THESIS

ECONOMIC AND ENVIRONMENTAL TRADE-OFFS OF IRRIGATION BEST MANAGEMENT PRACTICES IN THE LOWER ARKANSAS RIVER VALLEY

Submitted by

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ABSTRACT

ECONOMIC AND ENVIRONMENTAL TRADE-OFFS OF IRRIGATION BEST MANAGEMENT PRACTICES IN THE LOWER ARKANSAS RIVER VALLEY

The flows of the Arkansas River cascade through the Rocky Mountains and spill into Colorado's eastern plains. In the Lower Arkansas River Valley (LARV), these flows serve irrigators on over 250,000 acres, and are critical to the production of everything from corn to cantaloupes. Concurrent to the "goods" produced with this irrigation, are a series of "bads" occurring in the form of pollution. Elevated selenium, nitrate, and salinity concentrations have been related to high volumes of irrigation return flows, and threaten compliance with the Arkansas River Compact. Implementing a series of regional land and water Best Management Practices (BMPs) is thought to reduce the negative impacts ("bads") of irrigated agriculture in the region and in some cases, increase the productivity of land and water ("goods"). A deeper understanding of impacts of proposed BMPs is required.

The specific question I hope to answer with this thesis is "What are the economic and environmental trade-offs face by Lower Arkansas River Valley producers when implementing a series a land and water best management practices?" To answer this question, an economic linear programming (LP) model is written to maximize regional net returns for a representative area within the LARV, using the General Algebraic Modeling System (GAMS). The LP is calibrated to match the physical characteristics of the region, historic water application volumes, and the historic crop mix. BMPs are tested by constraining various equations in the model, resulting in a series of economic measures. These economic measures are then compared to the output of a water flow, and reactive solute transport model to quantify the trade-offs that exist between regional net returns, in-stream selenium concentrations, in-stream nitrate concentrations, and yield losses to soil salinity. The results of this analysis suggest the existence of win-win scenarios, which increase net returns, and reduce pollution concentrations. No single BMP outperforms all others, supporting the notion that LARV producers and water policy makers face trade-offs in their efforts to control irrigation-induced pollution.

ACKNOWLEDGEMENTS

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Introduction

Colorado's Lower Arkansas River Valley[1] (LARV) is home to substantial irrigated agricultural production; about 200,000 acres were irrigated in 2014 to produce a wide range of crops from grains to specialty vegetables. While irrigation plays a critical role in sustaining the region's agriculture, its impacts on regional water quality may be less favorable. Over the past 30 years, research has produced a better understanding about the relationship between irrigation and the environment. Specifically, studies of the LARV have linked irrigation to several concerning environmental conditions including elevated in-stream selenium and nitrate concentrations, shallow, saline water tables, and significant non-beneficial consumptive use of scarce water supplies (Seiler, Skorupa and Peltz 1999; Gates et al. 2002; Gates et al. 2009, Morway and Gates 2012). A series of Best Management Practices (BMPs) have been proposed as means of curbing the negative environmental impacts of irrigation. The physical impacts of these BMPs have been modeled using a two-stage hydrological model that estimates changes associated with water and fertilizer applications, and associated return flows (MODFLOW-UZF1[2] and MODFLOW-SFR2[3]), and reactive solute transportation (RT3D-OTIS[4]). However, the economic and political feasibility of said BMPs remains unclear. This thesis aims to answer the question "What are the economic and environmental trade-offs face by Lower Arkansas River Valley producers when implementing a series a land and water best management practices?" by describing the institutional

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[1] For the purpose of this paper, the Lower Arkansas River Valley (LARV) refers to the region of southeastern Colorado stretching from the Pueblo Reservoir in Pueblo, CO to the CO-KS Stateline, along the Arkansas River. The region consists of five counties including Bent, Crowley, Prowers, Pueblo, and Otero.

