_{d_r}	σ_{d_r}	μ_{s_r}	σ_{s_r}	$\hat{R}_{A,r}$	$R_{A,r}$
North	1,260,000	206,000	1,020,000	199,000	14.7%	18.0%
North Central	503,000	77,900	659,000	95,800	85.3%	91.9%
Central	318,000	58,400	384,000	91,500	79.4%	76.0%
South Metro	34,100	17,500	236,000	58,800	97.1%	99.9%
East	454,000	73,700	785,000	179,000	97.1%	93.7%

For future projections after solution of the model, mean supply and demand are defined as the expected supply and demand under the new water rights and land ownership with solved irrigation depth $I_{p,r}^*$ and cropland acreage $A_{p,r}^*$:

$$\mu_{s_r} = \sum_{p \in P} \frac{I_{p,r}^* A_{p,r}^*}{ce_r ae_r}$$

$$\mu_{d_r} = \frac{\hat{\mu}_{app,r}}{ce_r} \sum_{p \in P} A_{p,r}^*$$

When assuming that there is no change in variability, modeled future changes in supply and demand can be compared using the same distributions as were developed by historical data with changing means. Results displayed for indicators for the entire SPRB are simply the average of all regional indicator values.

4.6 Alternative management policies and institutions

Institutional agreements play a key role in shaping both the creation of vulnerabilities and the viability of coping responses. In a commitment to serve the agricultural community and prevent complete agricultural dry up, NCWCD has a limitation on the amount of CBT water that can be owned by municipalities equivalent to about 80% of total CBT shares (Squillace 2011 p. 99).[38] A constrain on municipal ownership of CBT and buy and dry trends are therefore considered a baseline scenario with which to compare alternatives. Primarily, three categories of alternatives embody major institutions being considered in this study: more economically efficient agricultural water transfer methods, constraints added to water rights administration as in the case of CBT water, and policies on urban conservation in new developments that are typically less costly than retrofits.

To combat agricultural decline due to "buy and dry," several alternative agricultural transfer methods have been suggested by decision-makers within Colorado's Water Plan (Colorado Water Conservation Board 2016). These include rotational fallowing, interruptible supply agreements, deficit irrigation, cooperatives, water banks, and flex markets. Colorado's Water Plan (CWP) also suggested targets for urban water conservation to decrease municipal water demand by 22% in the SPRB before 2050 (Colorado Water Conservation Board 2016). Trade-offs to cost, agricultural profit and vulnerability of water supply have remained largely unknown. So, this paper focuses on trade-off analysis of the following policy changes, repeated here from the methods section:

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[38] In addition, some core policies of the Northern Colorado Water Conservancy District are found in a document made in 2015 called "Index to Policies" from the Northern Water Projects and Administrative Workshop. This document is available at http://www.northernwater.org/docs/About_Us/EventsAndPresentations/PolicySUMMARIES_March18_2015.pdf

A. **Baseline:** Buy and dry governs water rights transactions and CBT municipal ownership is capped at 80%

B. **B&D 0%:** Buy and dry requirements are completely relaxed (land does not have to be sold with water right)

C. **B&D 50%:** Only 50% of land needs to be sold with the water right

D. **No M&I Cap:** Removed cap of municipal ownership from CBT water

E. **M&I Cap 80%:** Capped municipal ownership in every pool at 80% (required RWR to be 88% of baseline)

F. **RWR 90%:** Reduce urban water consumption and consequently water purchase requirement to 90% of baseline

G. **RWR 80%:** Reduce urban water consumption and consequently water purchase requirement to 80% of baseline

Policy A simulates the current water rights market by setting model coefficients for manipulating levels of buy and dry and cap of municipal ownership $k^{\mathrm{B\&D}}$ and k_d^{mcap}, respectively, to 1 for native water right pools $d \in D_n$ and $k_{cbt}^{\mathrm{mcap}} = 0.8$, which enforces buy and dry and provides a cap to municipal ownership of only CBT water at 80%. Policies B and C simulate different levels of alternative agricultural transfer methods that include rotational fallowing, deficit irrigation, and conversion to dryland farming. Policies D and E represent actions in response to the policy on municipal ownership of CBT water. Policy D sets $k_{cbt}^{\mathrm{mcap}} = 1$, reversing the policy so that municipalities can own up to 100% of the water, which would be a move toward a freer market. Policy E is a cap on all subregions and associated pools of water equivalent to the CBT policy such that $k_d^{\mathrm{mcap}} = 0.8$ for all $d \in D$. Policies F and G represent different levels of municipal water conservation up to about the CWP 22% goal by setting $k_{B\&D} = 0.9$ and 0.8, respectively. Policy G more closely represents the goal from CWP by requiring developers to purchase only 80% of the firm water supply otherwise purchased in the baseline scenario.

5 DECLINING AGRICULTURAL PRODUCTION IN RAPIDLY URBANIZING SEMI-ARID REGIONS: POLICY TRADE-OFFS AND SUSTAINABILITY INDICATORS[39]

In rapidly urbanizing semi-arid regions, increasing amounts of historically irrigated cropland lies permanently fallowed due to water court policies as agricultural water rights are voluntarily being sold to growing cities. This study develops an integrative framework for assessing effects of population growth and land use change on agricultural production and evaluating viability of alternative management strategies, including alternative agricultural transfer methods, regional water ownership restrictions, and urban conservation. A partial equilibrium model of a spatially-diverse regional water rights market is built in application of the framework to an exemplary basin. The model represents agricultural producers as profit-maximizing suppliers and municipalities as cost-minimizing consumers of water rights. Results indicate that selling an agricultural water right today is worth up to 2 times more than 40 years of continued production. All alternative policies that sustain agricultural cropland and crop production decrease total agricultural profitability by diminishing water rights sales revenue, but in doing so, they also decrease municipal water acquisition costs. Defining good indicators and incorporating adequate spatial and temporal detail are critical to properly analyzing policy impacts. To best improve agricultural profit from production and sale of crops, short-term solutions include alternative agricultural transfer methods while long-term solutions incorporate urban conservation.

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[39] Dozier, A. Q., M. Arabi, B. Wostoupal, C. G. Goemans, Y. Zhang, and K. Paustian (under review), Declining agricultural production in rapidly urbanizing semi-arid regions: Policy trade-offs and sustainability indicators, *Environ. Res. Lett.*, Focus on Urban Food-Energy-Water Systems: Interdisciplinary, Multi-Scalar and Cross-Sectoral Perspectives.

5.1 Introduction

Water from rivers throughout the western United States allows for the irrigation of lands that collectively are among the most productive agricultural systems in the world. However, maintaining agricultural production in these regions is increasingly challenging due to rises in demand for water associated with rapid population growth. Given the growing costs (social, environmental, and financial) and limited opportunities to develop new supplies, utilities have turned to purchasing agricultural water rights to meet new demands. The reallocation of water rights from agricultural to municipal uses often results in the permanent dry-up of agricultural lands (McMahon and Smith 2013; Payne et al. 2014), which often has significant negative impacts on the rural, agricultural economies from which water is purchased (Howe and Goemans 2003; Pritchett et al. 2008).

Concerns regarding the distributional impacts of permanent transfers, together with strong public sentiment for maintaining healthy rural communities, has created increased interest in the development of alternative means to meeting future demands (Colorado Water Conservation Board 2016; Thorvaldson et al. 2010). This includes an increased reliance on conservation, as well as various temporary transfer methods that would leave agricultural water right ownership intact, while providing cities with a secure water supply during periods of drought. Examples of the latter include rotational fallowing agreements (McMahon and Smith 2013) and option contracts (Michelsen and Young 1993). Despite public calls to increase the utilization of these alternatives, the majority of new municipal demands continue to be met by purchasing permanent water rights purchases at what is considered a "firm yield", or the amount of water supply from the source that meets average demand from the city nearly 100% of the time (Zellmer 2008).

An enhanced understanding of the coupled natural and human responses, interactions, feedbacks, and thresholds in food and water systems is vital to comprehensively assessing the feasibility, advantages, and disadvantages of alternative institutional settings. Identifying strategies that allow for the more efficient use of existing supplies is crucial to enhancing the resiliency and reliability of regional water systems for agricultural production. However, both of these require developing an understanding of not only the potential benefits and costs of various water management strategies, but also the distribution of those benefits and costs.

Previous analysis frameworks have relied on aggregate optimization or global welfare optimization assuming that decision-makers can “turn all the knobs” and have the sole objective of maximizing social welfare (Brown et al. 2002; Harou et al. 2009). However, these types of approaches fail to capture the full range of institutional constraints, the often conflicting objectives and the decision processes of specific segments of society (Britz et al. 2013). Input-output modeling techniques have been used to estimate the negative “economic impacts” of water rights transfers; however, these approaches require unrealistic “heroic” assumptions and only provide insight into impacts on expenditures as opposed to profit or consumer surplus (Howe and Goemans 2003; McMahon and Smith 2013; Thorvaldson and Pritchett 2007). Recently, advances have been made in the use of fully-coupled hydro-economic modeling to evaluate water allocation institutions and resulting impacts on agriculture for theoretical water systems (Bauman et al. 2015; Britz et al. 2013; Zhao et al. 2013). However, impacts and nuances of proposed policies, institutions, or governance systems across time and space cannot be broadly applicable without accurate parameterizations for specific cropping systems across regions. Previous studies neglected to incorporate these factors due to intensive data and modeling requirements.

The goal of this study is to develop an integrative framework for the assessment of the effects of population growth and land use change on agricultural production, municipal water acquisition costs, and water supply reliability in semi-arid regions. The framework aims to evaluate the viability and trade-offs of alternative management strategies across time and space to analyze the extent of direct impacts on agricultural producers and municipal water providers, as well as to identify potential negative third-party impacts to rural economies that result from changes in agricultural production. To meet this goal, the objectives of this study are to i) develop a mathematical characterization of water allocation in a semi-arid region, and ii) assess the viability of agricultural production systems amongst other stakeholder interests across time and space under various policy changes. The assessment framework developed in this study leads to a better understanding of resources under stress, integrating physical, ecological, and socioeconomic feedbacks. Integrated modeling and optimization reconciles regional water resource sustainability, socioeconomic, and institutional criteria to explore optimal solutions across various objectives of multiple sectors across both time and space. The framework serves several benefits: i) it reveals the feasibility of satisfying water demands under the prevailing governance systems, ii) it exposes components of the hydrologic and governance systems that are key to achieving water allocation targets, and iii) it determines cost-effective options to enhance the reliability of water resources while sustaining desired levels of agricultural production and livelihood of rural communities within spatially diverse semi-arid regions. No other study in peer-reviewed literature known to the authors has truly integrated agro-ecosystem, urban water demand, and agent-based modeling as is performed by this study.

5.2 Methods

An integrative assessment framework (Figure 1) was developed to rigorously evaluate the effects of institutional change in combatting decline of agricultural land and production. The components of the framework for a given river basin include: i) characterization of drivers of activity around water, water supply and demand regimes, and institutional agreements and other systems governing water allocation, ii) development of a hydro-economic model that mathematically defines relationships between sectors and institutions, and iii) system-level evaluation metrics for assessing the sustainability of the agricultural sector under policy and institutional alternatives.

The framework was applied to characterize the range of potential impacts associated with a variety of alternative management institutions currently being considered within the South Platte River Basin (SPRB) in Colorado, a basin encompassing one of the fastest growing areas in the U.S. The region provides an ideal test bed that is rapidly urbanizing and has significant agricultural production with intensifying competition for an already over-allocated water resource. Water in the region is allocated according to the prior appropriation doctrine where senior water right holders, those that obtained water rights first in time, are prioritized for water delivery before junior water right holders.

Transfers of water rights to other owners incur transaction costs associated with physical conveyance and treatment systems in addition to water court fees and processes that enforce the prior appropriation doctrine. To avoid injury to senior water right holders, Colorado water courts will typically require agricultural land to be purchased alongside water rights and the cropland subsequently permanently fallowed with no agricultural activity on the land after a specified amount of time when urban water demands match the size of the purchased water right. Any water right not put to a beneficial use can be, according to law, taken away and available for others to use. Thus, deficit irrigating a crop, or reducing losses of water through more efficient irrigation technologies could result in loss of the water right, although methods are just now being considered in Colorado (and are part of the focus of this paper) to ease these restrictions and incentivize more efficient water use. An exception to this "buy and dry" trend exists in the SPRB because of trans-basin water (i.e., water derived from another basin) which is treated differently than native water (i.e., water derived from precipitation, runoff, or recharge from within the basin). Imported water in the basin is primarily delivered by the Colorado Big Thompson (CBT) project from the Colorado River Basin west of the continental divide. Imported water can be used for any beneficial use within its service area and shares can be traded with no water court fees.

Since the 1970s, municipal and industrial (M&I) users of water have been purchasing water rights at a rapid rate and primarily from the agricultural sector. Figure 27 illustrates increasing water rights transfer to M&I entities and associated trailing usage of those water rights for municipal purposes, showing a preference of municipalities to own water and lease back to farmers in years of plenty than to lease water owned by farmers. Methodology in assigning municipal and agricultural ownership of water rights[40] in the figure is discussed in Appendix C. The most rapidly growing populations primarily reside in municipalities close to the Rocky Mountains while agriculture production takes place farther east. To explore effects of spatial patterns in urban growth, the SPRB region was split into five subregions labeled North, North Central, Central, South Metro, and East as depicted in Figure 27. The CBT project serves only the North, North Central, and East subregions. Section 4.1 contains further details about land use, cropping systems, and other information for the SPRB.

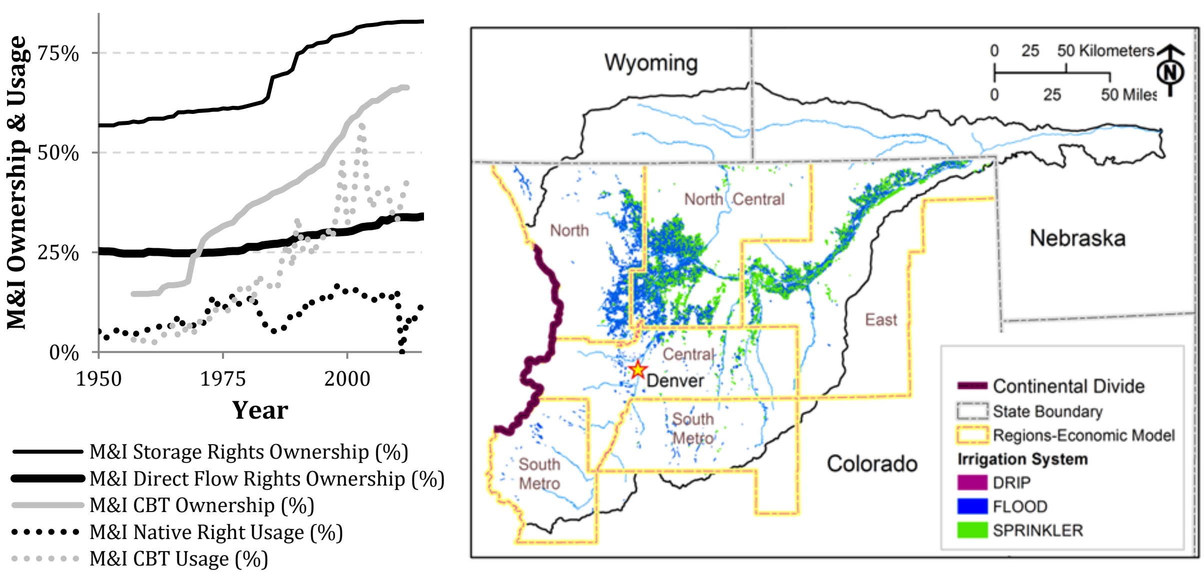

Figure 27: (Left panel) Percent of total water right (and CBT water share) ownership over time (solid lines) by municipal and industrial (M&I) water users is usually much larger than

[40] Water rights data (Hydrobase), irrigated land area, and irrigated crop types are from the Colorado Decision Support System through the Colorado Division of Water Resources and Colorado Water Conservation Board. Available at: http://cdss.state.co.us/Pages/CDSSHome.aspx.

actual usage of those waters (dotted lines) over time. (Right panel) Location map of the SPRB, irrigated cropland, irrigation type, and analysis subregions. Left panel includes data on CBT ownership and usage from Maas et al. (2017).

Hydro-economic modeling in this study builds primarily on developments with spatially-distributed partial equilibrium modeling with transactions costs (Bauman et al. 2015; Britz et al. 2013). The model integrates municipal and agricultural decision-making within a partial equilibrium model formulated as Multiple Optimization Problems with Equilibrium Constraints (MOPEC) characterizing a water rights market. Within the market, municipalities minimize cost to acquire a secure supply through purchase of water rights, and agricultural producers maximize profit from crop production and sale of water rights to municipalities. Section 4.2 further discusses the partial equilibrium model, its mathematical formulation and numerical solution procedure.

Characterization of supply and demand for the SPRB relies on extensive data collected by the State of Colorado Division of Water Resources. In particular, surface water supply for specific uses in the SPRB was estimated as historical annual average surface water diversions. Demand for water is characterized separately for profit-maximizing agricultural producers and cost-minimizing municipalities. Crop production curves presented in this study have two factors (acreage and irrigation volume) fitted to output of the DayCent agro-ecosystem model having constant elasticity of substitution (Solow 1956). A unique crop production function was estimated for each unique combination of cropping system, soil, county, and climate in the basin (see Figure 15-Figure 19). Municipalities, driven by population growth, purchase water as land development occurs. Future land development is estimated by an autoregressive statistical model, and municipal raw water purchase requirements informed the amount of water required to be purchased for each new parcel of developed land. Definition, characterization, and quantification of water supplies and demands in agricultural and municipal sectors are further discussed in Section 4.3.

System-level sustainability indicators were defined to assess the advantages and disadvantages of proposed management practices, policies, institutions, and governance systems on the viability of agricultural production. These indicators can be summarized in three classes: cost of water to municipalities, agricultural profit, and reliability of water supply. Reliability refers to the probability of a water supply (i.e., the amount that can be diverted from the river according to water rights) being greater than or equal to a water demand (i.e., irrigation water to meet consumptive use of crops) in any given year, and measures how likely suboptimal conditions of water supply will exist for agricultural producers (Howe et al. 1994). Selection and mathematical characterization of sustainability indicators are provided in Section 4.5. Sustainability indicators were quantified and compared for the following alternative policies:

A. **Baseline:** Buy and dry governs water rights transactions and CBT municipal ownership is capped at 80%
B. **B&D 0%:** Buy and dry requirements are completely relaxed (land does not have to be sold with water right)
C. **B&D 50%:** Only 50% of land needs to be sold with the water right
D. **No M&I Cap:** Removed cap of municipal ownership from CBT water
E. **M&I Cap 80%:** Capped municipal ownership in every pool at 80% (required RWR to be 88% of baseline)
F. **RWR 90%:** Reduce urban water consumption and consequently water purchase requirement to 90% of baseline
G. **RWR 80%:** Reduce urban water consumption and consequently water purchase requirement to 80% of baseline

These policy changes stem from proposed policies currently being considered within the SPRB that operate within the existing constraints of Colorado water law embodying alternative agricultural water transfer methods,[41] regional water rights management,[42] and urban conservation.[43] Policy A is baseline, because it represents the current institutional framework and policies regarding municipal ownership of CBT water (Squillace 2011). Policies B and C represents a move toward a more flexible institution allowing farmers to deficit irrigate crops instead of being required to sell and permanently fallow land in addition to the sale of water rights, but still incurs infrastructure and legal costs in transactions. Since 80% of water supplies could not serve all municipal needs, Policy E required the raw water requirement (RWR) to be lowered. The maximum RWR level equally applied to all cities was determined to be 88% of baseline levels. Lowered raw water requirement simulates less stringent municipal water purchase requirements for land developers granted they build with water-saving features. Policies F and G are similarly urban conservation policy scenarios. Further reasoning for and mathematical characterization of alternative management policies are discussed in Section 4.6.

The time period selected for analysis was from 1980 to 2050, solved each decade with a forty year planning period, because of the benchmark data available from 1980 and population projections available until 2050 (Camp Dresser & McKee and Harvey Economics 2010). The water rights market model was solved each decade to show general trends within the 70-year period of analysis, and for comparative analysis of policy changes. Although the model, its parameterizations, time period, and sustainability indicators that are explored in the case study are specific to the SPRB, the integrated assessment framework is generally applicable. The study river basin also includes trans-basin

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[41] Colorado Water Conservation Board, "Alternative Agricultural Water Transfer Methods Criteria and Guidelines for the Competitive Grant Program." http://cwcb.state.co.us/loansgrants/alternative-agricultural-water-transfer-methods-grants/documents/altaggrantprogramcriteriaguidelines.pdf

[42] Municipal ownership of CBT water is restricted by their ownership from other water sources as described in this document http://www.northernwater.org/docs/About_Us/EventsAndPresentations/PolicySUMMARIES_March18_2015.pdf

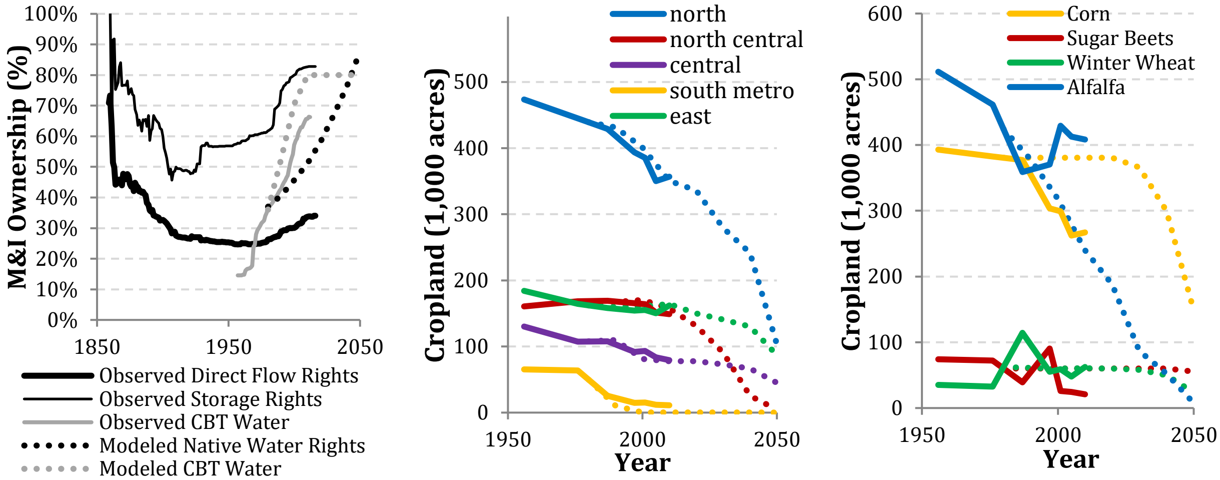
[43] Colorado Water Conservation Board (2016). Colorado's Water Plan. https://www.colorado.gov/pacific/cowaterplan/plan

water transfers (i.e., imported water) that would be suitable for the extension of the results to other regions.

5.3 Results and Discussion

Results of the modeling framework were corroborated with historical cropland acreage, water rights ownership, and water rights prices between 1980 and 2010, and then projected to 2050 for analysis of the effects of continued population growth. The rate of decline generally followed trends of historical observations since 1980 with varying effects on agricultural production by cropping system and subregion (Figure 28). Maintaining acreage in eastern Colorado is consistent with historical trends, likely because it is more expensive for cities to purchase water far downstream. Modeled alfalfa and corn showed opposite trends of decline compared to observed data likely due to unaccounted drought resilience of crops like alfalfa (and associated reduction of risk for the agricultural producer) or externalities that can drive alfalfa prices up such as livestock feed production. Even though the model incorporates constraints on the rate at which municipalities can purchase CBT water,[44] modeled municipal water rights purchases more heavily relied on CBT water than was historically observed because in reality cities face a higher cost of infrastructure development. Special attention was put on parameterization and calibration of spatial parameters in the model, particularly transactions costs to reproduce historical patterns of water prices and changes in cropland acreage by subregion. Further discussion on model limitations and potential future work can be found in Section 4.2, and discussion on model corroboration and calibration procedures are detailed in Section 4.3.

[44] Ibid. 42



a) Direct Flow Right Ownership **b) Regional acreage** **c) Acreage of Key Crops**

Figure 28: Historical (solid lines) and modeled (dotted lines) temporal trends of a) percent M&I ownership of native water rights (i.e., storage and direct flow water rights) and CBT water shares, b) agricultural cropland in production within each subregion, and c) cropland of key crops. Observed acreage comes from GIS data collected by the Colorado Decision Support System.[45] Panel (a) includes historical CBT ownership data from Maas et al. (2017).

The baseline institution projected a loss of approximately 24% (175,000 acres) by 2030 and 68% (500,000 acres) by 2050 of total cropland (Table 24), exceeding the estimated 33% loss in Colorado's Water Plan (Colorado Water Conservation Board 2016) while undershooting other predictions of 400,000 acres lost by 2030 (Thorvaldson and Pritchett 2007). The net present value (NPV)[46] of agricultural profit from production across the entire SPRB was about $6.1 billion, whereas sales from water rights purchases totaled about $17.9 billion. Thus, out of the total NPV of $24 billion, a large portion (about 75%) came from sale of water rights, displaying a strong financial motivation to sell water rights. The average net present value of water[47] to the agricultural producer was about $13,900 per AF, whereas the average price for native and CBT water was $10,400 per AF and $29,800 per AF, respectively. That is, for the agricultural producer that owns CBT water, it is more than two times more profitable to sell the water than to work for 40 years on

[45] Ibid. 40
[46] NPV was calculated over 40 years with a discount rate of 3%
[47] Ibid. 46

the farm, and for the native water right holder, it is almost just as profitable to sell the water today as it is to work for 40 years (not accounting for the rise of water prices and potential future sale of water). Any policies such as those investigated by this study that attempt to support or sustain agricultural production will naturally decrease the current value of water rights, which is not financially beneficial for farmers wishing to sell water rights.

Due to the heterogeneity of crop productivity in the SPRB, total acreage more rapidly declined as time progressed because municipalities in the Central subregion were driven by the regional water rights market to purchase water from the North subregion where producers utilize more cropland per unit of water than any other subregion. This pattern is consistent with historical trends in regional cropland decline, and could not have been achieved without properly informing the model of irrigation amounts and cropland acreages for each subregion individually (Figure 28b). Although total cropland in production continued to decline through the entire time period, annual profit from production climbed until it peaked in 2030, and then by 2050 dropped below original 2010 levels by about $20 million per year (-9%). This decoupled relationship of production profit from cropland acreage demonstrates the importance of adding spatial detail to subregion parameters and time-dependent detail such as historically observed growth patterns of crop yield and price due to technology improvements (Table 9-Table 10).

Table 24: Simulated time-varying outputs for the baseline institution

Year	Acreage	Irrigation (ft)	Diversion (AF)	Production (tons)	Yield (tons/acre)	Prod. Profit ($)
2010	736,000	1.09	2,170,000	3,380,000	4.9	$221,000,000
2020	682,000	1.08	2,000,000	3,380,000	5.3	$264,000,000
2030	562,000	1.07	1,790,000	3,170,000	6.1	$282,000,000
2040	454,000	1.09	1,590,000	2,890,000	6.8	$268,000,000
2050	237,000	1.04	1,370,000	2,210,000	10.0	$202,000,000

Each policy investigated in this study had both advantages and disadvantages (Table 25). Relaxing buy and dry agreements according to Policies B and C significantly reduced reliability of surface water supply to agricultural producers from 48% to 12% and 19%, respectively (Figure

31). According to the crop production submodel, farmers chose to keep cropland in production even while owning less water. Thus, despite the increased risk of loss to crop and profit, farmers deficit irrigated when they would have preferred (i.e., “demanded” according to the perspective of a water manager) more water to fully irrigate the crop. Reliability was insensitive to other policy changes that coupled land with water purchases. Policies B and C maintained agricultural profit from production and a large amount of cropland, including land that either converted to dryland or deficit irrigation practices, but still decreased total agricultural profit through lowered water rights prices. The policies caused a market-driven shift of purchases to the North subregion that has both lower productivity (marginal value) and lower transactions costs, driving down the price of water rights.

All policy changes except Policy D increased annual agricultural production profit 6-15%, but net present value of profit including water rights sales revenue decreased by 2-28%. Policies F and G lowered the cost of water rights purchases for municipalities more extensively than other policies by conserving water in new developments. Because it required a large amount of urban conservation (RWR was 88% of baseline), capping municipal ownership of water in all subregions (Policy E) closely resembled effects of Policies F and G, but better maintained agricultural profit and value of water rights at a larger cost to municipalities (Figure 29c).

All policies improved municipal costs for attaining water for new developments, especially policies with urban conservation (Policies E-F), although placing a cap on municipal water ownership (Policy E) did increase the cost of water relative to Policy F at a similar level of conservation. Some of the cost savings that Policy E would have attained with urban conservation, it lost by capping municipal ownership on all subregions at 80%. A regulation aimed at incentivizing certain behavior will perform worse for the system than the behavior itself, especially when spatially naive.

Table 25: Policy impacts on simulated agricultural cropland and profits (between 2010 and 2050), water rights prices, municipal costs, and reliability of surface water delivery. Green

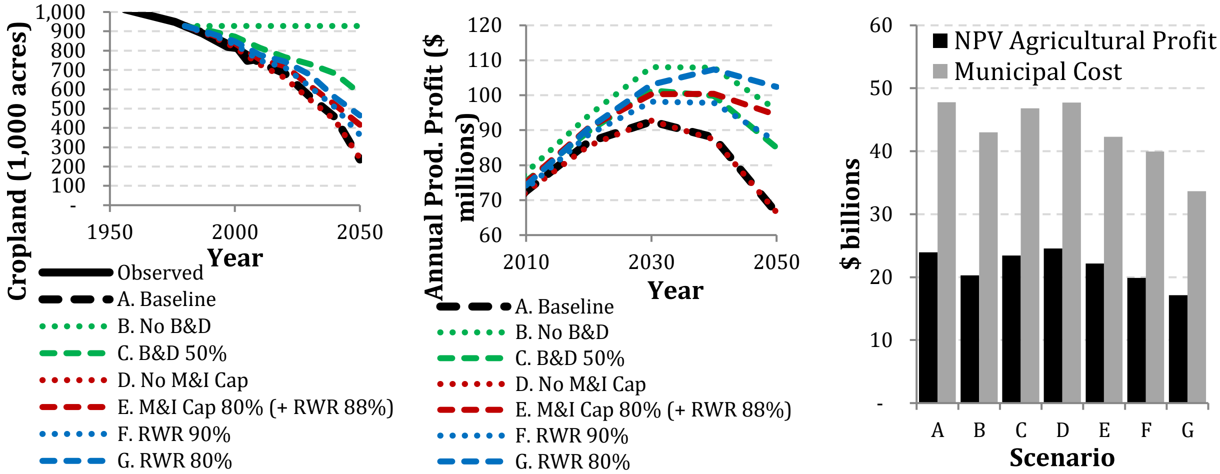
indicates the value improved and red indicates the value worsened. Some values are better when lower (e.g., cost), others are better when higher (e.g., profit). All dollar amounts are 2010 dollars.

Output	Baseline	Policy B	C	D	E	F	G
M&I Cost ($/new person)	$ 18,600	-10%	-2%	-0%	-12%	-16%	-30%
NPV of Total Ag. Profit ($ billions)	$ 23.9	-15%	-2%	+3%	-7%	-17%	-28%
Ag. Prod. Profit ($ billions)	$ 6.1	+15%	+8%	-1%	+9%	+6%	+12%
2050 Water Price ($/AF)	$ 12,000	-25%	-6%	+3%	-1%	-13%	-23%
Cropland in 2050 (acres)	221,000	+292%	+145%	+3%	+76%	+54%	+96%
Ag. Surface Water Reliability	48.0%	-36%	-29%	+0%	+2%	-2%	-2%

* Reliability is shown as absolute change instead of percent change since it is itself a percentage

** Net present value of total agricultural profit assumes that cities purchase water in 2010 and lease it back to agricultural producers until 2050 when cities use the water as expected by growth.

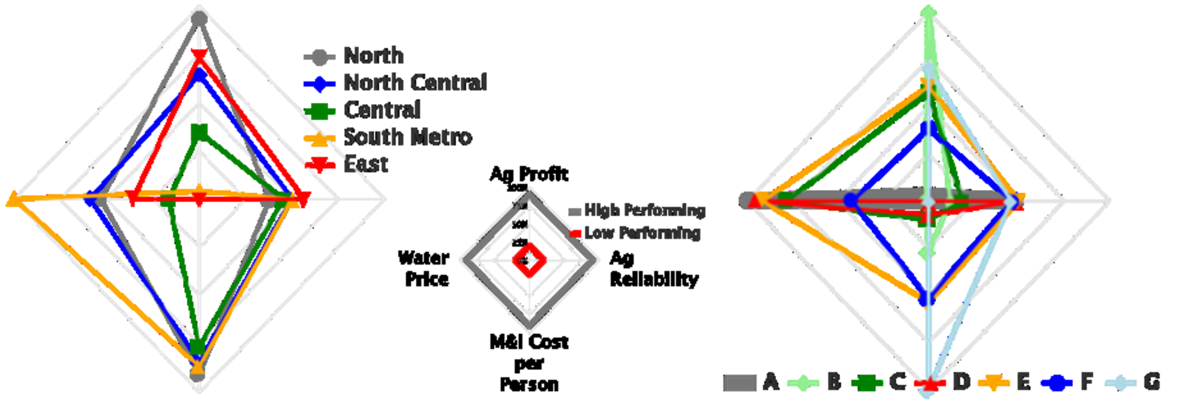
Most policies increased the total profit from production and the total number of acres in production above baseline policies, except for Policy D, where acreage drops below baseline slightly (Figure 29). Removing buy and dry constraints (Policy B) enhanced agricultural profit from production when planning 10-30 years in advance, but since cities are still buying up water at the same rate , agricultural production and profit continued to decline. Water conservation of new urban developments (Policy G), however, improved agricultural production profit more when planning 30-40 years in advance. Eventually, urban water conservation also cannot completely sustain agricultural production, and the only methods would be to i) support agricultural production in wet years while allowing cities to use water in dry years, ii) pursue new sources of water, iii) force cities to cap growth by water consumption and undertake reduction or reuse of water, or iv) a combination of these. Short-term optimal solutions are not the same as long-term optimal solutions.



a) Cropland in production **b) Annual Production Profit** **c) Profits and Costs**

Figure 29: Effects of policies on (a) cropland in production, (b) agricultural profit from production and sale of crops, and (c) total agricultural profit (net present value of profit from crop production plus revenue from water rights sales) and municipal cost of water rights purchases between 2010 and 2050

Effects of alternative water management policies on sustainability indicators vary considerably across subregions (Figure 30). The North subregion generated the most profit from production and sale of crops, the East subregion had the most reliable supply of agricultural water and the highest cost of water rights purchases to municipalities, and the South Metro subregion had the highest price on water. Figure 30b visually represents average performance of each scenario on a radar plot so that a fuller radar plot characterizes better (nondominated) solutions. The radar plot of Policy E is larger than Policy F, showing its dominance over Policy F using the indicators defined in this study. In reality, Policy E would likely receive much more political opposition than Policy F, which highlights the importance of determining a reasonable variety of key indicators to evaluate system performance that represent values and perspectives of as many stakeholders as possible, weighted by the size of their stake.



a) Baseline institution for each subregion **b) Impacts of policy changes across the entire SPRB**

Figure 30: Management indicators (a) across subregions and (b) across policies A-G. Values are scaled so that a completely filled radar plot is optimal (lowest cost, highest price, highest profit from agricultural production per acre, and 100% reliability).

Characterization of agricultural water supply reliability for one of the alternative agricultural transfer methods (relaxing buy and dry policy requirements as described for Policy B in Section 4.6) management policies is compared to baseline in Figure 31. Reliability is defined as the probability that water supply is greater than demand so that a value of 100% means water supply is always greater than demand (Section 4.5). Baseline policies with buy and dry constraints force demand for water to decline at approximately the same rate that supply of water declines because land must be sold along with water rights. Under Policy B, however, crop consumptive use ("demand") remains about the same when cropland acreage continues in production, while average available supply decreases due to increasing municipal ownership and associated use, forcing at least some farmers to deficit irrigate. Thus, relaxing "buy and dry" causes irrigation management for each acre of land to operate at a suboptimal level, having less reliable water supply. In practice, agricultural producers would require more crop insurance or stronger contractual agreements with cities to hedge against increased risk.

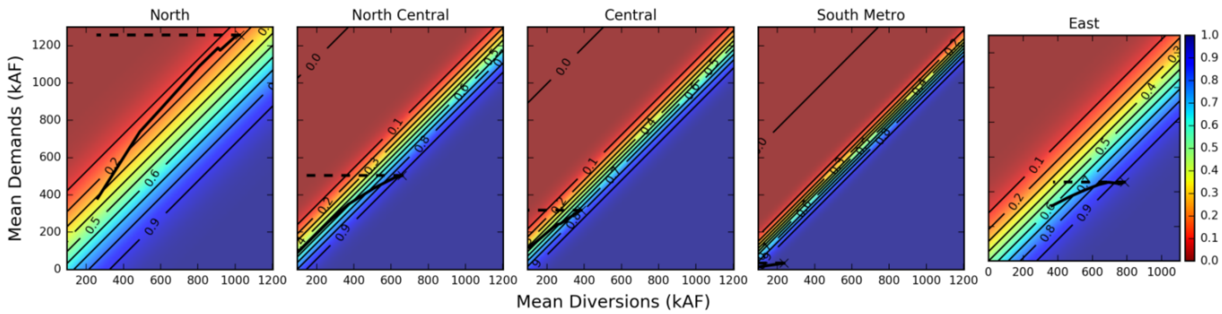


Figure 31: Reliability remained fairly stable for most subregions under the baseline institution (solid line) because both delivered supply and demand drop with purchase of water, but worsens rapidly when land is not purchased alongside water rights as in Policy B (Section 4.6) in which the buy and dry constraint is removed (dotted line). Red indicates lower reliability while blue indicates higher reliability.

5.4 Conclusions

Permanent purchases of water under current policies also permanently dry up agricultural land. This study reveals that cropland in rapidly urbanizing water scarce regions will continue to decrease except under complete removal of buy and dry transfer agreements. However, total profit from continued agricultural production can continue to increase especially under more flexible water rights administration and urban conservation. This decoupled relationship between agricultural cropland and profit illustrates the importance of carefully selecting key indicators to properly assess alternative policy impacts.

Water rights and trans-basin water shares are property rights that have much more value than continuing in production such that selling a CBT water share is about 2 times more profitable than the profit gained from 40 years of production (discounted over time at a rate of 3%). Modeling results revealed that 75% of total agricultural profit came from sale of water rights, and that any policy to sustain agricultural cropland diminishes total agricultural profit because of lost sales revenue from water rights.

Heterogeneity of productivity over space and trends of yield improvements and crop prices over time explained both historical water rights price trends and the decoupled relationship between agricultural acreage and profit, highlighting the importance of incorporating appropriate spatial and temporal detail in a water rights modeling framework. Optimal short-term solutions are not the same as optimal long-term solutions, but both are beneficial, and the framework presented here allows detailed evaluation of each policy combination. To best improve agricultural profit from production and sale of crops, short-term solutions include alternative agricultural transfer methods while long-term solutions incorporate urban conservation.

Policies that include alternative water transfer methods, restrictions on municipal ownership of water, and urban conservation are all shown to improve agricultural profit from production and sales of crops at a lower cost to municipalities, but at significant reduction to the price and underlying value of water rights. Relaxing buy and dry constraints (Policies B-C) kept the most acreage in production but hurt reliability and water rights prices, relaxing municipal ownership constraints (Policy D) was the only policy to improve total agricultural profit by shifting municipal purchases to CBT water, which is sold at a higher price than native water rights, and urban conservation (Policies E-G) most effectively reduced water acquisition costs for cities by reducing raw water purchase requirements for new developments. Restricting municipal ownership of water increased the cost of water to municipalities slightly, but maintained higher water rights prices and agricultural profitability.

6 WATER STORAGE IN A CHANGING ENVIRONMENT: THE IMPACT OF ALLOCATION INSTITUTIONS ON VALUE[48]

As populations increase in arid regions of the world, investment in water infrastructure improves resource management by increasing control over the location and timing of water allocation. Many studies have explored freer trade as a substitute for additional infrastructure investment. We instead quantify how water allocation institutions, reservoir management objectives, and storage capacity influence the value derived from a reservoir system. We develop a stochastic dynamic programming model of a reservoir system that faces within-year variation in weather-dependent water demand as well as stochastic semi-annual inflows. We parameterize the model using the Colorado-Big Thompson system, which transports stored water from the West Slope of the Rocky Mountains to the East Slope. We then evaluate the performance of the system under five institutional settings. Our results suggest that rigid allocation mechanisms and inefficient management objectives result in a decrease of up to 13% in the value generated from stored water when compared to a free trade scenario, an impact on par with predicted losses associated with climate-change-induced inflow reductions. We also find that under biased management objectives, increasing storage capacity can decrease the social value obtained from stored water.

6.1 Introduction

Throughout many arid regions of the world, policymakers are seeking ways to meet future water demands associated with rapid population growth and a changing climate (MacDonald 2010; Vörösmarty et al. 2000). For example, Colorado is currently forecasting annual water shortages of approximately 500 thousand acre-ft (kAf) per year by 2050 (Colorado Water Conservation Board 2016). Climate change is likely to exacerbate this deficit by reducing average annual water

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[48] Maas, A., A. Dozier, D. T. Manning, and C. Goemans (2017), Water storage in a changing environment: The impact of allocation institutions on value, *Water Resour. Res.*, doi:10.1002/2016WR019239.

availability and increasing inter- and intra-annual variability in supplies (Lukas et al. 2014). Addressing these challenges will undoubtedly involve a combination of investment in new infrastructure (e.g., reservoirs, pipelines) and improvements in the allocation of water using existing capacity (e.g., alternative transfer methods, lease markets).

As a result of demographic changes, the landscape surrounding water management has evolved considerably over the last 50 years. Large state and federal storage projects designed and managed to serve agricultural users are increasingly being used by Municipal and Industrial (M&I) users. Institutional settings surrounding water infrastructure must adjust to these changing demands in order to maximize the value derived from scarce water supplies. In this paper, we investigate the extent to which institutional change impacts the value of stored water. To address this question, we model a reservoir system with agricultural and M&I users in an environment of stochastic inflows and within-year water demands to quantify how reservoir management objectives, water allocation institutions, and storage capacity affect the social value derived from scarce water resources. The 'management objective' refers to how project operators make water release decisions across time while 'allocation institution' refers to the rules that determine how water is allocated among competing uses within a year. The model is parameterized using the Colorado-Big Thompson (C-BT) system in order to quantitatively compare impacts and interactions of management objectives, allocation institutions, storage capacity, and inflow regimes in determining the total value derived from a reservoir system.

While the importance of institutions for optimally allocating scarce water has been explored in the literature (Young 1986), few studies have investigated the impact of storage decisions that are biased toward particular shareholders. We find that moving from an efficient management institution to one biased towards M&I users results in a decrease in water value of 4-13%, or roughly the same magnitude as a 10% decrease in the average availability of water. Interestingly, with biased management focused on M&I water users, increasing storage capacity has an ambiguous effect on the total value derived from scarce water resources. Thus, investments to increase reservoir capacity in the context of biased management may actually decrease the total value of available water.

Previous literature related to water planning has typically evaluated potential projects in isolation or examined multiple options as substitutes for one another (Bekchanov et al. 2016; Gómez et al. 2004). The longstanding debate surrounding the development of additional supplies via new storage versus the reallocation of existing supplies via water markets (Goodman 2000) provides a useful example of this kind of thinking.

This evaluation paradigm is consistent with U.S. Federal Cost-Benefit Analysis (CBA) guidelines and how projects are evaluated in practice. Decisions regarding which projects to implement typically begin with the designation of need and a proposed solution (e.g., reservoir, pipeline, etc.) followed by a CBA involving a comparison of the project to several alternatives. However, there is a general criticism that U.S. Army Corps CBAs are, "biased against nonstructural alternatives" (Armah et al. 2009). In other words, behavioral and policy changes are often underrepresented. Project evaluations are often conducted based on static allocation or management rules where institutional change is seen as outside the scope of analysis.

Providing common pool resource users with the opportunity to modify institutional environments can enhance resource value (Gibson et al. 2000; Ostrom 1992; Ostrom et al. 1992). The purpose of this paper is to incorporate management and allocation institutions in our analysis and investigate how they interact with storage capacity and inflow regimes. This investigation is particularly relevant given the changes in water ownership over the past half century. Project operators face the challenge of updating management objectives to reflect the demands of all users while balancing the desires of large stakeholders. As we show, managing disproportionately for one user type (or over-emphasizing the preferences of new owners) can result in substantial losses.

Overall, our results suggest that management objectives and allocation institutions have a substantial impact on the value of stored water and must be considered in tandem with the physical characteristics of supply and distribution systems. In fact, investigating changes to one in isolation may miss important interactions between physical and institutional characteristics (Yoder et al. 2016). Therefore, our results have important implications for how projects are valued, the accuracy of valuations across time, and the ability to use benefit transfer methods to infer the value of public infrastructure.

The remainder of this paper is organized as follows. The next section describes water use in the western U.S. and places this paper within the hydro-economic modeling literature. Section 3 presents the stochastic dynamic model used in our analysis and details how each component of this model is parameterized using the C-BT system. Section 4 describes the alternative management and allocation mechanisms considered. Section 5 reports and compares model results under each scenario. In section 6, we discuss the implications of our results as well as their limitations and identify areas of future research.

6.2 Background

The southwestern United States depends on reservoir and conveyance systems to collect water during wet times and deliver it during periods of high demand, making it possible to irrigate large amounts of land and sustain growing populations. Across the Southwest, major runoff events happen in April and May, driven largely by melting snow, but field crops require irrigation through September and M&I demands exist year-round. In Colorado, rain and snow fall mainly on the West Slope of the Rocky Mountains, but most residential and agricultural use occurs on the East Slope, separated from the West Slope by the Continental Divide. Therefore, storage and conveyance infrastructure facilitates the delivery of water from areas and times with large supply to those with high demand.

While the number of new projects in the western U.S. has slowed from a peak of nearly 30,000 dams completed in the 1960s to approximately 3,200 completed since 2000 (United States Army Corps of Engineers 2016), infrastructure is still seen by many as the primary means of meeting growing demands and responding to changing climatic conditions. Recent droughts and concerns about climate change have renewed the public's appetite for large-scale storage projects, a number of which are currently under review (e.g. the Northern Integrated Supply Project or California's Proposition 1).

With new projects under consideration, there is a benefit to understanding the importance of management and allocation institutions in determining the value derived from new infrastructure. In a comprehensive review of water infrastructure CBAs from the 1960s, Prest and Turvey (1965) write that such analyses are not "constrained to physical projects, but can also be applied to proposed changes in laws or regulation." Half a century later, most CBAs of water infrastructure do not include the potential economic costs and benefits of changing the legal and institutional framework within which the infrastructure would exist (Armah et al. 2009). Accordingly, we contribute to the literature by investigating the relationship between institutional or legal constraints and the value of water stored in large infrastructure projects.

6.2.1 Water Allocation in the Western U.S.

Institutions governing reservoir release decisions and the allocation of released water vary considerably across the United States. Throughout the western U.S., reservoirs were traditionally constructed and managed to support agriculture in areas with fertile land but limited water. By one estimate, the 17 Western States account for 74% of all irrigated acres in the United States and 85% of total water withdrawals (United States Geological Survey 2016). However, as urban populations grow, the primary focus of some reservoirs is shifting from agricultural to M&I uses. As the stakeholders of water infrastructure projects change, the objective of reservoir managers may also shift.

In practice, there are a number of institutions and rules governing reservoir storage and release decisions across the West. In some cases, reservoirs are entirely privately owned, in others they are owned by public entities, and in many cases reservoir operations are jointly managed between a local organization and a federal agency. While the objectives of these managers are rarely considered in CBAs, they are key components in determining the value of stored water. For example, a single-owner-operated reservoir will make release decisions in the best interest of the owner, whereas most large-scale dams have many stakeholders with competing motives and storage preferences.

In addition to reservoir management objectives, water allocation institutions also have significant implications for the creation and distribution of total value generated from stored water. In practice, transaction costs such as court and lawyer fees often create barriers to trade and lead to inefficiencies with respect to water allocation (Booker and Young 1994; Brookshire et al. 2002, 2004; Colby 1990; Livingston 1995; Young 1986). A recent overview by Marston and Cai (2016) succinctly outlines the barriers to water reallocation and investigates losses associated with them.

Barriers that prevent heterogeneous users with differing marginal values from trading water can lead to significant value losses—particularly in highly developed basins (Reddy et al. 2015). These barriers also prevent the efficient use of other complementary inputs, such as land and capital-intensive conservation technologies (Chong and Sunding 2006). Thus, water allocated sub-optimally under rigid allocation institutions causes infrastructure to produce less value than identical infrastructure not subject to such institutional constraints.

C-BT water is West Slope water, so it does not have the same historic use and no-harm requirements associated with water native to the East Slope. As a result, the C-BT system has a well-functioning annual leasing and rights market. It is not subject to the high transaction costs associated with trading native East Slope water (Griffin 2006). Therefore, the base institution for our case study allows for free trade in water and assumes that managers choose release-quantities to maximize the total expected present value of water across all uses. We then impose more rigid allocation institutions and alter operational objectives to quantify the magnitude of inefficiencies created by more rigid allocation mechanisms or release decisions that disproportionately favor one user type.

6.2.2 Hydroeconomic Models

To model the impacts of institutions on water value in a stochastic environment, we develop a hydroeconomic model that captures the economic demands for water in a reservoir system while accounting for hydrologic realities across space and time. Bekchanov et al. (2016) and Harou et al. (2009) provide a comprehensive review of hydroeconomic models and their limitations. These models have traditionally been used to minimize cost (Yeh 1985), maximize net economic value (Cai 2008; Ward and Pulido-Velázquez 2008), and balance reliability, risk, and cost (Beare et al. 1988; Howe et al. 1994). Hydroeconomic models have also been developed to examine the impact of management on specific sectors (Knapp et al. 2003), the impact of water markets on efficiency and equity (Ward and Pulido-Velázquez 2008), the impacts of weather shocks on agricultural production and value (Maneta et al. 2009), and the economic impact of climate change (Draper et al. 2003; Reddy et al. 2015) and adaptation (Tanaka et al. 2006), including climate change impacts on optimal storage capacity (Fisher and Rubio 1997). Similar to our paper, Chakravorty et al. (2009) investigate the influence of allocation institutions on the value of water in a reservoir system, but they focus on the role of market power using a static model, which is quite different from our methods and objective.

Our model contributes to this rich literature by considering how allocation and management institutions interact with the physical characteristics of a storage system in influencing the value generated from water stored in public infrastructure. Because changes in reservoir capacity affect value and storage decisions (Tilmant et al. 2014), we also investigate how reservoir sizing interacts with allocation institutions and management objectives. The model developed herein also incorporates the novel feature of separable stochastic weather shocks at the source (where inflows accrue) and at the point of use (where water is demanded). This feature is relevant to water collection and conveyance systems in the West where users are often far from the location in which water is collected.

We use our model to explore the effect of institutional settings by simulating different reservoir management objectives and allocation institutions through changes to the model's objective function and constraints. In the baseline (optimal case) we allow for costless leasing markets in each period, and under the most rigid regime we allow water to be allocated according to proportional share ownership using original share allocations (reflecting a complete lack of trade in water rights). Because stored water is a state variable influenced by stochastic shocks, we consider how alternative institutions influence release decisions and overall value of stored water in a dynamic, stochastic model. The details of the model structure are presented in the next section.

6.3 Stochastic Dynamic Model of Reservoir Operation

6.3.1 Model Framework

To investigate the impact of institutional setting on the value of stored water, we develop a stochastic dynamic programming model that allocates water supplies between two users across time. The model is modified to reflect various allocation institutions, management objectives, and physical constraints for a single reservoir system. The reservoir manager considers the total value of water in period t, $F_t(w_t, \tilde{c}_t)$ where w_t is a choice variable for the total quantity of water released in period t and $\tilde{c}_t \sim N(\mu_c, \sigma_c)$ is a random variable representing deviations from mean effective precipitation. Effective precipitation refers to the amount of water that reaches and remains in a crop's root-zone to be used by that crop. $\tilde{c}_t$ is included to capture random weather effects on agricultural demand. The use of a tilde on $\tilde{c}_t$ and $\tilde{I}_t$ denotes that the variable is random and the absence of a tilde indicates a realization of the random variable. Deviations from mean effective precipitation, $\tilde{c}_t$, affect demand and consequently the benefits derived from water delivered to the agricultural sector. We assume that M&I demands do not depend on $\tilde{c}_t$, though in reality some outdoor use may fluctuate with the weather.