[2] A full description of the MODFLOW-UZF1 package is found in Niswonger, Prudic, and Regan (2006)

[3] A full description of the MODFLOW-SFR2 package is found in Niswonger and Prudic (2010)

[4] A full description of the RT3D-OTIS program is found in Shultz (2017)

system in which LARV water decisions are made, quantifying the economic cost of BMP adoption, and identifying efficient implementation of BMPs by comparing economic and environmental outcomes.

The cost-effectiveness of proposed BMPs is analyzed using a linear programming (LP) economic optimization model written in the General Algebraic Modelling Systems (GAMS) language, coupled with output from a surface flow (MODFLOW-UZF1 and MODFLOW-SFR2) and reactive solute transport (RT3D-OTIS) model. The combination of these models allows for a hydro-economic analysis of BMPs by identifying the trade-offs between regional economic net returns and pollution abatement in local waters associated with various levels of BMP adoption. An analysis of the modeled economic and environmental outcomes for different BMP adoption scenarios depicts economic tradeoffs between multiple environmental criteria simultaneously. It is found that no BMP can optimally improve all outcomes, suggesting that future water management strategies will require trade-offs between economic and environmental measures. The remainder of this thesis is presented as follows. First, I present a brief overview of the LARV region and institutions that govern water use. This is followed by an introduction into water challenges and BMPS in the LARV region. Then, I review previous hydro-economic modeling efforts. I then present an overview on the methods employed and a presentation of the mathematical model. Finally, I finish with a presentation of results and trade-offs, followed by my conclusions and recommendations.

Chapter 1: Overview of Legal Institutions, Irrigation Practices, and Water Concerns

The Arkansas River flows that originate high in Rocky Mountains near Leadville, CO, and spill into the eastern plains, have sustained irrigation in the Lower Arkansas River Valley (LARV) for over a century.