We define stored water at the beginning of a decision period as s_t, where s_{t+1} depends on storage in t, the release decision in t, a random inflow realization, $\tilde{I}_t \sim ln\, N(\mu_t, \sigma_t)$, and evaporative losses, e_t. Evaporative losses and the parameters of the inflow distribution vary across season to reflect physical differences between summer and winter. Future inflows cannot be 'borrowed' from the storage system such that $s_t + I_t \geq w_t$. Finally, the storage system has a fixed capacity, C. This means that $0 \leq s_t \leq C$. Given a discount factor, β, a system manager's optimization problem consists of choosing the amount of water to release in each time period, w_t, to maximize the expected present value derived from water. This objective can be expressed as:

$$\max_{w_t \in W} E\left[\sum_{t=0}^{\infty} \beta^t F_t(w_t, \tilde{c}_t)\right] \tag{53}$$

$$st.\, s_{t+1} = s_t + \tilde{I}_t - w_t - e_t$$

$$s_t + I_t \geq w_t$$

$$0 \leq s_t \leq C$$

$$s_0 \; given$$

An important feature of stochastic dynamic models is the timing of management decisions relative to the realization of inflows and the weather. We model a half-year time step that allows water demands to vary between summer and winter seasons. In practice, a water manager must make a release decision at the beginning of a season without knowing with certainty the quantity of water that will become available through inflows. Nevertheless, it may be desirable to use water throughout a season as it becomes available through inflows. Therefore, at the time of a release decision, the manager observes storage levels and makes a decision that accounts for expected inflows. Once an inflow is realized, the actual released water is the minimum of the optimal release quantity chosen and the sum of storage plus inflows during the time period such that $s_t + I_t \geq w_t$. This assumption ensures that water use does not exceed water availability in a given time period.

To more clearly demonstrate the timing of intra-annual decisions, information revelation, and consumption in the model, we present the model components in Figure 32. A semi-annual release decision was chosen to mimic the actual release decision timing in the C-BT system (October and April). The nodes in Figure 32 include storage decisions (triangular nodes), water allocation decisions (nodes marked with an 'x'), and stochastic realizations (circular nodes) that occur within each year of the model. At the beginning of a water year (1 October), an initial storage level is observed. Based on this information and on expectations about future weather and inflows, a reservoir manager makes a decision on the quantity of water to release and to store. Then, an inflow occurs over the winter season (November-March) and the released winter water is consumed by M&I users. Next, a summer storage/release decision (1 April) is made followed by an inflow (May-September). The inflow is added to storage levels which are reduced by released water and evaporation to generate the following year's initial winter storage levels.

In the summer, a weather realization occurs that determines the demand for water in agriculture and finally, the summer water is delivered consistent with the scenario's allocation institution. Note that under a proportional allocation mechanism, the allocation decision has been made implicitly in the release decision. However, such a feature is not true in the presence of a leasing market. For each model run, the allocation mechanism is held fixed across time and is not a decision of the reservoir manager.

The model incorporates differences in allocation institution and management objective by modifying the functional form of the objective function, $F_t(\, w_t, \tilde{c}_t)$. When a market for water exists, its marginal value equates across sectors during the summer time period when both agriculture and M&I use water. Marginal values do not necessarily equate between summer and winter periods because of weather realization and storage limitations. When water use is fixed by ownership, an additional constraint is required where proportions of total consumption are held constant at the annual level. For a given release decision, distinct marginal values emerge within each time step and use type. The marginal value of water is the demand function evaluated at the quantity of water delivered to the user in time period t.

6.3.2 Model Specification and Parameterization

We parameterize the model to the C-BT system using historic deliveries, water prices, reservoir inflows, weather, and agronomic information. We then use the parameterized model to explore the impact of management and allocation institutions on the value of stored water. The C-BT was designed to supplement native water supplies for agriculture on the East Slope. However, due to an active water rights market, the system has seen a significant shift in water ownership from agriculture to M&I consumers (as shown in Figure 33). Note that M&I ownership grew from ~15% in 1960 to more than 65% as of 2010. Much of this increased ownership is due to cities' requirements that new residential developers pay a tap fee or donate water rights. Because C-BT rights are relatively easy to transfer, they have become the preferred source for cities and developers in the area.

C-BT water is unique because shares of water can be leased or traded with very low transaction costs, enabling an efficient allocation of water within years and across time (Griffin 2006). Thus, despite a shift in ownership towards M&I, an active lease market for water has allowed agriculture to continue using the majority of delivered water by leasing it from M&I shareholders. As seen in Figure 34, water leases have increased over time because municipalities own more shares than is necessary to meet current demand in all but the driest years.

6.3.3 Demand Specification

The first step in parameterizing the model is to specify demand curves for each user type. We use constant elasticity (CE) demand functions of the form:

$$w_{i,t} = \frac{K_i p_{i,t}^{\varepsilon_i} - \tilde{c}_t}{\eta} \tag{54}$$

where $w_{i,t}$ is the quantity of C-BT water released for user $i \in \{ag, M\&I\}$ in a given time period, $\varepsilon_i < 0$ is the price elasticity, K_i is a calibrated constant, and $p_{i,t}$ is the price or marginal value of water. Conveyance efficiency, $\eta \in [0,1]$, represents the proportion of released water that reaches end users. Note that $\tilde{c}_t = 0$ for M&I because M&I demand is not a function of precipitation.

The CE demand function results in a marginal value spike as deliveries decrease, and inelastic CE demand implies a marginal benefit that goes to infinity as deliveries go to zero. This feature of the function is not realistic because C-BT water only supplements native supplies. Even as deliveries of C-BT water go to zero, total deliveries from all sources in the area do not. To address this issue, we assign a maximum marginal willingness-to-pay (mWTP) to each demand curve. This assigns a constant value to every unit of water below a given volume, meant to reflect the ability to substitute to alternative, native sources of water.

6.3.4 Municipal and Industrial Demand

To operationalize the M&I demand function, we estimate $K_{M\&I}, \varepsilon_{M\&I}$, and mWTP for both summer and winter periods. Determining mWTP for M&I use is challenging because this value is rarely observed in reality. We select an mWTP of $500/acre-ft for both winter and summer seasons. However, we acknowledge that recent water sales imply a considerably higher annualized use value than that used in our analysis. To ensure robustness, the model is solved using multiple values for mWTP; qualitative results persist across higher mWTP values (these results can be made available upon request).

Elasticity estimates were taken directly from the literature; $\varepsilon_{M\&I} = -0.7$ was used for summer time periods and $\varepsilon_{M\&I} = -0.2$ for winter time periods (Dalhuisen et al. 2003; Espey et al. 1997; Olmstead et al. 2007). While there has been considerable work deriving residential and municipal price elasticities (Andreoni and Miller 1993; Dalhuisen et al. 2003; Espey et al. 1997;

Kenney et al. 2008), the literature is sparse when it comes to industrial demand (Booker et al. 2012). With the exception of Dupont and Renzetti (2001) and Renzetti (1992), we know of no other robust estimate of industrial water demand in North America. Additionally, USGS 2010 data suggest that industrial surface water use in the area is small compared to the total withdrawals for irrigation and public supply (Maupin et al. 2014). For these reasons, we do not distinguish between Municipal and Industrial water users in our analysis.

An estimate for $K_{M\&I}$ was solved for by using demand elasticity along with average historic prices and quantities in equation (2). Lease prices in the area and previous work suggest the marginal value of water in use is approximately $41/acre-ft for agriculture (Faux and Perry 1999; Ward and Michelsen 2002; Young and Loomis 2014). Because the C-BT system operates in a functioning water market, the marginal value for M&I is also assumed to be $41/acre-ft. Initial quantity was calculated as the average water deliveries to M&I from 2002 to 2012, estimated at 81,867 acre-ft. To separately parameterize $K_{M\&I}$ for both summer and winter, total M&I deliveries are further divided into indoor and outdoor use. Summer use consists of both indoor and outdoor use while winter use consists of only indoor use. The city of Fort Collins, a large shareholder of C-BT water rights, estimates residential water consumption as 36% outdoor and 64% indoor use (Mayer et al. 2009). This means that outdoor uses consume 29,472 acre-ft per year and indoor uses consume 52,395 acre-ft per year. To break these annual totals into summer and winter consumption, we assume that outdoor M&I consumption is zero in the winter, implying that summer outdoor consumption equals the annual consumption of 29,472 acre-ft. If the total indoor use remains constant across seasons, indoor consumption equals $\frac{52,395}{2} = 26,197$ acre-ft in both winter and summer. Using these prices and quantities, we solve for $K_{M\&I}$ in both summer and winter, such that parameterized M&I demand equations are only a function of price. The parameterized demand function is then integrated over delivered water to obtain per-period M&I

water benefit functions, $f_{M\&I,t}(w_{M\&I,t})$ where $w_{M\&I}$ is the quantity of water demanded by M&I users.

6.3.5 Agricultural Demand

Estimating an agricultural demand function is more involved because water demand in the agricultural sector is a function of effective precipitation throughout the growing season. Consistent with actual water consumption, the benefit of agricultural water use outside the growing season is assumed to be zero such that agricultural demand only exists in our model for the summer season.

Using a simple accounting method and data from Colorado crop budgets and the U.S. Department of Agriculture, we find that mWTP for water in agricultural use is approximately $100/acre-ft (a brief description of this calculation is presented in supporting information S1). This estimate is in line with past research, but it is worth noting that values attributed to water through hedonic studies have a large range (Buck et al. 2014; Faux and Perry 1999). To ensure robustness in our results, we perform a sensitivity analysis that varies mWTP values. Qualitative model results persist across a range of mWTP levels (additional model results can be made available upon request). Based on estimates from the economics literature (Scheierling et al. 2006; Schoengold et al. 2006), a price elasticity of $\varepsilon_{ag} = -0.6$ is assumed for agricultural water demand.

Effective precipitation enters the demand function as a random volumetric variable distributed around historical mean effective precipitation, $\tilde{c}_t$. It is added or subtracted from summer water delivered to agriculture in year t such that in drier-than-average years, more water must be applied to achieve a given level of benefit. The distribution of $\tilde{c}_t$ is parameterized as a volume by estimating the total area of irrigated lands supplied with C-BT water and historic effective precipitation depth. This conversion is necessary because demand is a function of water volume, while precipitation is reported in water depth. A detailed explanation of the parameterization of $\tilde{c}_t$ can be found in supporting information S2. Using historic leasing prices, average deliveries, and effective precipitation, we solve for K_{ag} in equation (2) such that summer agricultural demand is a function of price and realized effective precipitation.

To illustrate the dependency of water demand in agriculture on effective precipitation levels and to clarify how mWTP is used in our demand estimation, Figure 35 presents the M&I water demand with an mWTP of \$500/acre-ft and the agricultural water demand function with mWTP of \$100/acre-ft under five realizations of effective precipitation. The realization of effective precipitation determines both the slope and quantity of water at which the mWTP is reached (labeled in Figure 35 for each realization of effective precipitation). For example, when $\tilde{c}_t = -30$ kAF, the realization of effective precipitation is -30 kAF below the mean. Given that this is a relatively low precipitation realization, a large volume of irrigation water (128.2 kAF) is required to reach the downward-sloping portion of the demand curve. On the other hand, with a high realization of effective precipitation (e.g., $\tilde{c}_t = 30$), less water (53.2 kAF) is required to reach the decreasing portion of the demand curve. The final step of the model is to integrate the agricultural demand function over delivered water to obtain the seasonal benefit of water in agriculture, $f_{ag,t}(w_{ag,t}, \tilde{c}_t)$.

6.3.6 Physical Specification and Constraints

Next, we obtain parameters that describe the hydrologic context of the C-BT system, including reservoir capacity, evaporation, conveyance loss, and inflow distribution. C-BT West Slope storage is composed of five reservoirs (Lake Granby, Willow Creek, Shadow Mountain, Windy Gap, Grand Lake), but these reservoirs work as an integrated storage facility such that our model only includes Lake Granby storage, which has an active capacity of ~470 kAf and accounts for 98.9% of total West Slope capacity in the C-BT system.

We first estimate reservoir surface area (A_τ) and evaporation depth to calculate water losses through evaporation. When reservoirs are full, the total surface area is 9,500 acres. Because data does not exist linking surface area to storage, we estimate via linear regression a curve, $s_\tau(z_\tau)$, that describes stored water on day $\tau (s_\tau)$ as a function of water elevation (z_τ) for Lake Granby. The surface area can then be inferred from the following relationship:

$$\frac{ds_\tau}{dz_\tau} = A_\tau \tag{55}$$

Lastly, we estimate the relationship between predicted A_τ and s_τ. This describes how surface area responds to changes in the amount of water in storage. The fitted curve, $A_\tau(s_\tau)$ for Lake Granby was estimated $(R^2 > 0.9989)$ as:

$$A_\tau(s_\tau) = \begin{cases} -5.89 * 10^{-9} s_\tau^2 + 0.0127 s_\tau + 2144 \text{ if } s_\tau > 0 \\ 0 \quad \text{if } s_\tau = 0 \end{cases} \tag{56}$$

Evaporation depth (the change in water level due only to evaporation) is estimated from a CoAgMet weather station in Fort Collins, Colorado. It is, on average, 38.27 and 12.56 inches in the summer and winter periods, respectively. At maximum reservoir surface area, total evaporation depth ranges from 43 to 60 annual inches of evaporated water. Since this range is small, about 2.7% of annual inflow and 1.6% of total reservoir capacity, average seasonal evaporation depth is fixed at 12.56 inches in winter and 38.27 inches in summer across the planning horizon. Multiplying this depth estimate by stored water surface area produces an estimate of total water volume evaporated.

Conveyance is also a major source of water loss. Conveyance efficiency, η, is assumed to be 80%, consistent with findings from the neighboring Arkansas River Basin (Gates et al. 2002; Triana et al. 2010a).

Reservoir inflow is a random variable whose distribution is estimated using historic inflow information from the U.S. Bureau of Reclamation. Semi-annual inflow, $\tilde{I}$, is fitted to a lognormal distribution using the mean and variance of the logged historical data such that $\tilde{I}_t \sim \ln N(\mu_t, \sigma_t)$, where μ_t and σ_t correspond to:

$$\mu_t = E[\ln(\tilde{I}_t)] = \begin{cases} 10.2, \text{if } t = 0 \text{ (winter)} \\ 12.4, \text{if } t = 1 \text{ (summer)} \end{cases} \tag{57}$$

$$\sigma_t = Var[\ln(\tilde{I}_t)] = \begin{cases} 0.262, \text{if } t = 0 \text{ (winter)} \\ 0.316, \text{if } t = 1 \text{ (summer)} \end{cases} \tag{58}$$

6.3.7 Other Model Assumptions

This model parameterization assumes cost-free spills so that the cost of any excess inflow beyond reservoir capacity is assumed to be only the opportunity cost of not using that water in subsequent periods. Previous models often penalize spills with a harm function (Fisher and Rubio 1997). A harm function is not included because the model has a relatively coarse timestep and the reservoirs are not purposed for flood control. Given that the vast majority of storage is on the other side of the Continental Divide relative to water consumers, storage reservoirs can do little to hold back water on the East Slope. The model also assumes costless trades in market scenarios, no demand trends, and no correlation between inflow to the West Slope collection system and precipitation or usage on the East Slope.

6.3.8 Solution Method

To solve the model, reservoir levels, release decisions, and annual inflows are discretized into 5 kAf intervals. The stochastic dynamic program is solved over an infinite time horizon using value function iteration (Judd 1998) with a tolerance of \$10,000, or ~0.003% of total optimized value for the free trade scenario. Our model includes several interesting features that require attention when solving. First, seasonal demands cause the value function to take different values in winter and summer periods; therefore, convergence is measured for season-specific value functions. We operationalize this by defining the value function as $V(s, \phi)$ where ϕ is an indicator equal to 1 in the summer and zero in the winter, and s is the quantity of water stored at the time of the decision. This can be expressed as:

$$V(s,\phi) = \max E_I \left[E_c[F_t(w,\tilde{c}_t) + \beta V(s^+(s,\tilde{I},w),\phi^+)] \right] \quad (59)$$

where the superscript + indicates the value of the variable in the following season. We require the value function to converge for each season and storage level.

Another noteworthy feature of this model is that even current payoffs are not known with certainty, because a given release decision occurs based on expectations about inflows and effective precipitation. Therefore, there is some probability that the desired quantity of water cannot be released because of a low inflow realization. In this case, the storage level plus the whole inflow is released. The calculation of expected value associated with each release decision accounts for this possibility. Finally, we do not allow storage levels to exceed the fixed capacity of 470 kAf. If an inflow results in water levels beyond capacity, the water must be released in the current period.

Solving the model produces policy functions that indicate optimal release decisions as a function of the state variable (reservoir level) and the season. Analysis of optimal release decisions involves simulating 100 stochastically generated inflow and weather time series over 50 years, held constant across institutional settings, with an annual discount rate of 3 percent.

6.4 Institutional Simulation

Using the parameterized model, we modify the institutional and physical settings to investigate the effects of restrictive allocation mechanisms, biased management objectives, changes in inflows, and changes in storage capacity on the value of water and water infrastructure.

To accomplish this task we run the model under two management objectives and three allocation institutions for a total of 5 scenarios. Table 26 provides a summary of annual water benefits considered by reservoir managers under each scenario. The first scenario is the baseline to which all other scenarios are compared. The baseline scenario assumes that there is a free market and that reservoir managers maximize the total expected net present value of water.

Deviations from the optimal institutional setting are made in two dimensions: the management objective (column 1), and the allocation institution (column 2). Column 3 describes the annual value from water considered by the manager under each scenario. The model is solved under each combination of management objective and allocation institution to assess their impact on the value of stored water.

Two management objectives are considered 1) maximizing total value across all users, and 2) biasing management towards the interest of M&I consumers. The second management objective represents an extreme case in which only the M&I users have a voice in influencing reservoir decisions. We report management objectives biased toward M&I users because cities may have begun to exercise influence over storage and release decisions as water has become majority owned by these customers. Biased management may have substantial total and distributional effects since agricultural and M&I interests often conflict. For example, in average water years, agricultural users often advocate for increased release quantities while cities, who have met their water needs, argue for leaving more water in storage to hedge against drought in future years.

The three allocation mechanisms considered are: (1) a costless water leasing market, (2) delivery proportions fixed at initial ownership shares where just 15% is allocated to M&I, and (3) delivery proportions fixed at current ownership proportions, with M&I receiving 66% of total water deliveries. The second allocation institution represents the case when no leasing or transfer of water rights can occur. In the third, there is no water leasing but rights have been transferred between uses. These scenarios loosely correspond to an extreme case in which transaction costs prevent trade or leasing of water rights.

Each of the 5 institutional scenarios is solved under varying distributions of inflows (where μ_t of the inflow distribution was scaled from 50% to 100% to represent changing supplies), and a range of storage scenarios (from no storage to 120% of current active capacity). A 50-year simulation is then run to obtain the present value of water in each scenario. Recall that, even though we construct a 50-year series of inflows, the decision-maker does not have access to these inflows in advance. Storage and release decisions are made with uncertainty about inflows and weather. This simulation exercise allows use to compare the importance of institutional setting versus physical reservoir system characteristics. Results of these 50-year simulations are presented in the next section.

6.5 Results

Our baseline scenario allocates water optimally across time and users under current inflow regimes and storage capacity. We then deviate from this scenario to compare the associated value losses with each scenario. More specifically, we investigate how deviations from optimal reservoir management and water allocation can affect the total value of water and water infrastructure across a range of storage and inflow scenarios. First, we present results that demonstrate the effect of institutions—management objectives and allocation mechanisms—on the value derived from stored water. Then, we present a sensitivity analysis, using a range of inflow and capacity scenarios, which demonstrates how institutions interact with physical attributes of the system.

The fundamental result of the modeling exercise is that the value created by water infrastructure depends as much on the effectiveness of institutions as the physical characteristics such as storage capacity or inflow quantities. Table 27 presents the expected present value (and standard errors) of benefits derived from stored water under each management scenario. Comparing scenario 1 with the suboptimal management scenarios confirms that value is maximized when all uses are valued and a market exists. Comparing scenarios 2 and 3 reveals the within-year allocation of water plays a substantial role in influencing the value of stored water. Representing the absence of a lease market, fixed allocation at current ownership (scenario 3) results in a 6% loss in value. If permanent trade in water rights is also restricted (scenario 2), the present value of water would fall by 13.2%. This additional drop in value is driven by high M&I marginal values of water at the initial allocation of shares in the C-BT system and is similar to a 30% reduction in average inflows using the baseline institution (see column 3 of Table 27).

Comparing scenario 5 with the baseline scenario shows that managing disproportionately for M&I consumers decreases the value derived from water by 4%. While less important than the allocation mechanism, the reduction in value from a biased management objective is greater than an inflow decrease of 10% (see column 2).

Interestingly, the gains of introducing a leasing market can mitigate the cost of biased reservoir management. With a leasing market in place, even if the manager's objective is to maximize value to only M&I, a market allows within-season reallocation such that 96% of the value created in the baseline scenario can still be attained, compared to just 93% when no market exists. Given the current contentions of irrigators and municipalities over water allocation, this result is encouraging for agricultural users who may express concern about the shift in shares to M&I. It suggests that even if M&I, as majority shareholders, can influence reservoir release decisions, losses will be minimal so long as leasing markets exist.

Table 27 also allows for an assessment of the interaction between management institution and average inflows. Value decreases non-linearly in inflow reductions because of the concavity of the benefit functions. Value losses are relatively small under inflow reductions of 10% across all institutions. A decrease in inflow of 50% results in a total value that is 76.4% percent of the current inflow levels under the same institution, although this value drops to 58.4% when water deliveries are fixed at original ownership. This suggests that small inflow changes may have relatively small effects on reservoir constituents.

Our results also indicate that the relationship between water availability and gains to trade depends on the severity of the original inefficiency in allocation. Under original ownership, gains to trade are relatively large compared to gains from trade given current ownership. This suggests that water rights markets can improve water value, even if active leasing markets do not exist. Next, under original ownership, gains from trade increase as water becomes scarcer. We see that under current inflow regimes the difference between original allocation (scenario 2) and market allocation (scenario 1) is 13.2% (100% – 86.8%). With a 10% reduction in inflow, this difference increases to 14.5%, and under a 50% reduction in inflow there is an 18% difference in value across allocation scenarios 1 and 2. This result is not consistent when comparing market allocation (scenario 1) to fixed allocations under current ownership (scenario 3). Comparing these scenarios we see a 6% difference in total value under the current inflow regime, but this value decreases to 2.4% with an inflow reduction of 50%. Therefore, while trade can compensate for reduced water availability, in some cases, the gains relative to fixed allocation may be diminished. Finally, the results in Table 27 suggest that moving to market allocation of water has the potential to offset losses associated with biased management objectives, though this result is not guaranteed. For example, under current inflow regimes, biased management without a market (scenario 4) results in 93.4% of the value created in our baseline scenario. If the same biasness exists in reservoir management, but water can be allocated via a market (scenario 3), the value created increases to 96.1% of the baseline scenario.

By modeling different objective functions, we can also examine the interaction of storage capacity and biased release decision. We find that when the reservoir is managed optimally, increasing storage necessarily (weakly) increases the total value of the project (see Figure 36 and Figure 37). However, when a manager's objective is biased towards M&I, increasing storage allows them to make storage decisions that negatively impact total value. Consistent with Yoder et al. (2016), we find that increasing storage has an ambiguous effect on total value and depends on the institutions under which the reservoir is managed.

A better understanding of why these values differ by institutional scenario can be illustrated in their corresponding policy functions (the solutions of the dynamic program). Figure 38 presents the optimal and biased policy functions at 100% and 40% of reservoir capacity. Note that the quantity of released water is the minimum of either the level of this policy function or the sum of storage plus inflow that occurs during the summer, such that infeasible solutions are included in these graphs. In Figure 38, the release decision is consistently higher in drier years when the manager considers the value of water created by both sectors.

Because the value of water to M&I is large at low levels of supply, biased managers prefer to release less in any given year, as to ensure sufficient supply for the following year. This result is consistent with conversations the authors have had with reservoir operators and M&I shareholders. While this reduced release may increase potential value to M&I users, it results in a total value loss because supplies to agriculture are insufficient in average and large inflow years. Increasing capacity only exacerbates this problem. Comparing the 100% and 40% capacity graphs illustrates that optimal decisions diverge in a higher proportion of cases when the capacity is larger. Under 40% capacity, the policy functions converge around 55,000 acre-ft, but at 100% capacity, the biased policy and optimal policy functions do not converge until storage and inflow reach approximately 355,000 acre-ft.

When reservoir managers make release decisions only considering value to M&I users, they consistently release too little in low inflow years. This result is driven mainly by relatively inelastic M&I demand and a high mWTP. Because of strong curvature, once cities receive an adequate amount, they prefer to store extra water for future years. On the other hand, agricultural users have relatively elastic demand functions and continue to gain from water released in a given year. Table 28 displays the average current and marginal value of each summer season across simulations when inflows are defined as low or high and water is allocated through a market. Note that in a dry year (inflows below 160,000 acre-ft), the seasonal value created by managing for M&I is actually higher. With a biased management objective, water releases in previous (average and wet) years have been lower such that storage levels are generally kept higher and more water is available for release in dry years. However, the value gained in dry years is outweighed by the value lost in wet years (inflows above 300,000 acre-ft) which leads to a decrease in total value across the 50-year time horizon.

Interestingly, in the case study presented here, storage across time periods has a relatively small effect on the present value of water. Because we use a semiannual time step for computational feasibility, the model ignores any value of storage derived from smoothing water supply within a season. At the semiannual time step, inflows and demands align relatively well. Winter snow melts in the summer, providing water in the same half-year as water is demanded for agriculture and outdoor M&I uses. However, within the summer time step, most of the inflow occurs relatively early in the season but is demanded in later months. Our model does not account for the value created by this intra-seasonal storage and conveyance; therefore, our results only apply to increasing the inter-seasonal or inter-annual storage capacity. Because of this, the relatively modest gains from storage across time periods make sense in this case study but should not be considered as a general result.