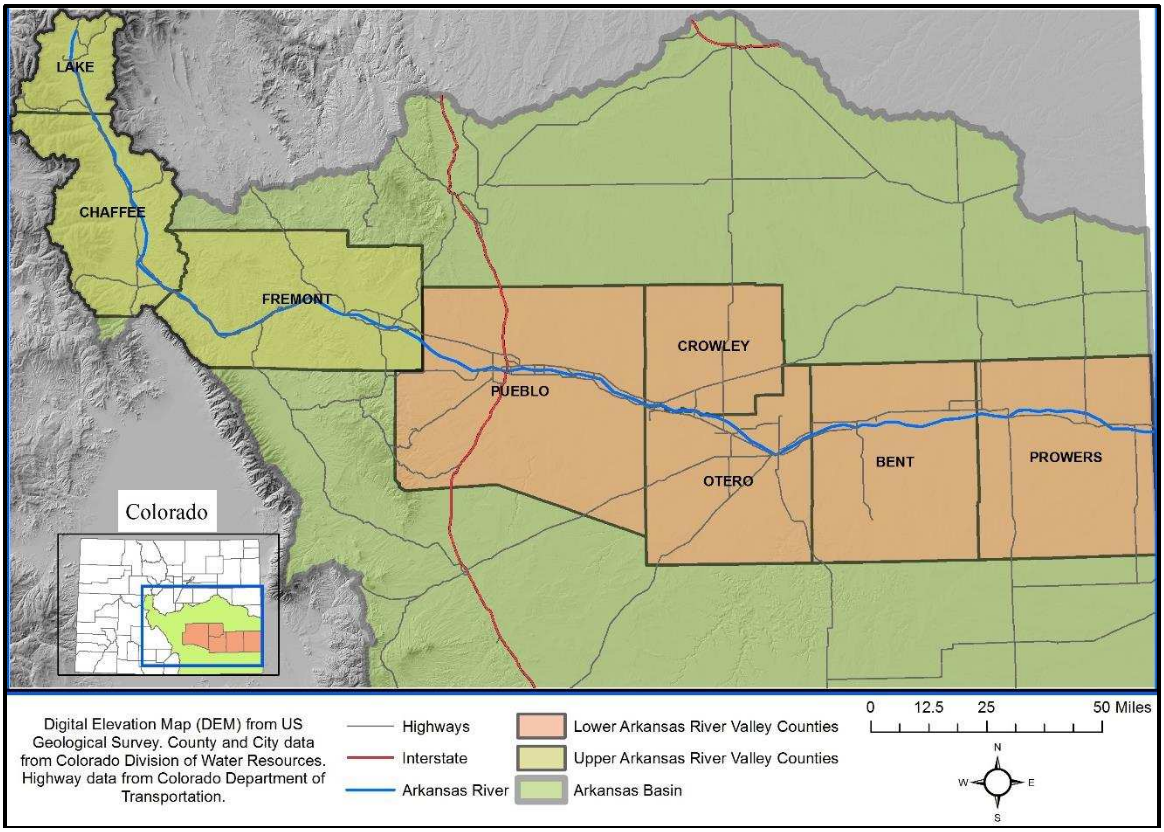

Figure 1. Map of Arkansas River Basin

Note: Map obtained from Blake Osborn, Colorado Water Institute

Like all surface water in Colorado, use of the Arkansas River is governed by the Doctrine of Prior Appropriation, which guarantees "… [t]he right to divert the unappropriated waters of any natural stream to beneficial uses."[5] When conflicts arise in times of water shortage, the prior appropriation

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[5] *See Colorado Constitution, Article XVI, Section 6*

system grants "… [p]riority of appropriation [to] the better right as between those using the water for the same purpose."[6] Priority is determined by the appropriation (or adjudication) date of the right, which corresponds to the date when water was first put to a beneficial use, and is based on the relative seniority of a specific water right to all other rights. The earliest decreed water right in the LARV has an appropriation date of 1859, and by the 1880's flows in average years were fully appropriated (Abbott 1985). However, claims on the river continued into the 20th century, leaving many to own water rights better described as "flood rights" (Abbott 1985). These later claims, referred to as "junior" rights, are only fulfilled in times of higher than average flows such as spring snowmelt and summer rainstorms, providing inconsistent, difficult to predict, and many times inconvenient surges of water. Based on interactions with producers during preparation for this research, managing voluminous surges of water was identified as a major challenge.

Another critical component to the priority water rights system is that of beneficial use. Beneficial use is defined in the Colorado Revised Statutes (C.R.S) "[as] use of that amount of water that is reasonable and appropriate under reasonably efficient practices to accomplish without waste the purpose for which the appropriation is lawfully made".[7] The definition of beneficial use is intrinsically vague, allowing for beneficial uses to evolve and change over time. The addition of in-stream flows to the beneficial use list in 1973[8], as means of preserving wildlife habitat and natural environment, is an example of the flexibility in the beneficial use definition. Operationalizing beneficial use requires a diversion from a water source, and an application to beneficial use. Beneficial use refers to the consumptively used portion of the diversion and occurs when water is made unavailable for other uses. In irrigated agriculture, consumptive use generally occurs in the form of evaporation, transpiration and

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[6] *See Colorado Constitution, Article XVI, Section 6*

[7] *See C.R.S. 37-92-103(4)*

[8] *See C.R.S. 37-92-102(3)*

crop evapotranspiration. Non-consumptive use refers uses that do not remove water from the system, making it available for other users/uses. In irrigated agriculture, non-consumptive uses are primarily used to account for transit and application losses, commonly referred to as seepage and return flows. Water rights are decreed based on a consumptive use amount, time, and location (Waskom and Neibauer 2002). However, river diversion volumes exceed the decreed consumptive use amount to account for non-consumptive losses in moving water to, and applying water on a field.

Historically, the notion of beneficial use has caused concern among Colorado water users as failure to put water to a beneficial use can result in "... forfeit[ure] in whole or in part as a result of the intent of the owner there of to discontinue permanently the use of all or part of the water available thereunder".[9] This situation if commonly referred to as "use it or lose it," and is often cited as a barrier to the adoption of more efficient irrigation systems, along with other institutional rules that favor return flow maintenance over system efficiency (Sharp et al. 2016A). Recent efforts have sought to dispel the notion that an irrigation efficiency improvement constitutes an abandonment (Waskom et al. 2016). Waskom et al. (2016) explain that adjustments made to diversion allowances after an irrigation efficiency improvement do not affect the consumptive use value of a decreed water right, they simply account for the increased efficiency of the new system which requires less "carriage water". This reduction in diversion allowance is of no economic value, considering it cannot be sold or transferred in a water right change case. It critical to reiterate that a decreed water right defines the **allowable consumptive use, adjudication date, and location of use.** In a complicated web of statutes, rules, and misconceptions, these three components drive water use in the LARV, and in Colorado as a whole.

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[9] *See C.R.S 37-92-103(2)*

1.1 Water Disputes and the Arkansas River Compact

Agriculture is unquestionably the dominate user of water in the LARV, accounting for over 96% of water withdrawals in four of the region's five counties (Ivahnenko and Flynn 2010). Pueblo County represents the only county in the region with a major urban area, which likely explains the use of water outside of agriculture as shown in Table 1. Of total LARV irrigation withdrawals, about 95% of water is sourced from surface water flows of the Arkansas River and its tributaries. The importance of the Arkansas River flows to agricultural production cannot be understated. However, since irrigated agriculture took a foothold in the LARV in the late 19th century, Colorado's downstream neighbors to the east in Kansas have challenged the use of Arkansas River water.

Table 1. Estimated Lower Arkansas River Valley (LARV) Water Withdrawals (2005)

County	Irrigation withdrawals (Thousand acre ft./year)	Total withdrawals (Thousand acre ft./year)	% of Total Withdrawals for Irrigation	Total Irrigation Withdrawals from Surface Water (Thousand acre ft./year)	% of Irrigation Withdrawals from Surface Water
Bent	234.48	236.90	99%	226.77	97%
Crowley	37.05	38.41	96%	32.83	89%
Otero	434.28	441.08	98%	414.98	96%
Prowers	542.74	547.06	99%	511.97	94%
Pueblo	138.87	337.31	41%	129.14	93%
LARV Total	1,387.42	1,600.76	87%	1,315.69	95%
Colorado Total	13,812.79	15,224.55	91%	11,178.37	81%

Notes: Percentage values are per author calculations. Withdrawal data per Ivahnenko and Flynn (2010).

Beginning in 1902, the U.S. Supreme Court presided over a series of lawsuits filed between the two parties. The general topics of the suits focused on the irrigation of non-riparian lands in Colorado, and the negative impacts this had on Kansas water users.[10] The U.S. Supreme Court used these cases to explicitly define what its powers were in water disputes between states, but never apportioned water between the two states. Instead, the Court encouraged collaboration between the states, and suggested the development of an interstate compact.

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[10] *See Kansas v. Colorado, 185 U. S. 125 (1902); see Kansas v. Colorado et al., 206 U. S. 46 (1907)*

In December 1948, a bilateral compact between the states of Colorado and Kansas was ratified, and so was created the Arkansas River Compact.[11] The Compact's objectives as defined in Article I are to:

> A. Settle existing disputes and remove causes of future controversy between the states of Colorado and Kansas, and between citizens of one and citizens of the other state, concerning the waters of the Arkansas River and their control, conservation and utilization for irrigation and other beneficial purposes.
>
> B. Equitably divide and apportion between the states of Colorado and Kansas the waters of the Arkansas River and their utilization as well as the benefits arising from the construction, operation and maintenance by the United States of John Martin Reservoir Project for water conservation purposes.