6.6 Discussion and Conclusions

In this paper, we use numerical simulations to demonstrate that the institutional environment within which public water infrastructure is built can have a meaningful impact on the value derived from water stored in the infrastructure. Going from efficient management objectives to focusing disproportionately on one user type can diminish the value derived from scarce water resources equivalent to a 10% reduction in expected water availability. Rigid allocation institutions further decrease water value. Institutional frameworks have important implications for the construction of new water storage infrastructure as well as for existing infrastructure with changing stakeholders. When performing a CBA, the calculated gross benefits of infrastructure are contingent upon the management objectives and allocation mechanism associated with the project.

As climate changes and water availability decreases, institutional reform can facilitate adaptation and ensure that new infrastructure achieves its maximum value.

Increasing water storage capacity also has the potential to increase the value obtained from stored water as supplies become scarcer. However, with biased management objectives, the impact of additional storage is ambiguous. If water managers disproportionately favor users with steeper demand curves, the ability to store more can decrease the total societal value obtained from the resource. While we demonstrate that this decrease can occur, the degree to which biased release decisions create losses depends on the degree of heterogeneity in the shape of users' demand functions. In the simplest example, only responding to M&I value would not cause losses if, for example, M&I's marginal value always exceeded agriculture's marginal value. This would also be true if both users had the same demand function. Therefore, as storage capacity grows in areas like the Southwestern United States, management institutions must properly balance the value of water across multiple uses.

While our results are generally informative, some results are specific to the C-BT setting. First, the storage capacity of the C-BT system is designed for larger inflows than occur in practice. Therefore, the capacity constraint rarely binds in our base model. Also, seasonal water availability in the C-BT system aligns with demand at a 6-month time step such that additional cross-season storage creates relatively small gains. In a more constrained system with differently timed inflows and demands, storage capacity likely plays a larger role in determining the value obtained from stored water.

Our work makes some simplifying assumptions that suggest potential avenues for future research. First, we assume just two water user types. In practice, industrial water demands differ from household consumers, meaning that the analysis may benefit from disaggregating M&I users. Additionally, we do not include environmental flows in this analysis, which have been shown to have significant value to society (Loomis et al. 2000). On a related note, while the CE demand functions reflect some realities of water demand, they do not create a satiation point such that there is always a benefit from releasing water. This assumption may not be accurate in many settings.

Another limitation is that, because we lack spatial data indicating where C-BT water is used in irrigation, we use a very general method, USBR, to estimate effective precipitation. This method can be insufficient in describing effective precipitation because it excludes potentially relevant variables such as soil type and wind speed. We also assume a 6-month time step. In reality, a large portion of water management involves the allocation of water at a daily or even sub-daily time step. Therefore, to capture the value of changes in storage capacity, it is important to account for changes in the ability to control the delivery of water at a finer time scale.

Our model also assumes that all storage decisions are made at the system level. In 2004, however, Northern Water reintroduced an annual carryover program (ACP) such that individual shareholders can bank up to 10% of their annual allotment. How personal banking interacts with management and allocation institutions has received little attention in the economics literature. Notable exceptions include (Brennan 2008, 2010), which highlight the potential for banking to reduce inefficiencies associated with rigid allocations and storage capacity constraints. Accordingly, the interaction between banking, institutions, and storage is an interesting topic for future research.

Lastly, our model produces estimates of the gross value generated from an infrastructure project. When estimating net social benefits of investment, it is important to consider the opportunity cost of water used in the system. In our example, water in the C-BT system could remain in the Colorado River, producing value in other regions and uses. This opportunity cost should be considered when weighing the benefits of a project against its cost.

Overall, the stochastic dynamic model we developed, parameterized, and solved under various institutional settings provides evidence for the importance of management objectives and allocation institutions in determining the value derived from scarce natural resources and public infrastructure. Sub-optimal reservoir management is an issue receiving considerable attention, particularly as evidence continues to grow for non-stationarity in hydrologic processes. Thus reservoir management objectives not only need to evolve as stakeholders change, but must also adapt to changing climate conditions wherein past inflow regimes may no longer be a good predictor of the future (Georgakakos et al. 2012).

As arid regions of the world cope with climate change and increasing populations, infrastructure investments will comprise a substantial part of adaptation strategies. By increasing storage and conveyance capacity, water infrastructure improves the timing and location of water consumption across and within years. Our results demonstrate that as infrastructure is built, the benefits derived depend on management objectives and water allocation mechanisms. In practice, these are often assumed to remain constant across time. However, a move toward more flexible, market-based water allocation, and managers who consider all water consumers in their release decisions can significantly increase the value of scarce natural resources and public infrastructure. Ultimately, aligning resource management objectives and institutions to optimize societal value can increase the value of public infrastructure and facilitate adaptation to changes in both the supply and demand for water resources.

Table 26: Objective Functions And Choice Variables Used To Simulate 5 Institutional Scenarios

Management Objective	Allocation Institution	Annual Benefits Considered by Manager, $F_t(w_t, \tilde{c}_t; \eta)$
1. Total Value	Lease Market	$f_{M\&I,t}(w_{M\&I,t}) + f_{ag,t}(w_{ag,t} + \tilde{c}_t)$
2. Total Value	Fixed Proportions (Original Ownership)	$f_{M\&I,t}(\mathrm{w_t}\alpha) + f_{ag,t}(\mathrm{w_t}(1-\alpha) + \tilde{c_t})$
3. Total Value	Fixed Proportions (Current Ownership)	$f_{M\&I,t}(\mathrm{w_t}\alpha) + f_{ag,t}(\mathrm{w_t}(1-\alpha) + \tilde{c_t})$
4. M&I Value	Fixed Proportions (Current Ownership)	$f_{M\&I}(w_{M\&I,t})$
5. M&I Value	Lease Market	$f_{M\&I}(w_{M\&I,t})$

Table 27: Expected Present Value Derived From Storage Decisions Over 50 Years

Management Objective (Allocation Mechanism)	(1) Current Inflow	(2) 10% Inflow Reduction	(3) 30% Inflow Reduction	(4) 50% Inflow Reduction
1. Total Value (Market)	100.0% (0.0)	97.0% (0.43)	88.8% (1.02)	76.4% (1.72)
2. Total Value (Fixed Allocation, Original Ownership)	86.8% (0.77)	82.5% (1.03)	71.5% (1.68)	58.4 % (2.06)
3. Total Value (Fixed Allocation, Current Ownership)	94.0% (0.38)	90.9% (0.68)	83.4% (0.96)	74.0% (1.33)
4. M&I Value (Fixed Allocation, Current Ownership)	93.4% (0.45)	90.3% (0.65)	83.0% (0.91)	73.9% (1.20)
5. M&I Value (Market)	96.1% (0.75)	91.5% (0.43)	82.5% (1.14)	72.9% (1.32)

PV for each scenario reported as a percent of baseline scenario value. Standard errors from 50-year simulations are in parentheses

Table 28: Current Total Summer Water Value in Wet and Dry Years

Allocation Mechanism (Management Objective)	Dry Year: Summer Inflow ≤ 160,0000		Wet Year: Summer Inflow ≥ 300,000	
	Annual Current Value	Marginal Value	Annual Current Value	Marginal Value
Total Mkt	$19,300,000	$66	$23,300,000	$28
M&I Mkt	$20,268,000	$29	$20,404,000	$23

Summer values averaged across all simulations

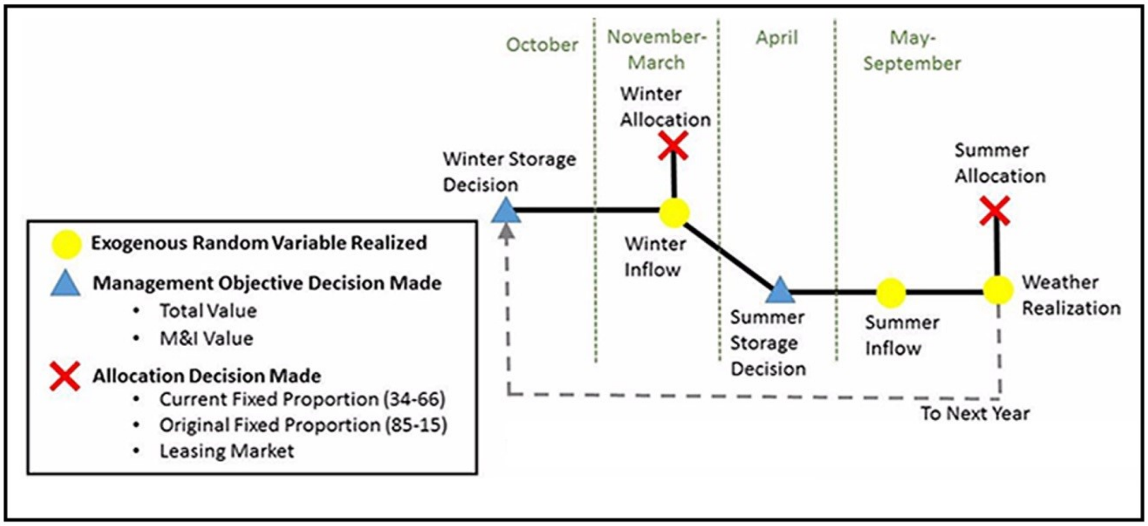

Figure 32: Graphical representation of the stochastic dynamic model.

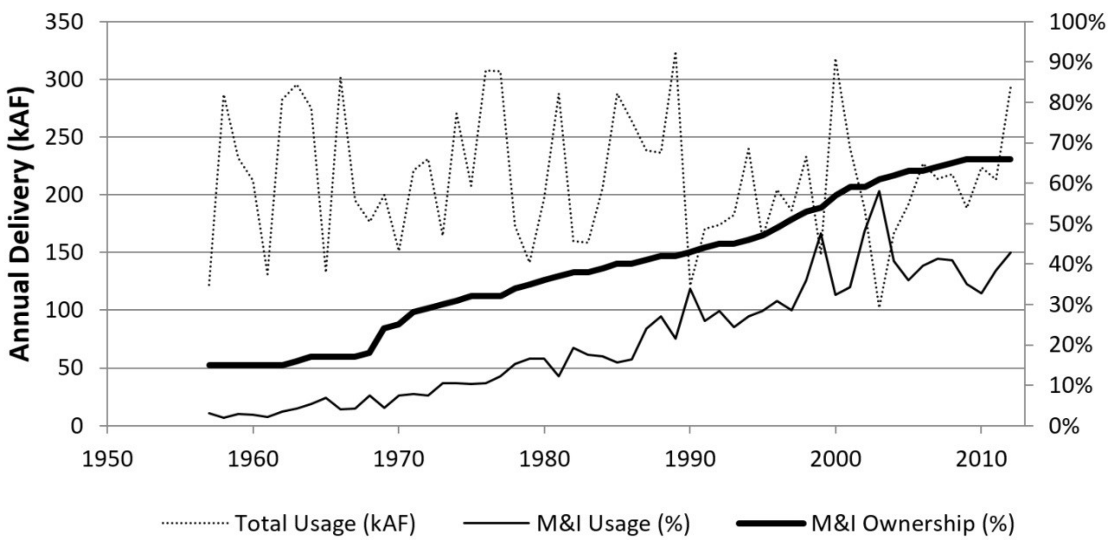

Figure 33: Total deliveries of the C-BT project and percentage of municipal share ownership and usage (data provided by Northern Colorado Water Conservancy District).

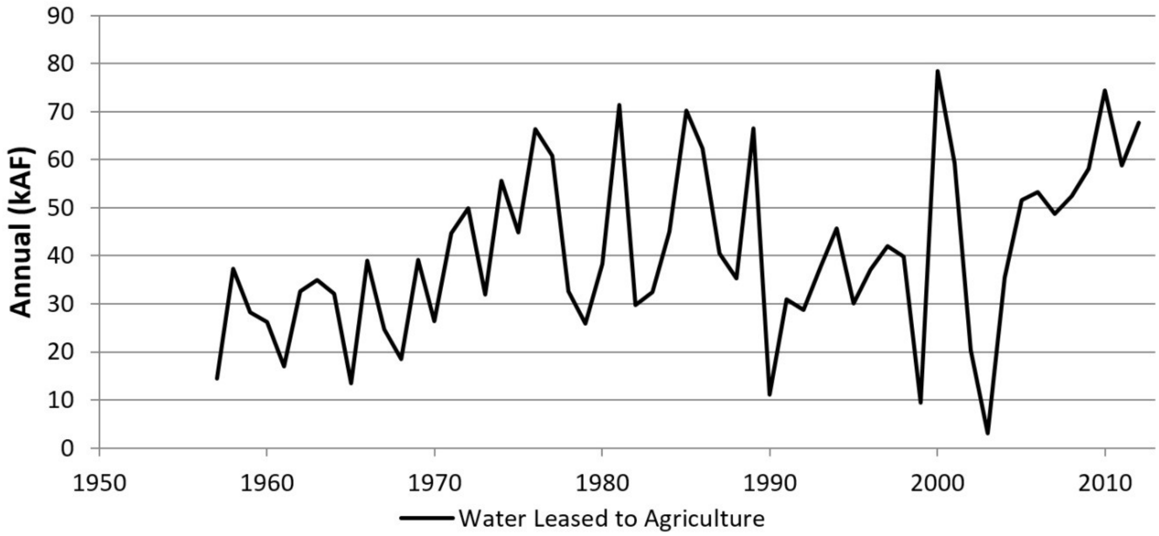

Figure 34: Annual C-BT water leased from municipal and industrial users to agricultural users.

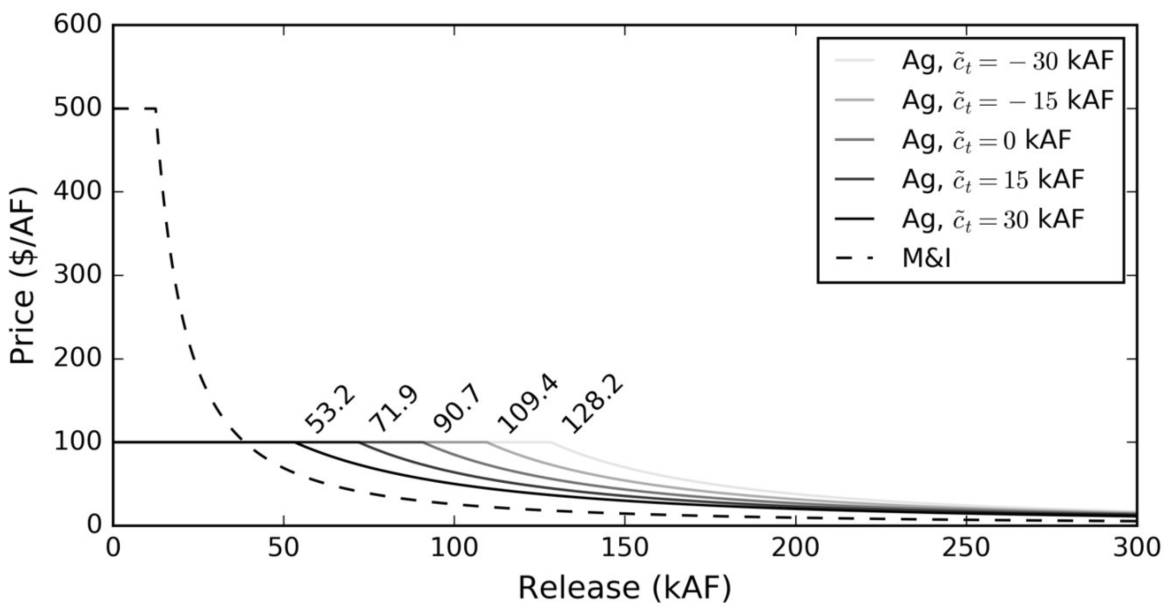

Figure 35: Demand functions with various realizations of East Slope effective precipitation, $\tilde{c}$, and a mWTP of $100 for agriculture. Quantities of water associated with the mWTP price value are indicated.

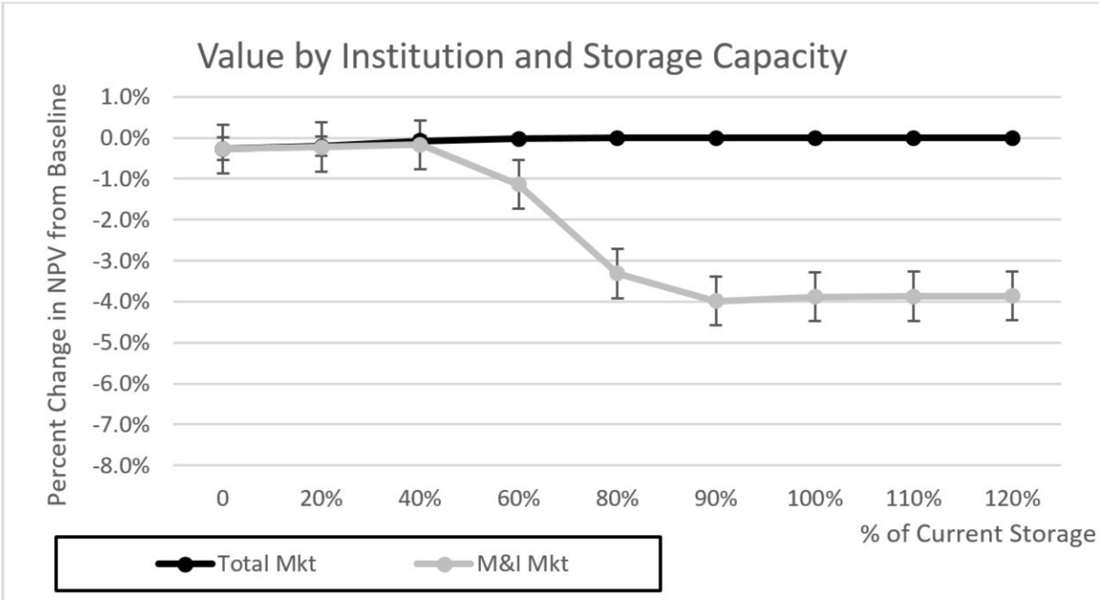

Figure 36: Decrease in value with an increase in storage capacity under market allocation.

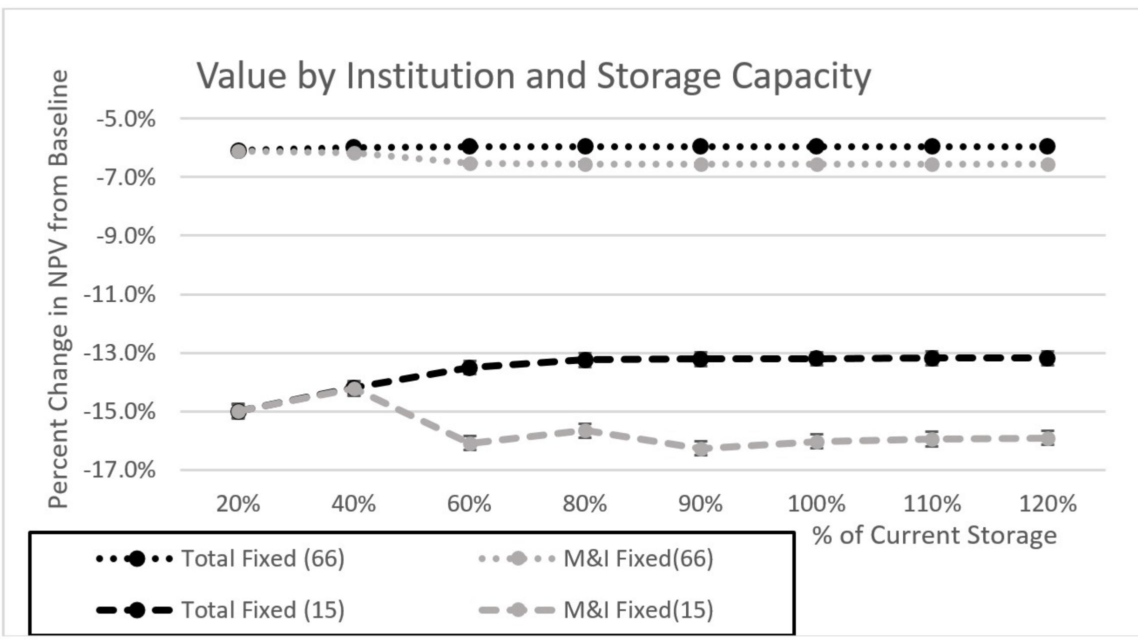

Figure 37: Decrease in value with an increase in storage capacity under fixed allocation.

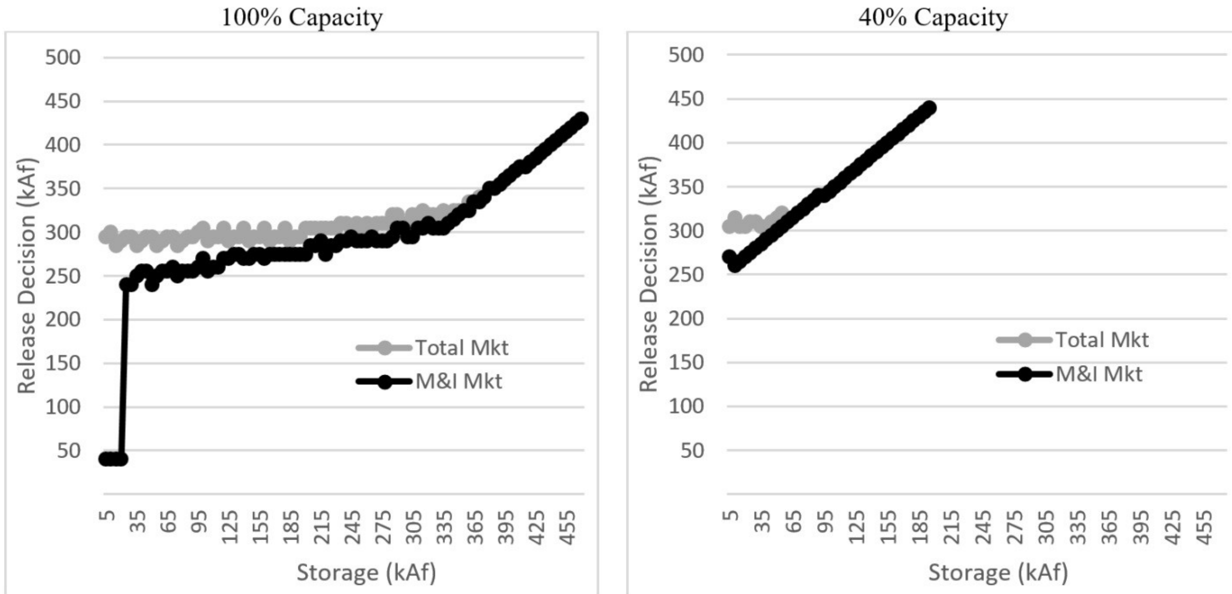

Figure 38: Comparing summer policy functions under biased and unbiased reservoir management. Note that release decisions are made with respect to storage and expected inflow such that a release decision may not be possible given a particular realization of inflow.

7 COMBATTING LOSS OF AGRICULTURE IN RAPIDLY URBANIZING SEMI-ARID REGIONS WITH INSTITUTIONAL CHANGE, INFRASTRUCTURE AND CONSERVATION[49]

Limited water supply in semi-arid regions drives municipalities to purchase agricultural water rights and subsequently permanently fallow the historically irrigated land, leading to economically impaired agricultural communities. Institutional changes to mitigate this pattern can help, but total agricultural production will likely continue to decline as populations grow. A model representing the market for water rights in semi-arid regions was utilized to assess trade-offs of both market-driven and policy-driven adoption of both supply-side and demand-side solutions: new storage reservoirs, efficient toilet upgrades, xeriscaping, and irrigation technology. Xeriscaping and irrigation technology are the most cost-effective strategies, without which significant losses are realized for both municipalities and agricultural producers. At the Pareto optima front, improving total regional agricultural profit by $1 billion increases municipal spending on water by about $10 billion or about an additional $6-12 per month for each water rate payer. Although all policy changes are an improvement to baseline conditions, lowering raw water purchase requirements for land developers had the largest benefit.

7.1 Introduction

Rapid urban growth in many semi-arid regions within the Western U.S., limited by water supply from contentious new sources such as water storage reservoirs and trans-basin diversions (Gleick 1998, 2003), is forcing municipal water providers to acquire agricultural water, resulting in worsening economic conditions for rural, agricultural communities (Gleick et al. 1995; Howe and Goemans 2003). To reduce the negative consequences of permanent fallowing and associated loss

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[49] Dozier, A.Q., Arabi, M., Wostoupal, B.C., Goemans, C.G., and Manning, D.T.

of agricultural production, policy and institutional changes to water rights appropriation and acquisition are being considered (Dozier et al. n.d.; Pritchett et al. 2008). Although improving agricultural profitability and viability of rural communities through continued crop production is possible, this cannot be achieved without devaluing water owned by farmers or diminishing a historically reliable water supply (Dozier et al. n.d.). Without understanding socioeconomic feedbacks and trade-offs of water supply and demand options ("strategies"), management decisions may end up worsening the very conditions they attempted to improve (Ward and Pulido-Velazquez 2008). Conversations in literature and policy settings in semi-arid regions are formulated around developing new water supply, advancing and incentivizing water use efficiency, adding flexibility to water allocation within the currently rigid system of Western water law, and restricting urban growth. No consensus has been agreed upon by all stakeholders because of conflicting objectives and heterogeneous impacts of solutions in space and time (e.g., farmers have historically opposed urban water reuse because of reduction of river recharge).

Some argue that much agricultural production can be sustained in semi-arid regions of the world even in the midst of population growth, speculating that conservation and other "soft paths" to meeting water supply are the means to go forward (Gleick 1998, 2003; Gleick et al. 1995). However, few have numerically tested outcomes of various solutions, costs and benefits. Utilizing hydrologic models with economic objectives, the value of some solutions has been documented, such as i) water markets improve total social benefit (Ward et al. 2006), ii) the use of incentive-based pricing mechanisms can reduce urban water consumption (Ward and Pulido-Velazquez 2009), iii) switching to more efficient irrigation technology can use more water than inefficient irrigation because of lowered groundwater recharge (Ward and Pulido-Velazquez 2008). Most simulation studies implement an overarching, aggregate optimization (i.e., using a single objective function) assuming that a decision-maker can optimize consumed water by every individual actor within the system. Britz et al. (2013) applied advancements in numerical optimization techniques to a synthesized water network solving multiple optimization problems with equilibrium constraints (MOPEC) where agents in the system act independently of others. Utilizing MOPEC has helped to identify impacts of transaction costs and institutional agreements on water rights markets and allocation (Bauman et al. 2015; Dozier et al. n.d.; Kuhn et al. 2016). In addition to simulating impacts of select solutions on regional water use and economic benefit, there is a need to explore various solutions for optimality across varying stakeholder objectives.

Water resource planning requires multiple levels of decision-making across institutions from the regional context to conservancy districts, to water districts, to cities and irrigation companies, to individual farmers and city residents. Formulated to solve numerically, these are NP-hard multilevel programming problems (Bard 1991). Such techniques have been motivated by Stackelberg game theory since the 1930s (Stackelberg 1952), and have since been developed and applied throughout areas of business, supply chain management, economics, decentralized systems management, electric grid planning and other energy management, transportation, engineering design, safety and accident management, irrigation management, and conjunctive surface water and groundwater management (Anandalingam 1988; Lu et al. 2016; Paudyal and Gupta 1990; Vicente and Calamai 1994; Yu and Haimes 1974). No study known to the authors performs trade-off analysis of basin-wide policy, infrastructural, and technological solutions by solving a multilevel programming problem with integrated characterization of physical, ecological, and socioeconomic processes.

The goal of this study is to develop an integrative, simulation-based optimization framework that supports identification of optimal water management practices and integrates multiobjective, multilevel decision-making with socioeconomic, physical, and ecological processes and feedbacks (Figure 39). In the context of limited water supply for urban and agricultural purposes, the study aims to i) develop a model of a western water rights market and of an overarching governance system that sets regional goals for water supply and demand, ii) identify the extent to which current trends, institutional arrangements and markets will sustain agricultural production, and iii) evaluate the impact of alternative institutional arrangements on the nondominated frontier. To complete these objectives, the following questions are posed and answered systematically:

1. Where would the uninhibited market lead selection of new supply and demand reduction?
2. Which management practices are optimal?
3. What policies act as largest barrier to improved solutions?

The framework integrates spatially diverse municipal and agricultural decision-making within the context of water scarcity, rapid urbanization, and declining agricultural cropland. Benefitting from characterization and integration of physical, ecological, and socioeconomic processes and feedbacks, the framework explores trade-offs between the cost of water, viability of agricultural production, and vulnerability of water supply. Outcomes of the framework lead to better understanding of key technological and institutional barriers to optimal allocation of a stressed water supply, and address critical knowledge gaps that could otherwise result in unforeseen negative consequences. The framework also overcomes computational barriers by utilizing a novel approach to simulation-based optimization with tens to hundreds of constraints and variables, equilibrium constraints, and independently optimized objective functions. The approach is embodied in a software tool called "Computational Semi-Arid Water Sustainability" or CSaws (Figure 39).[50]

A case study illustrates the application and use of the framework within a highly over-allocated river basin, the South Platte River Basin (SPRB), characterized by a rapidly growing urban population and declining agricultural cropland since the 1960s (Section 4.1). Management solutions

[50] Available at https://bitbucket.org/csuwater/saws or upon request by the authors

selected and discussed in this paper aim to sustain projected 2050 levels of agricultural production and profitability at lowest cost to municipalities.

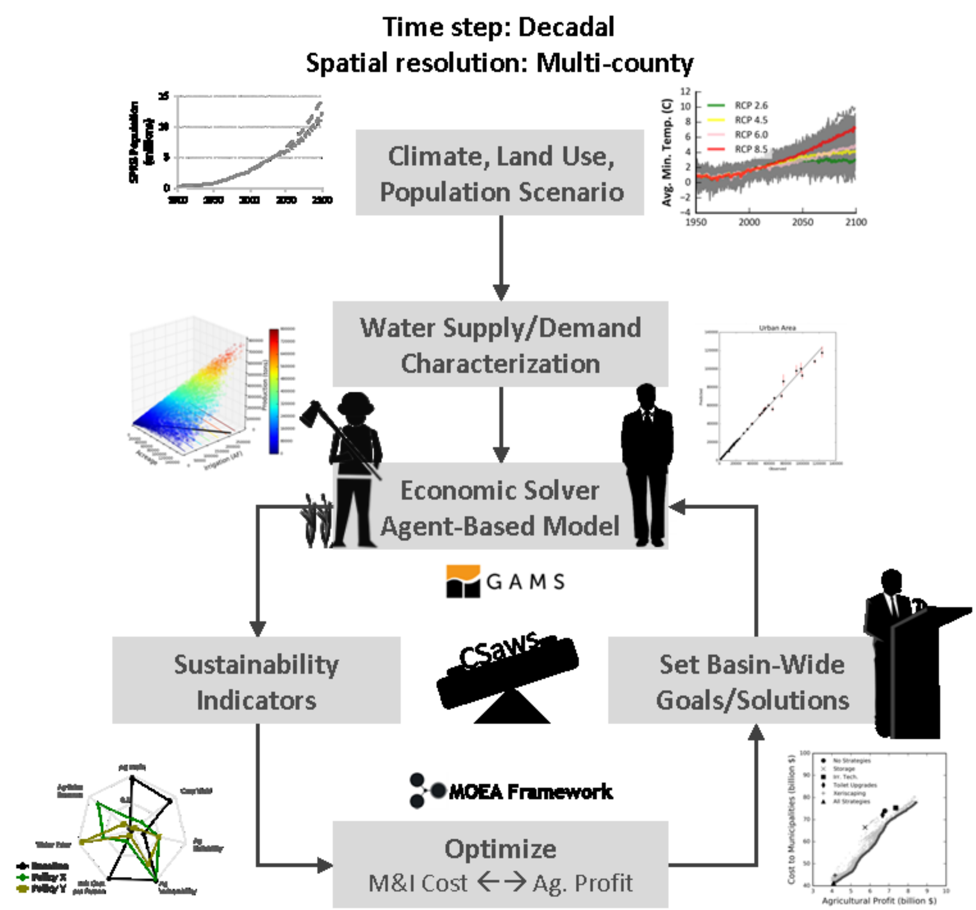


Figure 39: Simulation-based optimization framework and diagram of CSaws workflow

7.2 Methods

Climate, population, and land-use data drives the characterization of water supply and demand for each agricultural and municipal agent in the partial equilibrium economic model to represent projections of the water rights market in the SPRB. Projected outcomes (from 1980 to 2050) based on sustainability indicators were evaluated and optimized across the entire basin for each decade. Demand-side management strategies such as urban and agricultural water conservation were compared against supply-side management strategies. Only the largest water-saving features were considered: efficient toilet retrofits (urban indoor), xeriscaping (urban outdoor), and efficient irrigation technology upgrades (agricultural). Populations in semi-arid regions of the U.S. rely heavily on water supply reservoirs to supplement demands in periods of low natural stream supply. Many planned developments of storage reservoirs currently exist, regardless of how politically controversial. The supply-side management option considered in this paper is therefore the construction and development of storage reservoirs.

Indicators of agricultural sustainability were selected to be consistent with previous studies (Dozier et al. n.d.). A trade-off exists between the cost of water acquisition for municipalities and total agricultural profit including sales of water rights. Reduction in the cost to municipalities means a reduction to water sale revenue for agricultural producers, which is of concern for planners in the SPRB (Colorado Water Conservation Board 2016). Thus, two indicators were selected for this analysis: cost of municipal water acquisition (including legal and infrastructure costs), and total agricultural profit (including water right sale revenue).

A multiobjective optimization problem was utilized to represent policy makers and regional planners attempting to determine an optimal goal or target for water conservation or storage adoption. The policy maker sets a mandated regional level of conservation or level of storage adoption, but agents within subregions individually optimize the extent to which they participate. Although enforcing adoption of any particular strategy is unlikely in the U.S. and is not necessarily condoned by this study, the solution setup identifies strategies that would most benefit the river basin as a whole, and stimulates discussion about what strategies to promote from a regional-scale planning perspective. It should be noted that while basin-wide strategies can be optimized, individual benefits may be inequitable. Equitability was not investigated in this study, but it could be incorporated into the framework as another indicator (i.e., objective in the multiobjective optimization).

The solution methodology is an extension to the approach used by Britz et al. (2013) to solve Multiple Optimization Problems with Equilibrium Constraints (MOPEC). The partial equilibrium model of the water rights market solves a MOPEC problem to simulate effects of policies on the agents trading water rights (Dozier et al. n.d.). Then, an overarching multiobjective optimization algorithm (Section 7.2.4) controls basin-wide adoption of strategy portfolios (a system-wide constraint for all agents to attain collectively), while allowing agents to select buy-in of strategies individually. The problem thus characterizes a hierarchical system of governance and water management by utilizing a hierarchical, or multilevel, optimization approach (Anandalingam 1988; Vicente and Calamai 1994), or more specifically, a bi-level multi-objective (BLMO) approach (Lu et al. 2016). Mathematical representation of actors ("agents") in the SPRB is provided in the following subsection, which also includes parameterization of newly added parameters since the original simulation model development and parameterization (Dozier et al. n.d.).

7.2.1 Mathematical characterization of the water rights market model

The SPRB region is split up into 5 subregions "North", "North Central", "Central", "South Metro", and "East" (Section 4.1). Four crop producers and one municipality compete for water within each subregion, and have the option for purchasing water from another subregion at a high transaction cost. In addition to the subregions, another large pool of trans-basin water in the SPRB comes from the west slope of the U.S. continental divide via the Colorado Big Thompson (CBT) project. Trans-basin water incurs no legal costs, but still requires infrastructure development for conveyance, storage, and treatment.

Municipalities drive the model toward purchases and trade by requiring land developers to purchase raw water (raw water requirements, RWR) according to the following relationship adapted from Dozier et al. (n.d.):

$$\min_{B_{m,r,d},X^{\text{stor}}_{m,r,d},X^{\text{tlt}}_{m,r},X^{\text{xeri}}_{m,r}} C_{m,r} = \sum_{d\in D}\left[P^{\text{water}}_{d}\cdot B_{m,r,d} + c^{\text{tran}}_{r,d}\cdot B_{m,r,d} + \frac{b^{\text{tran}}}{\sum_{p,r} u^{\text{endow}}_{p,r,d}}\cdot B^{2}_{m,r,d}\cdot [d=r] + \left(c^{\text{stor}}_{d} + c^{\text{tran}}_{r,d}\right)\cdot X^{\text{stor}}_{m,r,d}\right] + \left(c^{\text{tlt}}\cdot X^{\text{tlt}}_{m,r}\right) + \left(c^{\text{xeri}}_{m,r}\cdot X^{\text{xeri}}_{m,r}\right) \tag{60}$$

$$B_{m,r,d}, X^{\text{stor}}_{m,r,d}, X^{\text{tlt}}_{m,r}, X^{\text{xeri}}_{m,r} \geq 0$$

where $C_{m,r}$ is the total cost to municipality m in region r. Decision variables for municipalities include i) the amount of water rights to buy from each pool d of water rights $B_{m,r,d}$, ii) the amount of firm yield (nearly 100% reliable water supply) to purchase from storage reservoirs $X^{\text{stor}}_{m,r,d}$, iii) the fraction of toilet water to save from existing toilets by converting to more efficient (low-flow) toilets $X^{\text{tlt}}_{m,r}$, and iv) the fraction of irrigation water to save by xeriscaping lawns ($X^{\text{xeri}}_{m,r}$). The set of all pools is D.

Purchased water is bought at a price of water P^{water}_{d} (\$/AF) and incurs transaction cost $c^{\text{tran}}_{r,d}$ (\$/AF) when an agent in region r purchases water from pool d. To account for spatial heterogeneity within a subregion, a quadratic term is added with a calibrated coefficient b^{tran}, which is scaled by the total water right endowment of agricultural producers $u^{\text{endow}}_{p,r,d}$ so that the cost of exploring water rights within the same region increases as more water rights in the region are purchased. Parameterization and calibration procedures for transactions costs $c^{\text{tran}}_{r,d}$ and b^{tran} are described in Section 4.3. The expression $[d=r]$ utilizes Iverson brackets to evaluate to 1 when the expression is true ($d=r$), and zero when false ($d \neq r$), thus introducing the quadratic term only when the municipality is buying from within its own subregion. Costs are also introduced for purchasing storage water c^{stor}_{d}, retrofitting efficient toilets c^{tlt}, and xeriscaping land $c^{\text{xeri}}_{m,r}$.

Land developers must buy at least q^{rwr}_{r} acre-feet of firm water ($k^{\text{rel}}_{d}\cdot B_{m,r,d} + X^{\text{stor}}_{m,r,d}$) per acre of developed land $a^{\text{devel}}_{m,r,t}$ for municipality m and region r when planning for future decade t:

$$\sum_{d\in D}\left[u_{m,r,d}^{\text{endow}} + k_d^{\text{rel}} \cdot B_{m,r,d} + X_{m,r,d}^{\text{stor}}\right] - \sum_{d\in D}\left(u_{m,r,d}^{\text{endow}}\right) \cdot \left(1 - k^{\text{tlt}} \cdot X_{m,r}^{\text{tlt}}\right) \cdot \left(1 - k_{m,r}^{\text{irr}} \cdot X_{m,r}^{\text{xeri}}\right) - q_r^{\text{rwr}} \cdot a_{m,r,t}^{\text{devel}} \geq 0 \tag{61}$$

where k_d^{rel} is an estimated reliability of water supply from pool d. Endowed (historical) ownership of water $u_{m,r,d}$ for municipality m in region r from pool d can be reduced by a fraction of total water use from toilets k^{tlt} and from lawn irrigation $k_{m,r}^{\text{irr}}$. Other municipal constraints and characterizations are the same as in Dozier et al. (n.d.).

Agricultural producers maximize expected net present value (NPV) of profit both sale of produced crops and water rights. The objective function for agricultural producer p in subregion r is characterized by the following adaption of Dozier et al. (n.d.):

$$\begin{aligned} \max_{\mathrm{V_{p,r}},\mathrm{A_{p,r}},S_{p,r,d},B_{p,r,d},X_{p,r,d}^{\text{stor}},\eta_{p,r}^{\text{a}}} \pi_{p,r} = \\ k^{\text{NPV}}\left[p^{\text{crop}} \cdot f_{p,r}\left(V_{p,r}, A_{p,r}\right) - C_{p,r}^{\text{water}}\left(V_{p,r}, \eta_{p,r}^{\text{a}}\right) - C_{p,r}^{\text{land}}\left(A_{p,r}\right) - \left(c_{p,r}^{\text{eff}} - b_{p,r}^{\text{eff}}\right) \cdot \eta_{p,r}^{\text{a}}\right] \\ + \sum_{d\in D}\left[P_d^{\text{water}} \cdot S_{p,r,d} - P_d^{\text{water}} \cdot B_{p,r,d} + c_{r,d}^{\text{tran}} \cdot B_{p,r,d} + \frac{b_{r,d}^{\text{tran}}}{\sum_{p,r} u_{p,r,d}^{\text{endow}}} \cdot B_{m,r,d}^2 \cdot [d = r]\right] \\ -\left(c_d^{\text{stor}} + c_{r,d}^{\text{tran}}\right) \cdot X_{p,r,d}^{\text{stor}} \end{aligned} \tag{62}$$

$$\mathrm{V_{p,r}}, \mathrm{A_{p,r}}, S_{p,r,d}, B_{p,r,d}, X_{p,r,d}^{\text{stor}}, \eta_{p,r}^{\text{a}}$$

Producer profit $\pi_{p,r}$ is scaled to net present value with k^{NPV} assuming a 40-year planning period and a 3% discount rate. Producers choose the consumptively used volume of water to irrigate $V_{p,r}$, the amount of acres to plant $A_{p,r}$, the total water endowment to sell $S_{p,r,d}$ and buy $B_{p,r,d}$, the amount of firm yield from reservoir storage to purchase $X_{p,r,d}^{\text{stor}}$, and the fraction of application efficiency improvements due to adoption of more efficient irrigation technology $\eta_{p,r}^{a}$. Crops are sold for an exogenously determined price that grows over time p^{crop} (\$/ton), while production costs $C_{p,r}^{\text{water}}\left(V_{p,r}, A_{p,r}\right)$ (\$/year) for water usage and $C_{p,r}^{\text{land}}\left(A_{p,r}\right)$ (\$/year) for land usage. Prices and transactions costs of water rights transfers and firm yield from storage are the same as those for municipalities. Application efficiency improvements cost $c_{p,r}^{\text{eff}} - b_{p,r}^{\text{eff}}$ where $c_{p,r}^{\text{eff}}$ is the initial estimate on the cost of efficient irrigation technology and $b_{p,r}^{\text{eff}}$ is a calibrated cost to adjust for true costs.

Crop production functions $f_{p,r}(V_{p,r}, A_{p,r})$ (tons/year) are the same as those from Dozier et al. (n.d.), while production costs and the supply constraint changed slightly.

$$C_{p,r}^{\text{water}}(V_{p,r}, \eta_{p,r}^{\text{a}}) = (c_{p,r}^{\text{water}} - b_{p,r}^{\text{water}}) \cdot V_{p,r} \cdot (\hat{\eta}_r^{\text{a}} - \eta_{p,r}^{\text{a}}) \tag{63}$$

$$C_{p,r}^{\text{land}}(A_{p,r}) = (c_{p,r}^{\text{land}} - b_{p,r}^{\text{land}}) \cdot A_{p,r} \tag{64}$$

$$\sum_{d \in D} (u_{p,r,d}^{\text{endow}} + B_{p,r,d} - S_{p,r,d} + X_{p,r,d}^{\text{stor}}) - \frac{V_{p,r}}{\eta_r^{\text{c}}} \cdot (\hat{\eta}_r^{\text{a}} - \eta_{p,r}^{\text{a}}) \geq 0 \tag{65}$$

where $c_{p,r}^{\text{water}} - b_{p,r}^{water}$ and $c_{p,r}^{\text{land}} - b_{p,r}^{\text{land}}$ represent costs of using applied amount of water $V_{p,r} \cdot (\hat{\eta}_r^{a} - \eta_{p,r}^{a})$ (the amount of water diverted through a farmer's headgate after conveyance) and of farming the amount of planted acres $A_{p,r}$. The total amount of water diverted from the stream (before conveyance) $\frac{V_{p,r}}{\eta_r^{c}} \cdot (\hat{\eta}_r^{a} - \eta_{p,r}^{a})$ must always be less than the amount owned after the market clears $\sum_{d \in D} u_{p,r,d}^{\text{endow}} + B_{p,r,d} - S_{p,r,d} + X_{p,r,d}^{\text{stor}}$ as asserted in (65). Other individual producer constraints, market-clearing constraints, and limitations on municipal ownership are the same as in Dozier et al. (n.d.).

7.2.2 Policy trade-off characterization and solution methodology

Another actor in the MOPEC setup characterizes a policy-maker that creates conservation and storage mandates for analysis of policy trade-offs. The policy-maker optimizes trade-offs between total agricultural profit and municipal water acquisition cost (a two-dimensional multiobjective objective function):

$$\min_{X_d^{\text{stor}}, \eta^{\text{a}}, X^{\text{tlt}}, X^{\text{xeri}}} \left(-\sum_{p,r} \pi_{p,r}, \sum_{m,r} C_{m,r} \right) \tag{66}$$

$$0 \leq X_d^{\text{stor}} \leq X_d^{\text{stor,max}}$$

$$0 \leq \eta^{\mathrm{a}} \leq \eta^{\mathrm{a,max}}$$

$$0 \leq X^{\mathrm{tlt}} \leq X^{\mathrm{tlt,max}}$$

$$0 \leq X^{\mathrm{xeri}} \leq X^{\mathrm{xeri,max}}$$

where mandated amounts of storage X_d^{stor} (AF/year), agricultural application efficiency η^{a}, fraction of toilet water saved X^{tlt}, and fraction of urban irrigation water saved by xeriscaping X^{xeri} are decision variables for the policy-maker. Policy-maker decision variables are constrained by estimated maximum supply or savings from each strategy $X_d^{\mathrm{stor,max}}$, $\eta^{\mathrm{a,max}}$, $X^{\mathrm{tlt,max}}$, and $X^{\mathrm{xeri,max}}$, respectively.

Overarching policy goals are set at the level of the entire SPRB, and agents optimize individual amount of strategy adoption such that:

$$\sum_{i,r} X_{i,r,d}^{\mathrm{stor}} = X_d^{\mathrm{stor}} \tag{67}$$

$$\sum_{p,r} \eta_{p,r}^{\mathrm{a}} = \eta_{p,r}^{a} \tag{68}$$

$$\sum_{m,r} X_{m,r}^{\mathrm{tlt}} = X^{\mathrm{tlt}} \tag{69}$$

$$\sum_{m,r} X_{m,r}^{\mathrm{xeri}} = X^{\mathrm{xeri}} \tag{70}$$

Following these constraints, basin-wide storage supply adoption, technology improvements, and consumption reduction follow the same pattern: sum of adopted improvements basin-wide must be equal to a value determined by the policy maker.

7.2.3 Model parameterization

In addition to parameterization of the model as performed in Dozier et al. (n.d.), parameters used in representing supply and demand management strategies were estimated from either historical observations or modeled processes. Dozier et al. (n.d.) describes the calibration procedures for the model, which remained the same other than the additional calibration parameter $b_{p,r}^{\text{eff}}$ that represents true additional benefits (when positive) or costs (when negative) of utilizing the historically observed application efficiency factor $\hat{\eta}_{p,r}^{a}$ (Table 29).

Costs to switch to more efficient irrigation technology $c_{p,r}^{\text{eff}}$ for agricultural producers were estimated using modeled changes to demand with various sprinkler upgrades to all croplands irrigated by flood or furrow. Irrigation system purchase and installation costs for five sprinkler systems were obtained from Scherer (2015). The five sprinkler systems considered were center pivot, center pivot with attachment, linear move, traveling big gun, and wheel roll, but since the traveling big gun and wheel roll systems had a lower efficiency and were more expensive than other options, these were not considered assuming that farmers will only purchase the more cost-effective systems. Costs were transformed from costs per acre of farmed cropland to costs per fractional irrigation efficiency improvement using DayCent estimated gross irrigation requirements (Section 4.3.1). Final estimates for cost of efficient irrigation technology $c_{p,r}^{\text{eff}}$ and maximum efficiency factor improvement $\eta_{p,r}^{\text{a,max}}$ (the sum of which equal $\eta^{a,\text{max}}$) found in Table 29 came from a simple linear regression performed on the total cost of upgrades against the fractional amount of water saved for each producer p and region r.

Table 29: Estimated application efficiency factors $\hat{\eta}^{a}_{p,r}$ for 2050, maximum potential irrigation efficiency improvements $\eta^{a,\max}_{p,r}$, costs of efficiencies improvements $c^{\mathrm{eff}}_{p,r}$ (\$/fractional efficiency improvement) and calibrated additional true benefits $b^{\mathrm{eff}}_{p,r}$ (\$/fractional efficiency improvement)

Crop	Subregion	$\hat{\eta}^{a}_{p,r}$	$\eta^{a,\max}_{p,r}$	$c^{\mathrm{eff}}_{p,r}$	$b^{\mathrm{eff}}_{p,r}$
Corn	North	1.65	0.54	14,500,000	4,500,000
	North Central	1.89	0.51	7,590,000	(6,900,000)
	Central	2.03	0.62	1,820,000	(1,700,000)
	East	2.16	0.69	5,950,000	(2,100,000)
Sugar Beets	North	1.65	0.53	4,460,000	943,000
	North Central	1.83	0.53	517,000	(670,000)
	Central	2.08	0.67	329,000	(370,000)
	East	2.09	0.66	733,000	(360,000)
Winter Wheat	North	1.65	0.55	1,540,000	1,210,000
	North Central	1.86	0.49	130,000	78,400
	Central	2.05	0.66	667,000	421,000
	South Metro	1.67	0.00	667,000	629,000
	East	1.96	0.61	237,000	171,000
Alfalfa	North	1.65	0.54	19,900,000	12,400,000
	North Central	1.67	0.50	4,880,000	(990,000)
	Central	1.94	0.61	4,860,000	(420,000)
	South Metro	1.98	0.66	4,940,000	1,730,000
	East	1.76	0.57	4,480,000	(230,000)

Municipal water conservation parameters were estimated from the Integrated Urban Water Management model (IUWM), which was calibrated to water use data by block group in the City of Fort Collins. IUWM simulations were from 1981 to 2014 using PRISM weather data (PRISM Climate Group 2004), National Land Cover Database, NLCD (Homer et al. 2015), and U.S. census population data. Section 4.4 further describes the IUWM model and equations governing the estimates of urban water use and reuse. The fraction of toilet water when compared to total CII and residential water use was estimated to be $k^{\mathrm{tlt}} = 0.043$. Lawn irrigation is estimated separately for each municipality m in region r to be between 47% of total water use for highly dense municipalities and 94% for rural municipalities.

Installation costs and 40 years of additional operations and maintenance cost (discounted at 3%) for xeriscaping a lawn amounts to about \$0.67 per sq. foot more than maintaining turf (in 1980 dollars). Existing rebates for turf conversion are close to this value: \$0.59 per sq. foot (\$2 per sq. foot in 2016 dollars) by both Las Vegas Valley Water District (2016) and California Division of Water Resources (2015). Average residential (single family or townhouse) irrigated lawn size is about 5,400 sq. feet according to Medina and Gumper (2004). The number of households (as estimated from a statistical model of households as a function of county population as described in Section 4.3) in 1980 multiplied by the average lawn size gives a total size of about 4.3 billion square feet of total irrigated urban lawns. After accounting for inflation, the cost to convert all lawns would be about $2.6 billion across the entire SPRB, as $c_{m,r}^{\text{xeri}}$ ranges from $68 million to $2.0 billion between the five subregions. The maximum amount that can be saved from xeriscaping $X_{m,r}^{\text{xeri,max}}$ is estimated from Medina and Gumper (2004) to be about 59% of 1980 water use, slightly lower than the 76% value from Southern Nevada given by Sovocool et al. (2006).

Costs of upgrading to efficient toilets c^{tlt} and the maximum fraction of water savings $X_{m,r}^{\text{tlt,max}}$ were estimated from a database of 185 homes in two cities within the SPRB (Denver and Fort Collins) that were both heavily monitored households for water use by appliance and had survey results from the same households on the number of toilets, flush volume of toilets, and household size (DeOreo et al. 2016). An average cost per household of $375 ($111 in 1980 dollars) for retrofitting a toilet (HomeAdvisor 2016) was multiplied by the number of conventional (>3.5 gallons per flush) toilets in each household (assumed to be all toilets in 1980) to determine average cost of home upgrade and scaled by consumer price index to account for inflation back to 1980 dollars. So, the cost of efficient toilet upgrades $c^{\text{tlt}} = \$647$ per fraction of volume of water saved. A target for total toilet water use by each household was determined by evaluating average water use (in gallons per household per day) for very efficient homes scaled to account for household size. Conserved toilet water is this target toilet water use subtracted from average historical water use of all inefficient households (assumed to be the average household in 1980). Average potential water savings per home is thus estimated to be about $X^{\text{tlt,max}} = 35\%$ of toilet water use, a value lower than was predicted by Vickers (1990) because the average household flushes low flush toilets 20% more often than flushing conventional toilets.