Article IV-D of the Compact further protects future beneficial development in the LARV provided said development does not "…materially deplet[e] in usable quantity or availability," the waters of the Arkansas River. This article ensures that new water developments on or along the Arkansas River cannot impact the "state-line flow" of water from Colorado into Kansas. The implications and importance of Article IV-D would later become obvious as new irrigation technologies that increased the efficiency, and consumptive use of water, were adopted.

In 1985, Kansas filed a complaint to the Supreme Court appointed Special Master for violations of the Compact due to the growing acres of sprinkler irrigation, fed by groundwater wells, which was influencing return flow patterns and alluvial aquifers, and materially depleting the Arkansas River.[12] In 2005, Colorado paid Kansas in excess of $34 million for damages associated with an estimated 428,000 acre-feet worth of depletions to usable Stateline flow occurring between the years 1950-1996 (Littleworth 2008). Under the Special Master's guidance, Colorado and Kansas developed the Hydrologic-Institutional model (H-I), which simulates water use and return flows throughout the LARV,

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[11] *See C.R.S. 37-69-101 (1949)*

[12] *See Kansas v. Colorado, 514 U. S. 673 (1995)*

and is used to maintain Compact compliance with a changing irrigation landscape. The H-I model became the basis for Irrigation Improvement Rules; a set of state agency rules that ensure compact compliance following an improvement to one's irrigation efficiency.

1.2 Irrigation Improvement Rules

The "Compact Rules Governing Improvements to Surface Water Irrigation Systems in the Arkansas River Basin in Colorado"[13] were filed by Colorado State Engineer Dick Wolfe in September 2009, and took effect January 1st, 2011. As a result of previously described lawsuits, the "Rules" were enacted to ensure that efficiency improvements to irrigation systems and conveyance structures did not violate Article IV-D of the compact by materially depleting the waters of the Arkansas River. The Rules require an annual application to the State Engineer's Office for improved efficiency stating the location of the improvement, description of the improvement, and any other relevant information such as engineering reports describing potential consumptive use impacts or return flow pattern changes.

Applying for an irrigation efficiency improvement can be completed in one of two ways; either through an unaccompanied application (single farm) or through a joint application (conservancy district or mutual ditch company). Rule 8 defines the process for an individual application. This route is generally cost prohibitive for a single entity, and therefore an extremely rare occurrence. Rule 10, the joint application, is far and away the most common form of applying for an irrigation efficiency improvement. Joint applications benefit LARV growers by allowing the cost of engineering analysis to be divided between multiple growers, and benefit the State Engineer's office by aggregating paperwork and modeling efforts into one analysis. Rule 10 plan costs and benefits will be discussed in later

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[13] Hereon referred to as Rules. Full text of the Rules available at: http://water.state.co.us/DWRIPub/Documents/ArkRBIrrigationImprovementFinalRulesAndAttachmts.pdf

sections. This policy has significantly reduced the transaction costs of making a change to one's irrigation system.

1.3 Irrigation Systems and Performance

Agricultural production is made possible in the semi-arid LARV through irrigation. With average summer precipitation ranging between 5.1 and 7.8 inches, most crops would not produce without the supplementary water that irrigation provides (Schneekloth and Andales 2017). Therefore, it is understandable that such large percentages of LARV water withdrawals are used for irrigation (See Table 1). However, the design and performance of irrigation systems are vast and variable; highly dependent on management, maintenance, and measurement. It is common to measure the performance of an irrigation practice on its efficiency in both conveying water to the field, and applying water to a crop. The measures referred to throughout this thesis are conveyance efficiency (E_c) and application efficiency (E_a), and are calculated as follows according to Rodgers et al. (1997):

$$\mathrm{E_c} = \frac{\text{Volume of water applied to field}}{\text{Volume of water diverted from water source}} \tag{1}$$

$$\mathrm{E_a} = \frac{\text{Volume of water consumed by crop14}}{\text{Volume of water applied to field}} \tag{2}$$

This thesis examines the characteristics and performance of the primary conveyance mechanism, and five irrigation practices that are commonly employed in the LARV. The specifications of these irrigation practices vary significantly across land types and operation habits. Generalizations are necessary to describe and model these systems at the region-wide scale. A description of the conveyance mechanism, and five irrigation practices (siphon-tube, gated-pipe, laser-leveled gated pipe, center-pivot sprinkler, and drip) follows.