Maximum firm yield from adopted storage that can be adopted within pool $X_d^{\text{stor,max}}$ and storage costs c_d^{stor} were estimated assuming construction of four major reservoirs currently being considered in the SPRB as outlined in Table 30. The North subregion includes only the Halligan Reservoir Expansion project. Gross Reservoir expansion benefits the largely municipal "Central" subregion. CBT reservoir projects include the Windy Gap Firming Project and Northern Integrated Supply Project that would serve agricultural and municipal water users throughout the North, North Central, and East subregions.

Table 30: Parameterization of modeled storage reservoirs[51]

Region	Planned Reservoir Project	Capacity	Annual Yield	Total Cost	c_d^{stor} ($/AF)
North	Halligan Reservoir Expansion	8,125	7,000	30,000,000	$ 4,300
Central	Gross Reservoir Expansion (Moffat)	77,000	18,000	380,000,000	$ 21,000
CBT*	Windy Gap Firming Project	90,000	26,000	223,000,000	$ 12,000
	Northern Integrated Supply Project	215,600	40,000	600,000,000	

* Value determined from linear regression of cumulative costs of reservoirs against cumulative yields

7.2.4 Optimization methodology

An adapted version of the MOEA Framework (Hadka 2017), an open-source Java-based framework for developing and utilizing multiobjective evolutionary algorithms (MOEA), was utilized for performing multiobjective optimization. The epsilon-dominance nondominated sorted genetic algorithm-II (NSGAII) was selected for exploring the trade-off because of its robust solution characteristics (Deb et al. 2000; Kollat and Reed 2005). Adaptations to the MOEA Framework included generalized initialization routines for incorporating solutions with many zero-valued

[51] Data obtained from http://www.northernwater.org/WaterProjects/ProposedProjects.aspx, http://www.northernwater.org/docs/NISP/NISPHome/2015_NISP_Fact_Sheet.pdf, http://www.northernwater.org/docs/News_Releases/Reclamation_%20release_12-19-14.pdf, http://cdm16021.contentdm.oclc.org/cdm/ref/collection/p16021coll7/id/10, http://www.fcgov.com/utilities/what-we-do/water/halligan-reservoir-enlargement-project, and https://grossreservoir.org/about-the-project/dollars-and-cents/

variables, and distributed (across multiple machines) objective function evaluation using Hazelcast (https://hazelcast.com/). A custom objective function provides policy-maker variable realizations to GAMS through input files, runs the GAMS policy model as adapted from Dozier et al. (n.d.), and extracts net present value of agricultural profit and total municipal cost of water acquisition.

7.3 Results

Strategies to mitigate the decline of agricultural production in semi-arid regions are investigated based on both market-driven selection of technology and Pareto optimal technology selection. Xeriscaping and irrigation technology are the most cost-effective technologies, without which results show significant losses to both municipalities and agricultural producers. Although all strategies are an improvement to baseline conditions, policy changes reveal the main driver for purchases, raw water requirements for land developers, has the largest effect on optimal solutions and generation of most nondominated strategies. Multiobjective optimization in this study reveals benefits associated with each individual strategy. Individual research questions posed by this study are answered systematically below.

7.3.1 Where would the uninhibited market lead selection of new supply and demand reduction?

Innovation, technology improvements, and water savings are already occurring in both urban and agricultural sectors, but likely not at optimal levels. Market-driven adoption of technologies leads to a corner solution that is also a nondominated solution: the solution that minimizes cost to municipalities ("All Strategies" in Figure 40). Reasons for this might be because municipalities have a perfectly inelastic demand by assumption in the model, meaning that municipalities will pay any price to meet a demand (Section 4.2.1).

Table 31 reveals the mix of selected variables for market-driven adoption of individual strategies. All strategies are selected to their full extent (because strategy costs are linear) when selected by a particular agent, and were beneficial for improving outcomes. Storage and irrigation technology were not selected by all municipalities and producers while municipalities unanimously select toilet and xeriscaping practices. The highly dense municipalities in the Central subregion utilize all storage from the Central and North subregions, but no CBT storage is adopted because municipalities in the Central subregion are disallowed from purchasing it. Only alfalfa producers in the North Central, Central, and South Metro regions do not adopt irrigation technology; all other producers adopt the full amount of irrigation technology possible.

Table 31: Market-driven adoption level of each strategy under the baseline institution

Strategy	Adoption
Storage	34%
Irrigation Technology	82%
Toilet	100%
Xeriscaping	100%

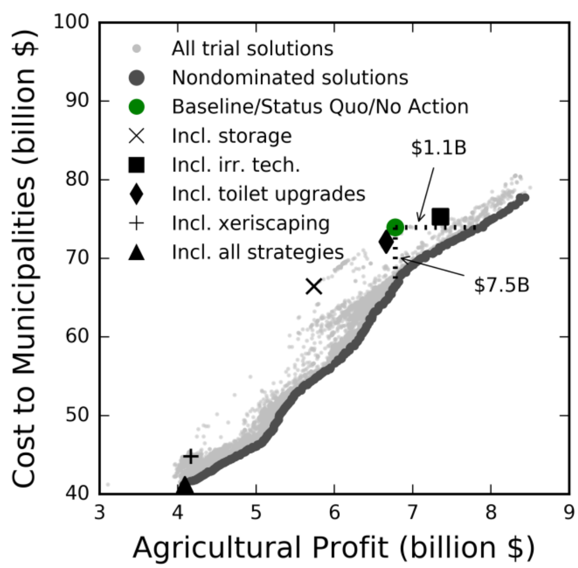


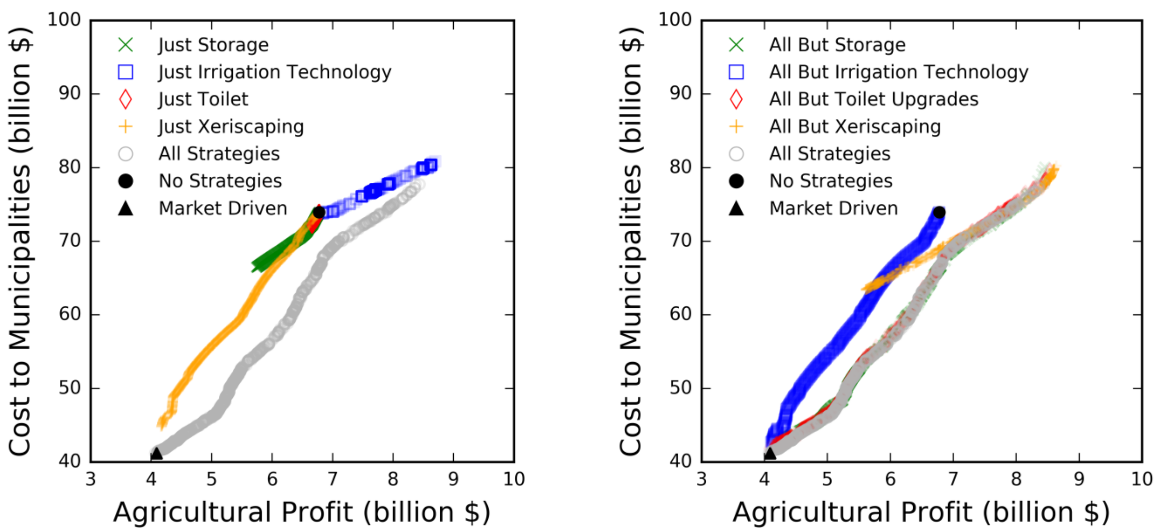
Figure 40: Market-driven solutions with solutions included individually or all together compared with nondominated solutions and all optimization trial solutions. The two dotted lines distinguish the distance between the baseline (i.e., status quo or no action) solution in 2050 and the Pareto optimal front.

Irrigation technology adoption primarily benefits agriculture, while additional storage, efficient toilet retrofits, and xeriscaping primarily benefit municipalities. Xeriscaping drops the cost of water acquisition for municipalities significantly, and is nearly equivalent to the market-driven solution that includes all other strategies. Losses and gains to total agricultural profit are primarily due to loss of sales revenue, because the value of selling water rights is much higher than continuing in production. As agricultural production and profit from production increases, total agricultural profit decreases, except when adopting irrigation technology.

Without policy intervention, market-driven solutions for individual strategies are nondominated by other individual market-driven strategies. However, with policy mandates, optimal solutions at the basin-level can improve both total agricultural profit by $1.1 billion and cost of water for municipalities by $7.5 billion (Figure 40). Average slope of the Pareto optimal front was determined by simple linear regression to be about 9.6 (ratio of an increase in municipal cost to an increase in agricultural profit). That is, policies that increase total agricultural profit by $1 billion will incur a cost of *at least* $9.6 billion for municipalities, perhaps more if policies are suboptimally informed as is likely the case due to uncertainties in data and models. So, for each additional billion dollars of agricultural profit, each water utility rate payer will pay $1,500-3,000 total between 2010 to 2050, or about $6-12 per month assuming an interest rate of 4% (the range in cost estimates is determined by spreading the cost to either the total number of rate payers in 2010 or those in 2050).

7.3.2 Which management practices are optimal?

Multiobjective optimization was performed on each strategy individually (Figure 41a) and by removing one strategy at a time (Figure 41b). Each revealed something unique about the solutions. Irrigation technology improvements always benefit agricultural producers while urban conservation benefits cost of water acquisition for municipalities by reducing water requirements. Storage reservoirs benefit municipalities and decrease agricultural revenue from lowered water rights sales. Xeriscaping drastically reduces municipal water acquisition cost, while irrigation technology can improve agricultural profitability regardless of how much urban conservation is selected.



a) Optimize each strategy individually **b) Optimize by removing each strategy**

Figure 41: Pareto optimal management practices of different strategies compared with a solution that considers no conservation or new supply development ("No Strategies") and a solution that allows agents to independently select strategies ("Market Driven").

When removing storage and toilet adoption policies, near-optimal solutions can still be achieved (Figure 41b), highlighting the key strategies to support: xeriscaping and irrigation technology. For any level of urban conservation or municipal storage adoption, flood irrigators can improve profitability by adopting more efficient irrigation technology. To benefit agricultural profitability, which is one of the primary goals of "Colorado's Water Plan" (Colorado Water Conservation Board 2016), policies that incentivize irrigation technology without detracting from the value of the agricultural water right will be key to help agriculture. Although new storage and more efficient toilets will improve costs for water utility rate payers, outdoor reductions to water use such as xeriscaping can much more cost-effectively reduce costs. Hidden costs to xeriscaping such as personal landscaping preferences are not incorporated in this analysis.

Figure 42 displays the extent to which each policy variable was adopted along the Pareto optimal front. Large squares mean more of the strategy was adopted while smaller squares mean less of the strategy was adopted. Optimal levels of xeriscaping clearly increase as municipal costs decrease, while irrigation technology is adopted regardless of location on the Pareto optimal front. Optimal or near-optimal solutions can be achieved at a variety of levels of adoption of efficient toilet retrofits and Central storage, while storage in the North subregion is typically always optimal to adopt, and the full amount of CBT storage is typically not optimal to adopt (at least when using a 40 year planning period).

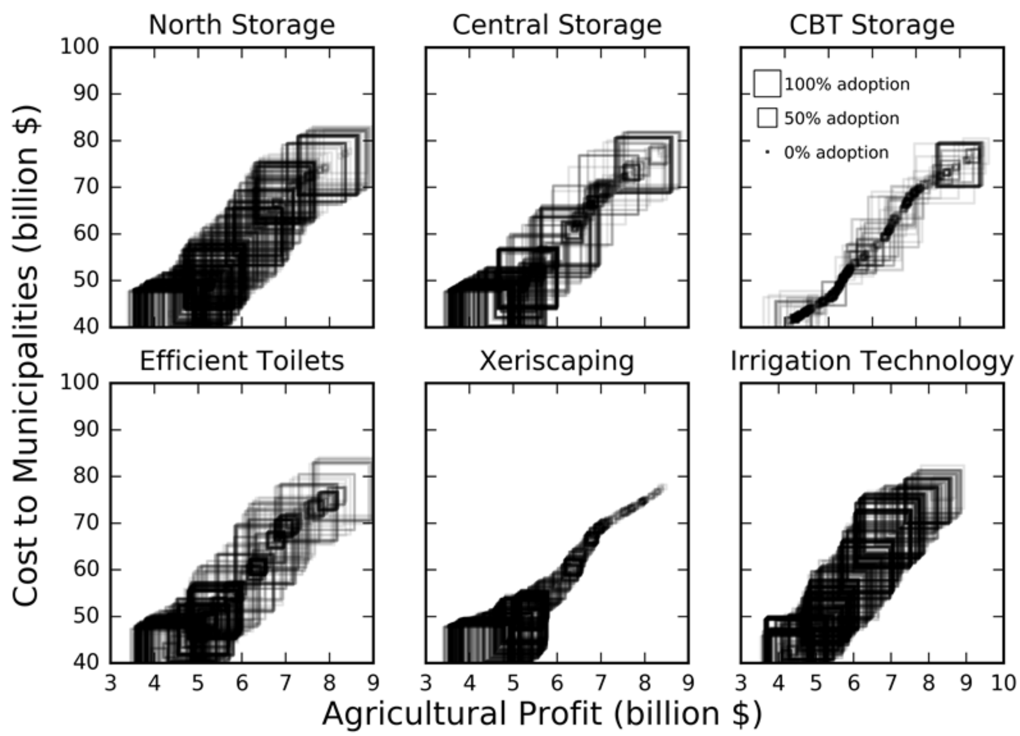


Figure 42: Magnitude of strategy adoption within nondominated solutions (size changes with magnitude of strategy adoption). Big squares represent near 100% strategy adoption while small squares are near 0% strategy adoption

7.3.3 What policies act as largest barriers to improved solutions?

Institutional agreements represent the contexts, boundaries, and rules within which agents make decisions. The same institutional and policy changes (A-G) considered by Dozier et al. (n.d.)

are evaluated here in the context of optimally defined policy mandates. If institutional agreements and policies change, optimal decisions may change. Some policy changes surprisingly did not change the Pareto optimal front much at all (Figure 43). Metrics to measure the distance, distribution, and extent of the generated nondominated sets of solutions generally showed that policies made an improvement above the baseline policy. The Lebesgue hypervolume between a reference point and the nondominated solution sets combines all three measures (distance, distribution, and extent) into one, but is sensitive to where the reference point is set (Ahmadi et al. 2013; Zitzler et al. 2000). Therefore, it was included with a couple other metrics: i) the percent of solutions dominating any baseline solution, and ii) the average distance from baseline to the solutions that dominate at least one baseline solution. Displayed results in Figure 43 show the Lebesgue hypervolume and average distance metrics as percentages of the maximum value. Higher values of all three metrics represent better solutions. No institutional agreement or policy change was found to dominate all other institutions because of inherent trade-offs associated with each change, indicating that combinations of policy changes are better than individual policy changes.

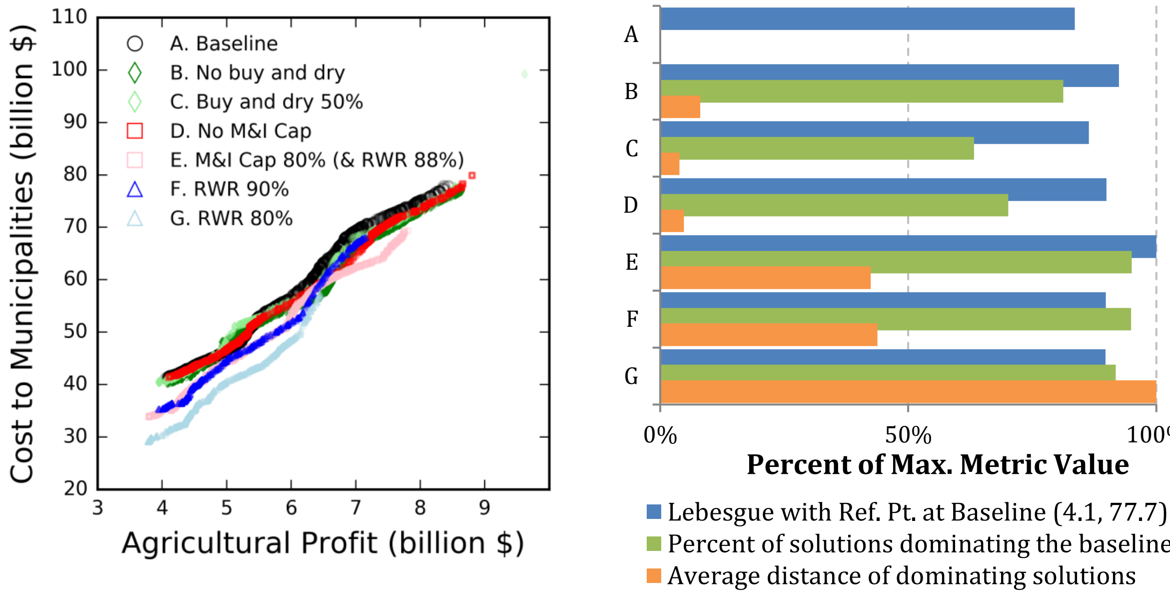


Figure 43: Impacts of policy changes on nondominated solution sets (left) and three different metrics of nondominated performance as compared to the baseline policy (right). Policies A-G are the same as Dozier et al. (n.d.).

Western court systems often require permanent fallowing of agricultural land after a municipality purchases the water and changes its type and location use. This is called "buy and dry." It is a policy indirectly derived from the prior appropriation doctrine that governs water use and transfer in much of the Western U.S., and is therefore more likely to be amended than the prior appropriation doctrine itself. It is a trend that causes thousands of acres each year to be permanently fallowed as thirsty cities buy up water. Market-driven solutions with buy and dry policies removed completely keep a significantly larger number of acres in production, but total agricultural profit remains less affected (Dozier et al. n.d.). Similarly removing buy and dry constraints completely does not affect the Pareto optimal front very much in terms of average distance from the baseline, except at about $6 billion of agricultural profit, when removing buy and dry performs better than all other policies for a small set of special circumstances. A high percentage of solutions under any policy change dominate the baseline. Note that this number is not 100% because some alternative solutions do not dominate any baseline solution, but are not dominated by any baseline solution either.

Raw water requirements (RWR) are water right purchase requirements placed on land developers based on an estimated water usage per acre of newly developed land. Although many cities have just a set value, some cities will account for the density of development and type of units being developed to allow more accurate estimates of RWR. Many cities will also allow developers to pay the city cash in lieu of acquiring water rights themselves. Although conservation measures, goals, restrictions, and features are installed in many new developments, RWR have remained the same or have even increased in expectation of climate change or in the realization of devastating droughts (2002 was the worst drought on record for the SPRB as a whole). Reducing RWR by 20% for new developments (the RWR 80% scenario) can lower water acquisition costs by more than 25% (Figure 43). RWR reductions result in the largest average dominating distance from the baseline and nearly all of the nondominated solution set dominates all other policy changes, highlighting the sensitivity of system-wide benefits to RWR. Institutional and behavioral change from within municipalities would need to take place to be able to realize benefits of lowered RWR. Since RWR applies to new developments only, and not to more expensive retrofits, changes to RWR can occur at very little cost. However, water utilities have understandable reservations to lowering RWR because of both uncertain future water supply and demand, rapidly increasing value of water rights, and a commitment to supply safe and reliable water to their customers.

Limiting municipal ownership of water rights within each subregion of the SPRB to 80% ("M&I Cap 80%") extends the current policy governing CBT water ownership to all other subregions and pools of water. Since by 2050 more than 80% of total water rights will be obtained according to the modeling framework, the RWR for land developers was minimally reduced to 88% of the baseline institution. At lower municipal costs of water acquisition, this scenario performs consistent with RWR 90% scenario, but at higher municipal costs, the scenario dominates all others by protecting most productive and valuable agricultural acreage. Because of this additional extent, limiting M&I ownership of water across all regions resulted in the largest measure of Lebesgue hypervolume, while other metrics remained very similar to its sister policy scenario RWR 90%.

7.4 Limitations and Future Work

Any modeling study has limitations. Primarily these limitations are due to incomplete representation of the system. Atmospheric and subsurface (groundwater) processes and feedbacks are not included in this analysis, but could potentially reveal a trade-off with conservation techniques that the current modeling framework cannot explore: having more water evaporate instead of percolate into groundwater may exacerbate water supply limitations. Other externalities to the water rights market such as livestock production and its dependence on regional alfalfa feed could help to explain sustained alfalfa production.

Sensitivity analysis and global uncertainty analysis could be performed on the model to see how likely conclusions would change with reasonable variation or uncertainty in model parameters. Uncertainty of stakeholder adoption, technological or construction costs, water delivery, and water savings from each of the strategies discussed in this paper should be explored to better characterize expected outcomes.

More efficient multiobjective solution methodologies such as Amalgam (Vrugt et al. 2009; Vrugt and Robinson 2007) could be tested to more robustly investigate global optimality of solutions. The two objectives selected for trade-off analysis could be changed slightly so as to investigate other research questions such as the trade-off between municipal water acquisition costs and agricultural profit from production and sale of crops. More objectives and criteria in the analysis may also help to reveal further trade-offs to more properly inform policies and the public.

When optimizing regional agricultural profit and cost to municipalities, identification of individual winners and losers within the regions or subregions is difficult. “Optimal” policy impacts determined based on regional-scale outcomes may actually lead to largely inequitable solutions. Therefore, refining the spatial resolution of the model could significantly benefit representation of equitability.

The analysis time period restricts application of the model to a planning period 1980-2050. Solutions and strategies for planning beyond 2050 may be different because time period matters when discussing optimality of solutions (Dozier et al. n.d.). Ultimately, if populations continue to increase beyond 2050, agricultural production will decline and may even vanish barring some policy that somehow forbids this outcome. At longer time scales with no foreseen end in population growth, conservation has a limit because people need water to live. Other options will be necessary such as new water supplies or water-limited urban growth in arid to semi-arid regions.

7.5 Conclusions

A goal of decision-makers in many semi-arid regions such as those in the South Platte River Basin is to sustain agricultural production and profitability even as urban populations are rapidly growing and purchasing the limited supply of water rights. Analysis of Pareto-optimal curves for a case study in the SPRB revealed policy trade-offs of supply-side and demand-side solutions strategies: agricultural conservation, urban (indoor and outdoor) conservation, and new storage reservoirs. Given the assumption made in this study that municipalities will pay whatever price to secure a fixed amount of firm water supply for projected population growth (i.e., perfectly inelastic demand), market-driven solutions favor reducing water acquisition costs for municipalities. For the time period of analysis and associated parameterizations, all solution strategies are optimal to use at some level with the exception of CBT storage and irrigation technology for alfalfa producers. Key strategies required for near-optimal policy selection are xeriscaping and irrigation technology upgrades because the cost to water-savings ratio is very small for those strategies.

A strong trade-off exists between agricultural water rights sales revenue and cost to municipalities, while co-benefits exist between municipal cost and agricultural profit from production. To increase total regional agricultural profit by $1 billion, it will cost municipalities about $10 billion or about an additional $6-12 per month for each water rate payer. Although buy and dry policies were originally thought to have the largest impact on optimal solutions, the primary barrier to improved Pareto optimal solutions is raw water purchase requirements that cities have imposed on land developers for many decades and yet (understandably) do not tend to update even as new developments and residents conserve.

8 A "DECISION SUPPORT GAME" FOR ELICITING SOLUTIONS AND PREFERENCES FROM STAKEHOLDERS AND THE PUBLIC

A novel stakeholder-driven optimization methodology is developed for crowdsourcing potential sustainable water management solutions while eliciting stakeholder or public preferences. The preliminary "decision support game" places gamers in a water management role to plan for future water resources with both supply-side and demand-side management strategies. Although the game is still in development, an introduction and literature review motivates its development and a proposed framework, then a brief introduction to the gaming interface as it stands provides a clearer methodology and roadmap for fulfilling its final purpose.

8.1 Introduction

Vulnerability of agricultural water supply in rapidly urbanizing semi-arid regions of the world threatens the economic viability of agricultural communities and associated crop, food, and feed production (Dozier et al. n.d.; Howe and Goemans 2003). Many top-down, policy techniques exist where decision-makers build a representative model of the system and explore management solutions and operations either manually or through use of numerical optimization methodologies (Labadie 2004; Wurbs 1993, 2005; Yeh 1985). Detailed simulation models of water systems often aid decision-making by assessing solution strategies formulated by system managers and simulating the consequences in a very detailed and methodological manner (Rani and Moreira 2009). Simulation benefits from being intuitive and descriptive of the system it represents, but finding good solutions through simulation proves difficult in large, multidimensional, highly constrained decision spaces. Prescriptive optimization techniques efficiently explore these spaces for more beneficial solutions (Hashimoto et al. 1982), but have difficulty fully representing integrated geophysical processes due to limited simulation capability (Reid et al. 2010). To explore decisions optimally while integrating process representation across disciplines, simulation-based optimization techniques have played a key role (Chapter 2).

Top-down, policy-oriented optimization of solution strategies to mitigate agricultural decline can bring benefit to total social value (Chapter 7). However, if agents are left to themselves to find market-driven solutions, outcomes will result in minimized cost to municipalities, a diminished value of agricultural water rights, and degraded environmental resources (Dozier et al. n.d.; Gleick 2003). Although appealing to municipalities, the regional decision-makers and agricultural water right holders would cringe to hear that nearly half of the value of their water rights could vanish. Conflicting objectives like these complicate the decision-making process. According to the principles of integrated water resources management, decision-makers should elicit, categorize, and weigh various stakeholder preferences ultimately to identify nearly “win-win” solutions (Gleick 2003; Voinov and Gaddis 2008).

Through empirical field data, collective action has been shown to effectively manage multiple-use common-pool resources (e.g., water) for equity (Hanemann 2006; Ostrom 1990; Steins and Edwards 1999). Participatory modeling efforts can benefit decision-makers with more useful modeling results and more probable stakeholder consensus through stakeholder engagement in characterizing the system to selecting appropriate model assumptions to interpreting results (Voinov and Gaddis 2008). Little is known about how well community-based solutions perform with respect to solutions generated from numerical optimization because of disparate field and lab problem specifications. However, it has been shown that a lay population of gamers has more varied search capacity than computer algorithms (Cooper et al. 2010a), which led to the discovery of new algorithms (Khatib et al. 2011) and was even shown to outperform computers in searching for solutions to highly complex problems (Savage 2012). Thus, a novel methodology that merges traditional numerical and quantitative engineering approaches with stakeholder-engaging approaches via a video game is established to explore solutions and policy trade-offs in sustainably managing scarce water resources.

The goal of the "decision support game" (DSG) is to establish a framework to identify stakeholder-driven solutions for addressing water supply vulnerabilities in response to changes in population, land use, and climate. Objectives are to i) develop an integrated, web-based decision support system and game application to visually characterize water administration and allocation in response to management decisions and ii) identify stakeholder-driven solutions and preferences as compared to numerical optimization and survey results. To be clear, a large portion of the first objective is accomplished, and none of the second. The proposed DSG framework i) reconciles sustainable water resource management with institutional and stakeholder criteria by identifying Pareto optimal (or near-optimal) solutions that simultaneously minimize vulnerability at lowest cost and implicitly represent stakeholder preferences; ii) leads to advanced understanding of the value of water resources systems to human populations, organizations, and institutions; iii) identifies key institutional obstacles to meeting policy targets, iv) reveals the feasible range for desired policy outcomes, v) explores impacts of various solutions on stakeholders, vi) highlights preferable solutions to stakeholders, and vii) exposes where traditional system performance metrics fail to accurately represent stakeholder preferences.

8.1.1 Background and literature review

Crowdsourcing idea generation in scientific and large geographic contexts has recently shown potential to solve difficult problems (Table 32). Games with a purpose (GWAPs) extend the search for solutions to the general public ("citizen scientists"), providing immediate and decentralized analysis of the impacts and trade-offs associated with those solutions enhancing applicability of results (von Ahn 2009; von Ahn and Dabbish 2008; le Bars and le Grusse 2008; Cooper et al. 2010a; Kim et al. 2014). Games also provide a mechanism to arouse awareness over specific issues (Rebolledo-Mendez et al. 2009; Rizzoli et al. 2014). When applied to water resources management, GWAPs can act as a DSG and simultaneously improve system representation through simulation and collect stakeholder-driven management strategies and preferences, an impossible achievement for traditional optimization methods (Harou et al. 2009) and survey methods for eliciting stakeholder preferences (Kodikara et al. 2010; Kragt 2014; Page et al. 2012; Whitmarsh and Palmieri 2009).

Table 32: Various names and descriptions used by previous researchers for games with a purpose or similar methodologies

Method Name	References
Games with a Purpose Gamification Serious Games	von Ahn and Dabbish 2008 Cooper, Treuille, et al. 2010 Cooper, Khatib, et al. 2010 Deterding et al. 2011 Good and Su 2011 Groh 2012 Paran et al. 2008 Schrope 2013 Xu 2011
Microworlds	Gonzalez et al. 2005
Experimental Games Role-Playing Games	Barreteau 2001, 2003 Barreteau et al. 2003, 2007a, 2007b Bousquet et al. 1999 Dare and Barreteau 2003 Smajgl and Barreteau 2014
Crowdsourcing	Good and Su 2013 Savage 2012 Sui et al. 2013 Wightman 2010
Citizen Science	Hand 2010 Iacovides et al. 2013 Kasemir et al. 2003 Kawrykow et al. 2012
Human-based computation	von Ahn 2009 Law and von Ahn 2009 Yuen et al. 2009 Zhang et al. 2012

Role-playing games and economic experiments directly utilize stakeholder decision-making capabilities to generate solutions (Barreteau et al. 2007a). Several physical board games, computer simulation games, and hybrids have also been utilized in localized contexts to solve water management issues throughout the globe (le Bars and le Grusse 2008; Dray et al. 2006; Lankford et al. 2004; Rebolledo-Mendez et al. 2009). Games aid stakeholder understanding, expression of opinions, and generation of solutions and consequently reduce collective disagreement (Dray et al. 2006). The massive amount of brain power, hundreds of millions of hours per day, entering into game play across the U.S. and the globe is staggering (von Ahn and Dabbish 2008) and can solve problems that computers struggle to solve (von Ahn and Dabbish 2004; Cooper et al. 2010a). Many gamers are increasingly interested in participating in a more purposeful goal than entertainment (Good and Su 2011).

A growing interest in harvesting scientific knowledge from video gamers is evident by the growing number of GWAPs:

1. **Foldit:** a protein-folding game (Cooper et al. 2010a)
2. **Phylo:** solves Multiple Sequence Alignment problems (Kawrykow et al. 2012)
3. **Autopia:** analyzes market dynamics of fuel-efficient cars (Bremson et al. 2013)
4. **The Cure:** selects genes to improve prediction of breast cancer survival (Good et al. 2013)
5. **EteRNA:** a synthetic RNA designer game (Lee et al. 2014), and
6. **EyeWire:** finds pathways within the brain for detecting motion (Kim et al. 2014)

In parallel, growing interest in crowdsourcing data collection has been pervasive in environmental and earth system sciences such as geographical information, weather networks, and nutrient management (Sui et al. 2013). Although the number of players that significantly contribute to the above games is much less than those that initially register to play the game, the crowdsourcing potential of GWAPs is evidenced by the thousands to hundreds of thousands of players they attract (Table 33).

Table 33 Number of GWAP players

Game	Number of registered players	Reference for number of players
Foldit	300,000	(Schrope 2013)
EteRNA	133,000	(Bohannon 2014)
Phylo	12,000	(Kawrykow et al. 2012)
Eyewire	100,000	(Kim et al. 2014)
The Cure	1,000	(Good et al. 2013)

Games also have potential to introduce more diversity than has traditionally participated in engineering and water management. In 2004, 40% of game players were women while only about 20% of engineering bachelor's graduates were female (Dickey 2006; Yoder 2011), and the percentage has grown to 48% female game players in 2014 (Entertainment Software Association 2014). The average female player of *EverQuest 2* plays on average 29.3 hours ,which is about 4 hours per week more than the average male player (Williams et al. 2008). Between 2005 and 2014, the percentage of female game developers grew from 11.5% to 22% whereas the percentage of female engineering students moved from 19.5% in 2005 to 17.8% in 2009 and back up to 19.9% in 2014 (Edwards et al. 2014; Yoder 2014).

8.2 Gaming components

A preliminary decision support game (DSC) for demonstration of a proof of concept is provided here, and can be installed on many devices using the Unity platform.[52] A well-tested prototype and experimental study are still to be performed. The game is called *Dipsa*, a Greek word meaning *thirst*, to represent the key driving factor of the game. Dipsa gamers act as water managers with increasingly challenging level-based water scarcity problems to solve. Dipsa water managers can choose between potential solutions to limited water supply such as more efficient irrigation technologies, efficient home appliances, new or alternative supplies of water, and policy changes.[53]

[52] The Unity Game Engine https://unity3d.com/ was used to develop the game. Games built using Unity can automatically publish to over 25 platforms.
[53] Note that not all of these options are enabled yet

Each solution (in panel on left) can be applied to an appropriate actor in a visual network of rivers represented by water supply nodes, farmer demand nodes, and city demand nodes (Figure 44). More detailed selection of solutions can occur for portions of agricultural producers (Figure 45) and cities (Figure 46). When solutions are applied, demand or supply is changed appropriately and a network flow model runs in the background, allocating water to each user on a daily basis over 30 years. Spider (radar) graphs quickly show feedback on a variety of sustainability metrics[54] and bar graphs show relative costs. System-wide performance and cost is displayed in the upper right. Currently, there are six levels that incrementally introduce a new challenge or water user presented within one introductory river basin or "world" (Figure 47).

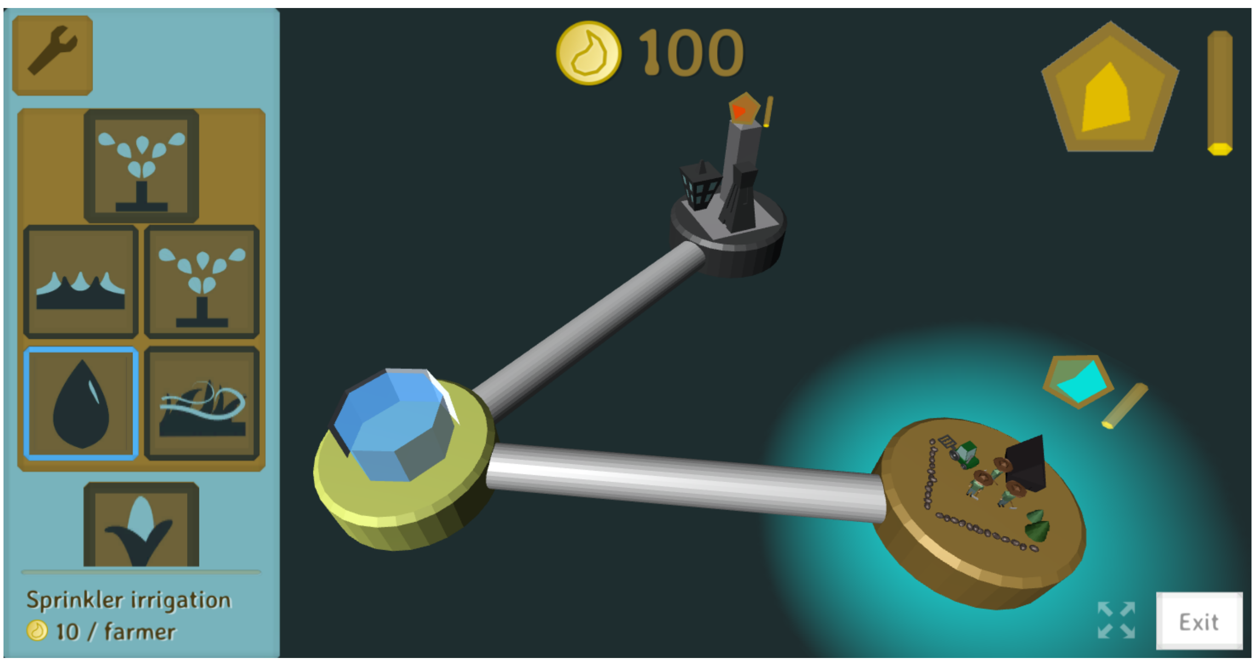


Figure 44: Dipsa network of water supply, cities, and agricultural producers. Solutions are in the panel on the left with costs on the bottom of the panel. Total amount of money to spend is at the top of the screen. Outcomes are displayed above each demand node as spider (radar) graphs containing a mix of sustainability metrics and a bar graph for relative cost. Performance of the entire system is displayed in the upper right hand corner of the screen.

[54] Note that reliability is the only metric implemented currently, but others will be added as game development continues such as vulnerability resiliency, sustainability, agricultural profit, municipal cost, etc.

Figure 45: Change irrigation technology and crop types for segments of individual Dipsa farming communities

Figure 46: Change household water use efficiency and landscapes for individual Dipsa cities

Figure 47: Worlds (i.e., river basins) are first selected (left) and then levels (i.e., discrete scenarios within the river basin) are selected (right)

8.2.1 Network flow model

At the core of the simulation engine to the game is a minimum-cost network flow model called *Dynet* (short for Dynamic Network)[55] that solves convex nonlinear networks with gains in three different modes:

1. **Static**: solve one network of nodes and arcs
2. **Simulation**: solve a network each timestep over time, passing data through time
3. **Dynamic**: build a single network for entire time period, then solve across time

Dynet utilizes an ϵ-relaxation method for solving networks with the following mathematical form (Guerriero and Tseng 2002; Tseng and Bertsekas 2000):

[55] Open-source access to the Dynet code can be found here: https://bitbucket.org/adozier/dynet and https://bitbucket.org/adozier/dynetcore

$$\min \sum_{i,j \in A} f_{ij}(x_{ij}) \tag{71}$$

$$\text{s.t.} \sum_{\{j:(i,j)\in A\}} x_{ij} - \sum_{\{j:(j,i)\in A\}} \gamma_{ji} x_{ji} = s_i, \quad \forall\, i \in N \tag{72}$$

where N is the set of all nodes, A is the set of all arcs, $x_{ij} \in [0, \infty)$ is the flow across arc (i, j) from node i to node j, $\gamma_{ji} \in (0, \infty)$ is the gain parameter across arc (j, i) coming into node i, and s_i is additional supply at node i.

For Dipsa, the engine simulates water allocation of rivers over time. However, Dynet is generalized to simulate any network flow problem (with convex arc costs and gains) with the following nodes:

1. **Default/Supply**: supplies commodities to the system (Figure 48)
2. **Demand**: removes commodities from the system with a specified demand (Figure 49)
3. **Storage**: stores commodities over time with capacity constraints (Figure 50)
4. **Source/Sink**: acts as an infinite supply or sink to any amount of flow (Figure 51)
5. **Custom**: custom, user-defined node behavior, C# coding is involved

and arcs:

1. **Basic**: routes commodity between nodes with costs, capacity constraints, and gains/losses
2. **Routing**: routes flow of commodity to later timesteps (Figure 52)
3. **Gauge**: calibrates gains/losses to match historically measured flows (Figure 53)
4. **Custom**: custom, user-defined arc behavior, C# coding is involved

Each arc in the network can utilize any of the following cost functions, including a custom cost function, as long as it is convex:

1. **Linear**: $f_{ij}(x_{ij}) = c_{ij} x_{ij}$
2. **Quadratic**: $f_{ij}(x_{ij}) = \frac{a_{ij}}{2} x_{ij}^2 + b_{ij} x_{ij}$
3. **Power**: $f_{ij}(x_{ij}) = c_{ij} x_{ij}$

4. **Step function**: $f_{ij}(x_{ij}) = c_{ij0}x_{ij} + \sum_{k=1}^{s} c_{ijk} \cdot [x_{ij} > d_{ijk}]$

5. **Custom**: $f_{ij}(x_{ij})$ convex, C# coding involved

where $[exp] = 1$ if exp is true, otherwise $[exp] = 0$. Solution of the ϵ-relaxation method produces prices at each node that solve the system, which can be used in an economically meaningful manner given that the problem set up is economically meaningful. All parameters of nodes, arcs, and cost functions can be defined as a fixed single value, a timeseries, or values based on supply or flow at another node or arc.

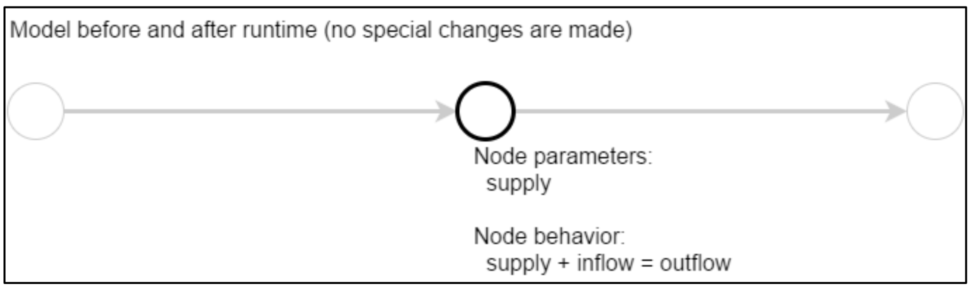


Figure 48: Default node structure and parameters

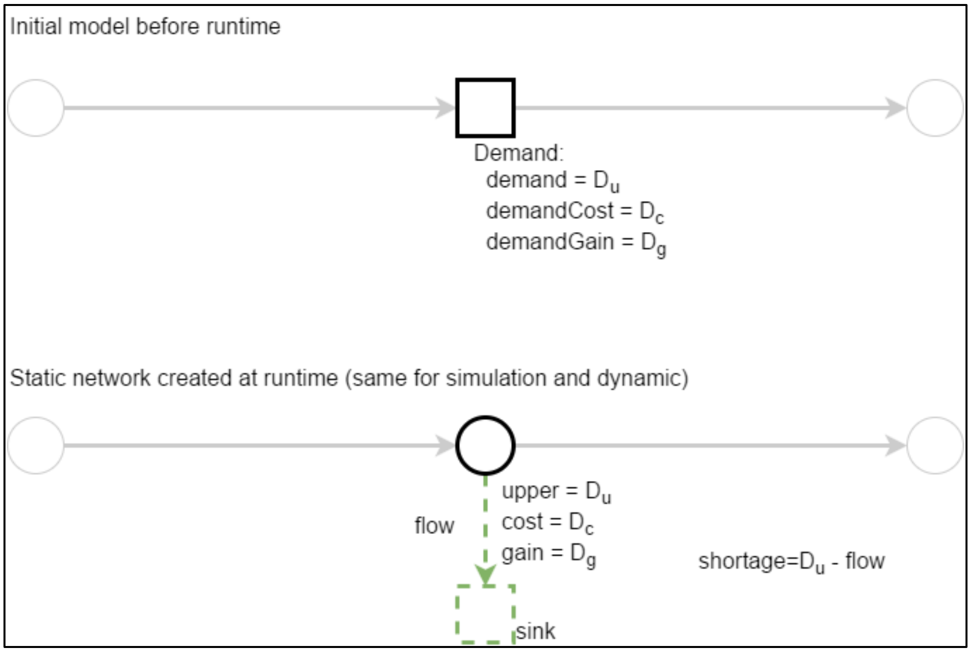


Figure 49: Demand node structure, parameters, and behavior before runtime and at runtime for all execution modes

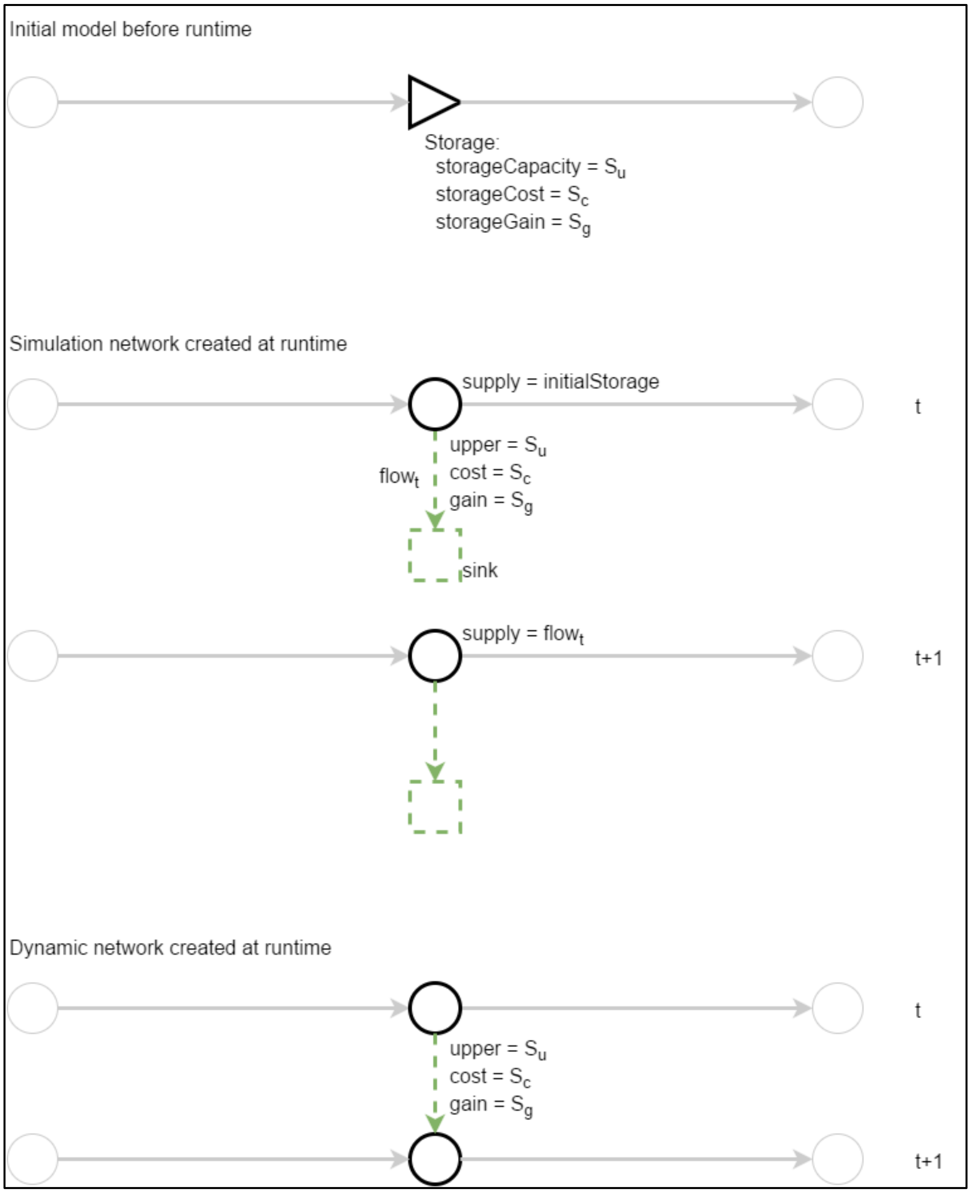


Figure 50: Storage node structure, parameters, and behavior before runtime and during runtime in simulation mode and in dynamic mode. Green objects are created automatically.

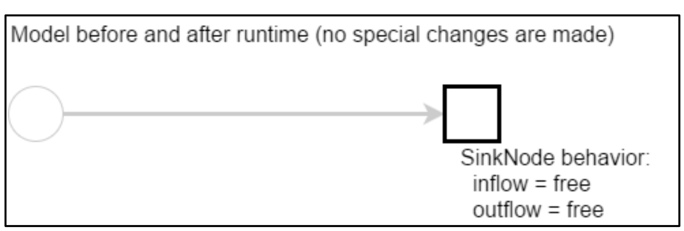


Figure 51: Source and sink node structure and behavior

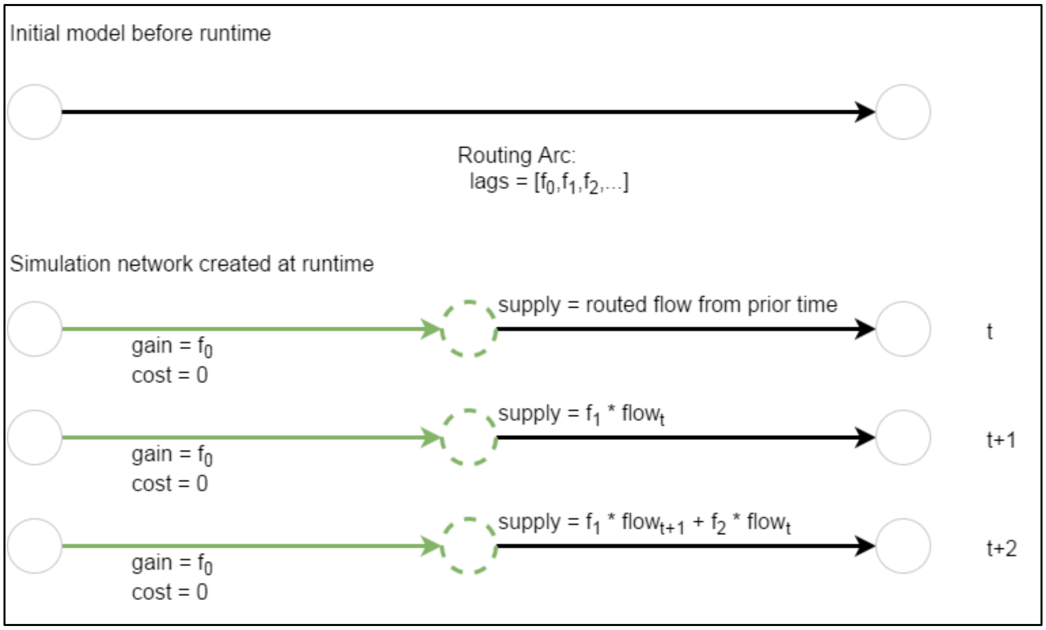


Figure 52: Routing arc structure, parameters, and behavior before runtime and at runtime during simulation mode, does not work in dynamic solution mode. Green objects are created automatically.

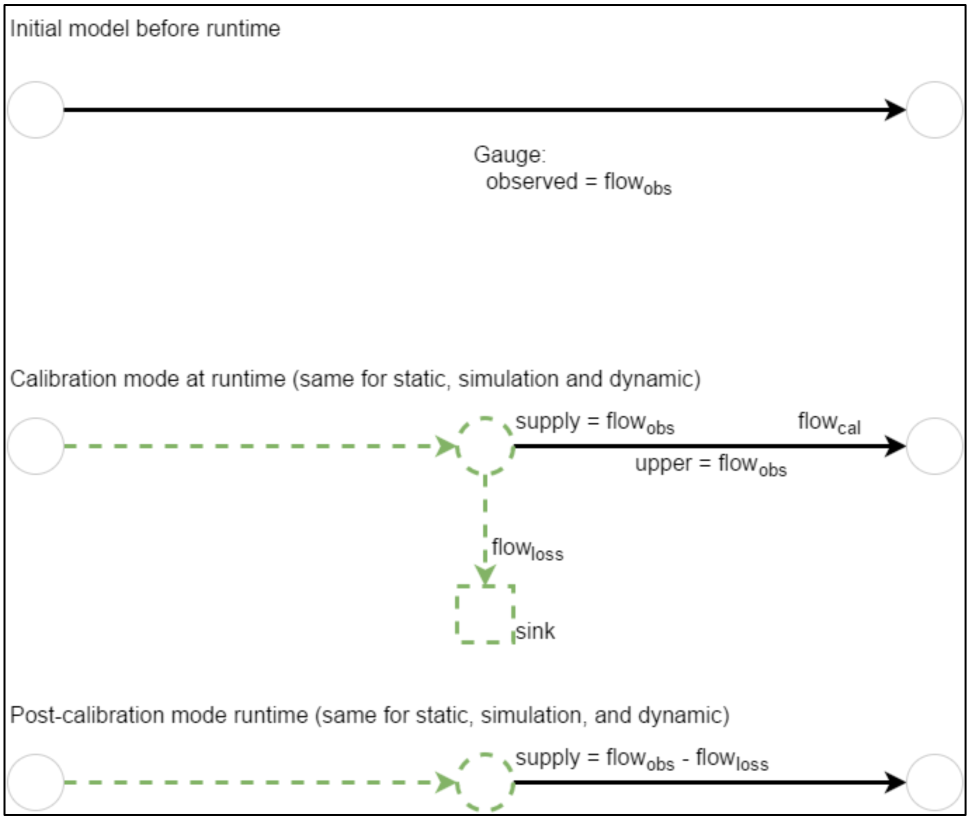


Figure 53: Gauged arc structure, parameters, and behavior before runtime and at runtime in all modes for both a calibration run and a post-calibration run.

8.2.2 Web services to support decision support game

Two web services were built to support scalability and updates to Dipsa. The primary web service, found at http://dipsagame.com hosted by Google App Engine,[56] is publicly available and provisions worlds (river basins) and levels (scenarios in the river basin) to individual Dipsa applications (Figure 54). Gamers can sign up online to build their own Dipsa world and levels and share them with other Dipsa gamers. The Dipsa website also stores profile information for each gamer for research purposes. Demographic and other personal information is stored in a separate table from personally identifiable information according to institutional review board (IRB) standards and any private information entered is secured by SSL.

[56] https://cloud.google.com/appengine/

The second web service runs the network flow solver Dynet in Microsoft Azure cloud[57] for mobile applications so that users do not burn up battery life running the game on their phone. Although this service is not activated by the Dipsa application yet, it is currently being utilized by a web-based interface for Dynet found at http://erams.com/ in "Tools->Network Analysis."

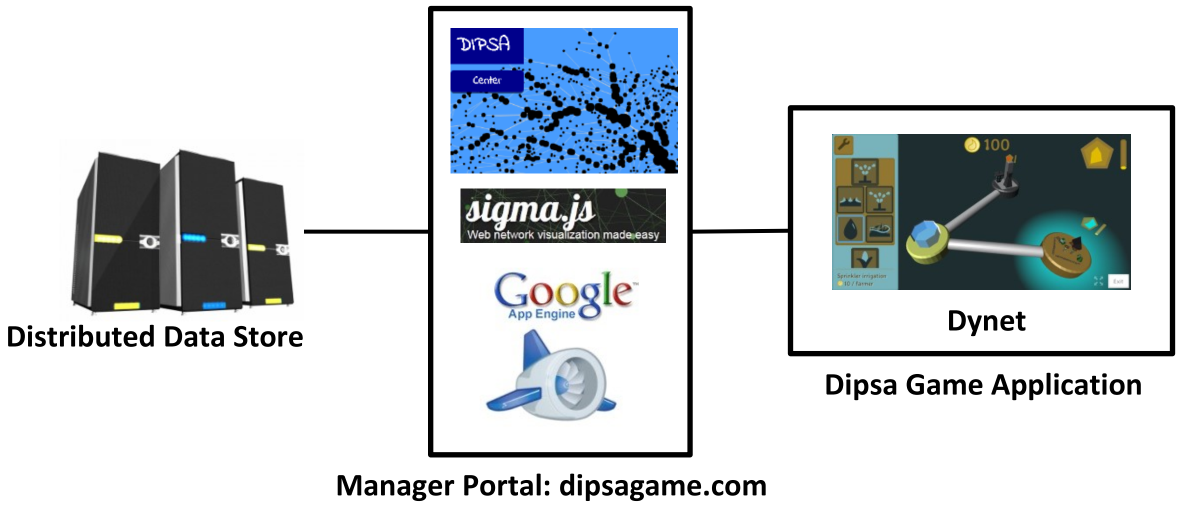


Figure 54: Worlds, levels, and results from the Dipsa decision support game are stored in the Google App Engine datastore, while http://dipsagame.com provisions data to individual game applications

8.3 Future Work

The Dipsa decision support game has a lot of the "scaffolding" in place: a simulation engine, a website that provisions gamer-developed levels, and a beautiful interface. However, the game still needs a scoring mechanism. That is, optimality and system performance of various gamer-generated solutions need to be evaluated, stored, and presented to gamers as feedback to their water management decisions. Lessons learned from Chapters 5-7 also can still be used to inform

[57] https://azure.microsoft.com/en-us/?b=17.14

model structure, solution methodology, and which stakeholder values to include as system performance metrics (i.e., sustainability indicators). Demand characterizations have been identified and defined for four types of agricultural producers and four management strategies in the South Platte River Basin (SPRB). More management strategies need still to be characterized for the full scaffolding of the Dipsa game to be useful. Although anybody can build a Dynet model, calibrate it, characterize demands for it, and submit to the Dipsa Game website for other gamers to play, quick scalability of the model to other regions is not possible without nation-wide supply and demand characterization which could significantly speed the process of application to other regions outside of the SPRB.

9 CONCLUDING REMARKS

A focus on integrated water management has driven a fundamental change in evaluation of management solutions, particularly in simulation, optimization, and stakeholder engagement techniques. Research literature has indicated this trend with increased attention to model integration, evolutionary and multiobjective algorithms, and stakeholder engagement through participatory modeling and role-playing games.

While linear and dynamic optimization techniques are still used often, popularity of evolutionary algorithms has outgrown traditional methods of optimization. As management trends toward integrated water resources management, incorporation of stakeholders in decision-making processes have driven research needs toward multiobjective optimization for incorporating multiple viewpoints and criteria, participatory modeling and stakeholder engagement through group games. Research focus for improved modeling of physical and ecological systems has driven integration with socioeconomic impacts and feedbacks, highlighting the importance of both hierarchical and simulation-based optimization techniques in water management. Future prospects of video games seem promising for crowdsourcing idea generation and the search for optimal solutions in addition to engaging stakeholders and the general public.

A minimally invasive model data passing interface was developed to tightly couple biophysical system models with very little model code changes for improved system representation. The interface was found to have very little overhead and benefits such as interoperability of models across languages, platforms, frameworks, and machines.

A particular problem in semi-arid regions (as in the western U.S.) is negatively impacted rural and agricultural communities as rapidly growing urban populations purchase water from historically irrigated lands. Agricultural producers that own shares in water rights benefit significantly because sale of their water shares is worth up to 2 times more than 40 years of continued agricultural production within the case study region of the South Platte River Basin. Any management strategy or policy meant to sustain agricultural production will naturally reduce water acquisition cost for municipalities and decrease the value of agricultural water rights because of the socioeconomic feedbacks from the market. Out of the institutional changes modeled, the best for sustaining agricultural production was alternative agricultural water transfer methods in the short-term while requiring and accounting for conservation in new urban developments was best in the long-term. Appropriate spatial and temporal scales and details determine the value of water rights. Selection of system sustainability indicators is important to highlight varying stakeholder perspectives and preferences.

Storage reservoirs in the Western U.S. are prominent solutions for securing municipal and agricultural water supply. However, value of stored water diminishes with rigid allocation institutions as in the case of the prior appropriation doctrine that governs water ownership and allocation in most western states. Freed trade in water markets could nearly counterbalance the average projected drop in water supplies due to climate change. To maximize social benefit, reservoir operators and managers need to pay close attention to water users in all sectors; otherwise, when managing only for one select group of users (e.g., cities), new or expanded storage capacities reduce the value of stored water.

Out of demand-side and supply-side management strategies considered, xeriscaping and irrigation technology are most cost-effective. At optimality, increasing total agricultural profit imposes a nearly tenfold increase in cost to municipalities. If cities were to lower raw water purchase requirements for new developments, a fairly cheap solution, significant benefits at the system level could be realized.

A novel methodology to reconcile numerical simulation and optimization techniques with stakeholder engagement and preference-based alternative selection is proposed and a preliminary proof-of-concept has been implemented. In the decision support game, stakeholders play the role of water managers to explore and identify trade-offs and optimal solutions in the context of multiple physical, ecological, socioeconomic, and institutional criteria. The game affords opportunities to engage, educate, and even learn from stakeholders and the general public while simultaneously exploring trade-offs and minimizing system vulnerabilities at lowest cost.

9.1 Outputs

Beyond the research goals and findings of this dissertation, outputs or products were generated as part of the data collection and storage, modeling, and analysis activities. Outputs include several software applications for analysis of water resource supply and demand systems and web-based data and modeling services (Table 34).

Table 34: Software applications and web services produced from the proposed project

Name	Description
Software Applications	
MODPI[j]	Model Data Passing Interface: integrates models across languages, frameworks, and machines in a minimally invasive manner
Dynet[a]	A generalized minimum-cost network flow solver with gains, nonlinear arc cost functions, and three different execution modes: static, simulation, dynamic. Contains scripts for generating river networks from national hydrography datasets.
Dipsa[b]	A decision support game to engage stakeholders and public on water management and to crowdsource solutions
Dypro[c]	A dynamic programming tool built to analyze storage and water allocation institutions (Maas et al. 2017)
IUWM[d]	Integrated Urban Water Model: A model that simulates urban water use and management at various scales (Section 4.4)
CSaws	Computational Semi-Arid Water Sustainability: Solves multiobjective optimization problems related to water sustainability in semi-arid regions, focused on water rights policies. Contains an Java-based adapter between the MOEA Framework (Hadka 2014),[e] Hazelcast parallel computation,[f] and GAMS.[g]
Web Services	
erams.com/sprb	Geowebpage inside of the Environmental Risk Assessment Management System (eRAMS) containing analysis, querying, and visualization tools for water rights and diversions, DayCent and StateCU[h] model output, IUWM, and climate data products for the South Platte River Basin
dipsagame.com	Website to collect, store, and provision Dipsa Game worlds and levels, gamer information, and crowdsourced solutions
multiobj.appspot.com	Website that performs multiobjective optimization for teaching and visualization purposes. Contains a web service that runs custom Java-based objective functions through the MOEA Framework (Hadka 2014).[e]
DayCent Modeling Service	Web-based modeling service that runs DayCent for estimating crop production, water budget, and nutrient requirements under various management scenarios
IUWM Modeling Service	Web-based modeling service that runs IUWM for calibration, visualization, and evaluation of urban water management and conservation technologies
DayCent Output Datastore	Local datastore of management scenario output from DayCent for the South Platte River Basin, distributed across 32 4TB drives by MongoDB[i]
Dynet NHD Network Builder	Local web-based service that produces a Dynet model from NHDPlus value-added NHD data.

[a] https://bitbucket.org/adozier/dynet
[b] https://bitbucket.org/ironcord/dipsa
[c] https://bitbucket.org/adozier/dypro
[d] https://bitbucket.org/iuwm/iuwm
[e] http://www.moeaframework.org
[f] https://hazelcast.com
[g] https://www.gams.com
[h] http://cdss.state.co.us/software/Pages/StateCU.aspx
[i] https://www.mongodb.com/
[j] https://bitbucket.org/adozier/fortmodpi

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APPENDIX A: LITERATURE TREND ANALYSIS

A broad and automated analysis of literature from 1950 to 2013 provided helpful insight into evolving trends within various subdisciplines of integrated water resources management. Figure 3 shows the number of publications regarding categorized methodologies in addition to a comparison of single objective and multiobjective analyses. We assembled a list of more than 50 optimization methods categorized by linear programming (2 methods), nonlinear (mathematical) programming (17 methods), decomposition techniques (3 methods), dynamic programming (6 methods), evolutionary computation (17 methods), and multiobjective analysis (7 methods). In addition to mathematical, gradient-based methods, nonlinear programming techniques included discrete programming methods such as integer programming, mixed-integer programming, branch-and-bound, and cutting plane methods. The top four nonlinear programming techniques returned in the search for water resource management related topics consist of conjugate-gradient method (147), mixed-integer programming (106), quadratic programming (105) and integer programming (100 records). We searched the **Web of Science ®** database for each method within literature topics, which includes any occurrence of a word within the title, abstract, or keywords. Searches were constrained to a specific water-related discipline by adding a keyword to each query, such as “river”, “irrigation system”, etc.

The number of articles containing a multiobjective analysis was estimated by placing an additional constraint on the query: AND (“multiobjective” OR “multi-objective” OR “multiple objective*”). Single objective analyses were queried using the NOT operator instead: NOT “multiobjective” NOT “multi-objective” NOT “multiple objective”. The total number of articles that contain multiobjective analyses is 1,635 from 1950 to 2013, 958 of which also contain descriptions of multiobjective-specific methods (MCDA, goal programming, compromise programming, AHP, etc.), and 580 of which also discuss evolutionary methods. Figure 3 displays the total number of articles found within **Web of Science ®** for each category.

Data included in the trend analysis are derived from the **Web of Science ®** prepared by THOMSON REUTERS ®, Inc. (Thomson®), Philadelphia, Pennsylvania, USA: © Copyright THOMSON REUTERS ® 2015. All rights reserved. Data before the 1960s or 1970s is of lower quality and sometimes does not contain article abstracts. Conference proceedings were incorporated into the metadata collection only after 1990, which may explain the large increase in all areas of research at that time.

APPENDIX B: ADDITIONAL MODPI PERFORMANCE RESULTS

Additional model scenarios are assessed in this appendix to quantify potential computational overhead for a variety of machine setups. The DayCent-HYDRUS model was executed on two different physical machines labeled "PM1" and "PM2" for operating systems running on "bare metal", and on two virtual machines labeled "VM1" and "VM2". These scenarios are compared with the MODPI-connected system straddling both machines, with DayCent on Machine 1 and HYDRUS on Machine 2 ("Both PMs" for physical machine cases, "Both VMs" for virtual machine cases). Due to increasing support for and usage of virtual machines in addition to interest in Modeling-as-a-Service within the cloud [David et~al.(2014)David, Lloyd, Rojas, Arabi, Geter, Ascough, Green, Leavesley, and Carlson], tests are executed in both a private cloud environment and within Amazon Elastic Compute Cloud (Amazon EC2) cloud platform, which help to assess performance in the presence of network jitter.

Machines in the private cloud environment are SUN Blade x6270 servers that run Eucalyptus 3.1 Infrastructure-as-a-Service (IaaS). Each machine has identical hardware with two quad-core 2.8 GHz Intel Xeon processors each with hyper-threading for a total of 16 logical cores, 72 gigabytes of random access memory (RAM), 145 gigabytes hard disk storage, and use a virtual local area network (VLAN) network connected with a 1 gigabit switch. Virtual machines execute on a XEN 4.1.2 hypervisor, have 8 logical cores, 4 gigabytes RAM, and 30 gigabytes hard disk storage. The same network adapter is used for communication on both physical and virtual machine runs. For performance tests in Amazon EC2, we use the c3.xlarge virtual machine instances, which have one quad-core 2.8GHz Intel Xeon processor with 7.5 gigabytes of random access memory (RAM) and 40 gigabytes storage on a solid state drive. All machines in the analysis run Ubuntu 12.04 as the operating system.

By default, Open MPI utilizes shared memory when running on the same machine, but a large variance in performance occurs due to internal tuning options within the shared memory modules of Open MPI. To address this issue, we conduct tests restricting message passing communication to the Transmission Control Protocol (TCP), which gives more consistent performance results, and supports direct comparison as all tests then use TCP inherently.

Table 35 displays mean runtime in seconds of 200 identical test runs for each model integration scenario, and Figure 55 summarizes runtime variability when comparing specific scenarios. Most observable differences in Table 35 are statistically significant according to t-tests because of the large sample size and small variance. Many differences are very minuscule when normalized against the subroutine method on Machine 1 (SUB-M1) except for computationally inexpensive cases executed in the private cloud environment.

Table 35: Mean runtime (in seconds) for 200 DayCent-HYDRUS test runs for both the subroutine integrated system (SUB) and the MODPI integrated system (MODPI) executed on both a physical and virtual machine in a private cloud (PM1 and VM1), in Amazon EC2 (Amazon VM1), and with DayCent on one machine and HYDRUS on another communicating over the network (Both PMs, Both VMs, and Amazon VMs). Four models were run with varying number of soil layers (50, 100, 300, and 1000) within HYDRUS to arbitrarily increase computation time between network access.

Integration type	Machine	HYDRUS Layers			
		50	100	300	1000
SUB	PM1	2.4	5.8	43.8	75.5
	VM1	2.4	5.8	43.8	75.7
	Amazon VM1	2.1	5.1	38.5	66.1
MODPI	PM1	2.4	5.8	43.4	74.9
	VM1	2.4	5.9	44.5	76.7
	Amazon VM1	2.3	5.5	41.4	71.2
	Both PMs	2.9	6.3	44.2	75.7
	Both VMs	3.1	6.6	44.4	76.0
	Amazon VMs	2.7	5.6	38.4	65.6

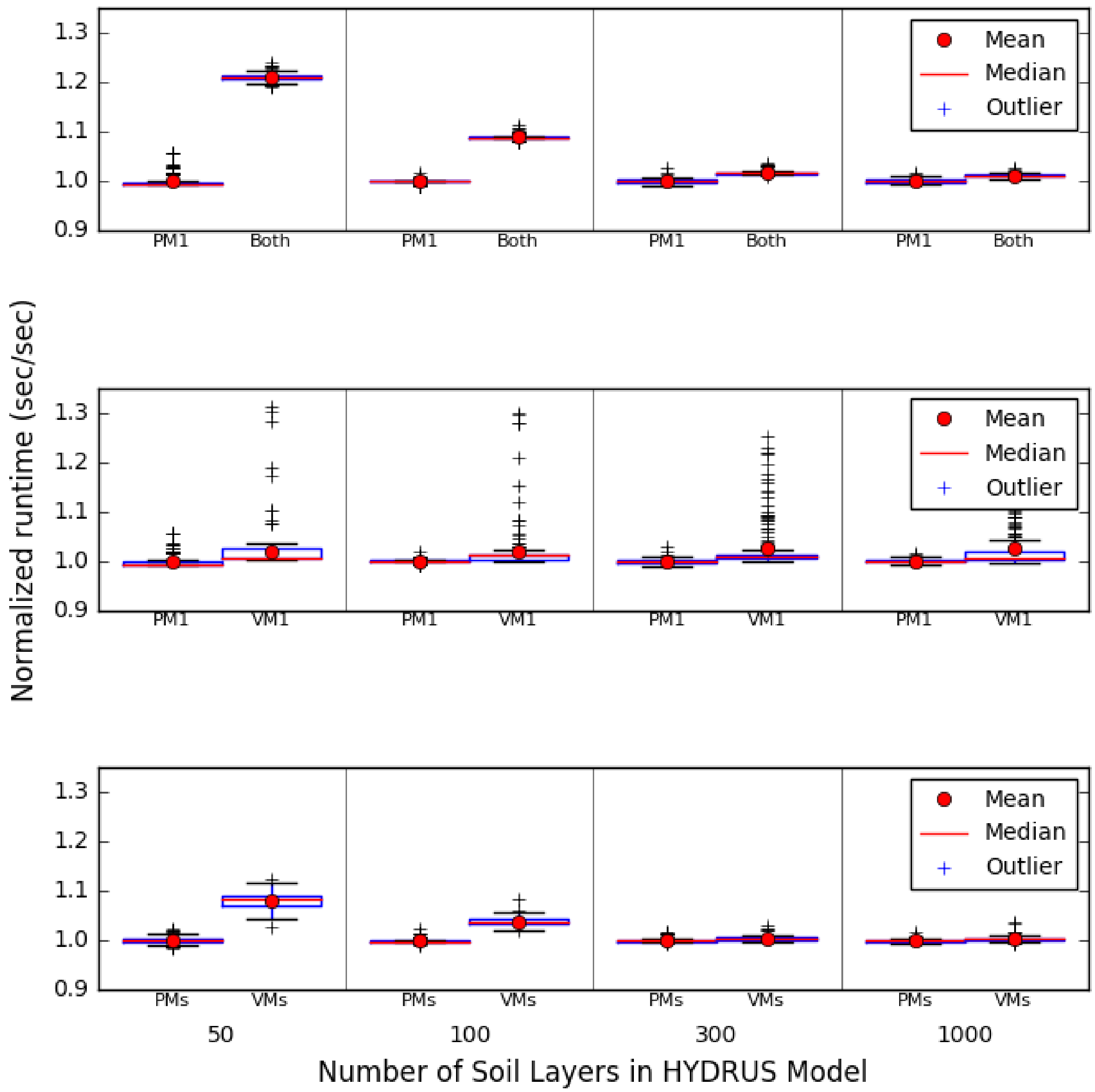

Figure 55: Boxplots of normalized model runtime of 200 identical simulations on a private cloud comparing (top) a MODPI execution on a single physical machine and across two machines, (middle) a MODPI execution on a single physical machine and a single virtual machine, and (bottom) a MODPI execution across two physical machines with that across two virtual machines. Runtime is normalized by the mean runtime of the case on the left of the panel for each HYDRUS model setup (see mean runtimes in Table 35). Outliers are runtimes that occur outside of the 95% confidence interval assuming a normal distribution.

As discussed in the Results section, overhead due to MPI network communication when running on one machine within MODPI-connected DayCent-HYDRUS is minimal and is outweighed by benefits of parallelization for the more computationally expensive scenarios when running on a physical machine. MPI network communication across machines in a private cloud has a much larger effect on runtime results. Increases in mean runtime when using the MODPI method on both physical machines (MODPI-Both-PMs) range from 1.1% to 20.9% as compared to the MODPI method running on one physical machine (MODPI-PM1) as shown in the top of Figure 55, but absolute differences in mean runtimes is relatively the same across scenarios, ranging from 0.5 to 0.8 seconds.

Overhead due to virtualization is minimal when on one machine, 0.1-0.5% more than baseline runtime for SUB scenarios and 2.0-2.5% more than baseline for MODPI scenarios. As shown in the middle component of Figure 55, much more variation in runtime occurs for MODPI-connected models when running on virtual machines. The cost of virtualization is more exaggerated when running across two machines, increasing runtime by 0.3-8.2% when compared to MODPI running across two physical machines (see the bottom component in Figure 55) and by 1.5-30.8% when compared to MODPI performance on a single physical machine.

Performance results of scenarios executed within Amazon EC2 show a different pattern as summarized in Table 36. MODPI executing on one virtual machine has approximately the same relative slowdown when compared with the SUB approach of 8% regardless of the number of computations. This may likely indicate a computational bottleneck due to scheduling of tasks in the virtualized environment instead of a network bottleneck, which would be expected to have the same absolute overhead in runtime. Operating across machines, MODPI has a relatively higher cost for jobs with little computational requirements with slowdown of 10.6-28.5%, but little overhead for jobs with high computational requirements with speedup of 0.3-0.9%.

Table 36: Increases in runtime (%) for MODPI scenarios with two different machine setups within the private cloud and within Amazon EC2. The SUB-VM1 serves as the baseline scenario.

Platform	Machine	HYDRUS Layers			
		50	100	300	1000
Private cloud	VM1	2.5%	1.4%	1.5%	1.3%
	Both VMs	31.4%	12.5%	1.2%	0.4%
Amazon EC2	VM1	8.7%	7.9%	7.5%	7.6%
	Both VMs	28.5%	10.6%	-0.3%	-0.9%

APPENDIX C: SECTOR ASSIGNMENT TO WATER RIGHTS AND DIVERSIONS

Readily available water rights and diversions data[58] are not linked with owners and associated sectors, and therefore a methodology for assigning sector ownership of water rights and usage of diversions was developed and automated. So that the datasets used are reproducible, a small local web-service hosts the Hydrobase data, runs queries, and assigns sectors automatically to any diversion structure (e.g., ditch, headgate, and reservoir) within Colorado. This methodology has been adapted from the South Platte Historic Crop Consumptive Use Analysis (Leonard Rice Engineers 2010). A "USE" code is available for each right and diversion record, and is mapped to one of five sectors according to values in Table 37 where "UNK," "ENV," "AGR," "IND," and "MUN," denote unknown, environmental, agricultural, industrial, and municipal sectors, respectively.

[58] Ibid. 40

Table 37: Use codes, descriptions, abbreviations, and assigned sector

USE Code	Abbr.	Sector	Description
0	STO	UNK	STORAGE
1	IRR	AGR	IRRIGATION
2	MUN	MUN	MUNICIPAL
3	COM	MUN	COMMERCIAL
4	IND	IND	INDUSTRIAL
5	REC	ENV	RECREATION
6	FIS	ENV	FISHERY
7	FIR	MUN	FIRE
8	DOM	MUN	DOMESTIC
9	STK	AGR	STOCK
A	AUG	MUN	AUGMENTATION
B	EXB	UNK	SUB-BASIN EXPORT
C	ACR	MUN	CHANGE OF USE RETURN FLOWS
D	DCR	MUN	CUMULATIVE DEPLETION FROM RIVER
E	EVP	MUN	EVAPORATIVE
F	FED	MUN	FEDERAL RESERVED
G	GEO	IND	GEOTHERMAL
H	HUO	MUN	HOUSEHOLD USE ONLY
K	SNO	IND	SNOW MAKING
M	MIN	ENV	MINIMUM STREAMFLOW / LAKE LEVEL
N	NET	ENV	NET EFFECT ON RIVER
P	PWR	IND	POWER GENERATION
Q	QUA	UNK	QUANTIFICATION OF AMOUNT
R	RCH	AGR	RECHARGE
S	EXS	MUN	EXPORT FROM STATE
T	TMX	MUN	TRANSMOUNTAIN EXPORT
W	WLD	ENV	WILDLIFE
X	ALL	MUN	ALL BENEFICIAL USES
Y	AWP	AGR	AGRICULTURE WATER PROTECTION
Z	OTH	MUN	OTHER

Since municipal owners will often have multiple possible uses for a water right, including irrigation possibly, records are assigned with the following algorithm:

6. If any uses are mapped to municipality, assign “MUN” and exit
7. If any uses are mapped to industry, assign “IND” and exit
8. If any uses are mapped to agriculture, assign “AGR” and exit
9. If any uses are mapped to environment, assign “ENV” and exit
10. All remaining rights are assigned unknown, but these should include only uses “B” and “Q” and “0”

Yearly rights ownership tables are acquired by querying Hydrobase with a pre-built SQL query obtained from the Colorado Division of Water Resources[59] with the addition of filtering by year of ownership. The exact year of ownership is difficult, and sometimes impossible, to find in the database, but the following algorithm covers many cases:

1. Check for a date formatted as “m/d/yyyy” or like “DD MON YYYY” in the action comment field which refers to final change of use date in change of use cases. If it exists, retrieve year and exit.
2. Check for a date in the appropriation date field. If it exists, retrieve year and exit.
3. Check for date in the case number field as the last four digits of case numbers 10 characters in length, otherwise for 8 or 9 character length case numbers, year is either last two digits or first two depending on the format of the string. If it exists, retrieve year and exit.
4. Check for a date in the adjudication date field. If it exists, retrieve year and exit.

[59] SQL code obtained from Doug Stenzel at the Colorado Division of Water Resources