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[14] Water consumed by a crop is the volume of water used by the crop for growth and cooling purposes.

1.3.1 Conveyance System

All irrigation systems presented are assumed to be irrigating with surface water, delivered through an irrigation ditch. Irrigation ditches are open-channel conveyance structures, operated and maintained by a ditch company. Ditch companies, also referred to as mutual ditch companies, are non-profit, private entities generally organized by and for localized groups of irrigators to transport water from a surface water source, to non-riparian area for purposes of crop irrigation. Irrigators purchase shares in a ditch company, proportional to the amount of water they have a right to, and pay annual membership dues for operation and maintenance services. Ditch companies manage a portfolio of water rights owned by the shareholders (Jones and Cech 2009). As previously stated, ditches in the LARV are generally open-channel, earthen bottom structures. Losses in conveyance occur primarily in the form of seepage, but also occur through evaporation. Efficiencies of earthen canals vary depending on underlying soil material and length. The United States Department of Agriculture's National Engineering Handbook (Martin, Gilley and Baumer 1993) estimates conveyance in earthen canals to be between 65% and 90% efficient.

1.3.2 Irrigation Systems

This thesis focuses on five commonly employed irrigation practices in the LARV. These practices were identified with the assistance of the Arkansas River Management Action Committee (ARMAC[15]), a stakeholder group consisting of local growers, water managers, and policymakers who were organized in 2015 to advise this research. The practices included in this analysis are thought to represent the vast majority of irrigation practices in the LARV. The most basic of these systems are gravity-fed, and apply water to a series of earthen channels (furrows) running between rows of crops. Furrow irrigation is the dominant method of irrigating in the LARV, and is accomplished through a variety of application

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[15] More information on the ARMAC available at: https://www.coloradoarmac.org/about-us

systems. Application efficiencies (Eq. 2) for furrow irrigation carry the most variability, and are expected to range between 40% and 90% (Irmak et al. 2011; Barta et al. 2004; Rodgers et al. 1997). Siphon-tube furrow involves applying water from an irrigation field ditch into furrows, using a set of curved plastic or aluminum tubes and gravity, requiring one siphon-tube per irrigated furrow. This process is labor intensive, requiring significant field preparation, siphon-tubes to be hand set, and furrows to be continually monitored and kept clear. An improvement to the siphon-tube system is the gated-pipe furrow system. Replacing siphon-tubes is a series of PVC or aluminum pipes with small, sometimes adjustable slots (gates) that distribute water into furrows. Gated-pipe can be less laborious than siphon-tubes because pipes are do not need to be set for each irrigation event. Gated-pipe systems also reduce on-farm irrigation losses since water is now conveyed through the pipe as opposed to field ditches. Because gated-pipe systems are still a furrow irrigation system, they are assumed to have the same range of efficiencies (40%-90%), although it is reasonable to expect a higher average efficiency due to reduction in losses associated with application through pipes. The final furrow irrigation system considered is a gated-pipe system, on a field that has been laser-leveled. Laser-leveling is a practice to reduce and smooth the slope of irrigated fields using laser-guided excavation techniques. Reduced irrigation runoff, increased uniformity, and reduced soil erosion are benefits of laser-leveling. This practice is expected to reduce the variability of expected efficiencies to between 60% and 90%.

The other class of irrigation systems examined in this thesis are pressurized, and include center-pivot sprinkler[16] and drip irrigation. Pressurized systems vary significantly from gravity-fed surface systems in that they apply water in uniform, precisely measured fashion. Employing pressurized irrigation requires consistently supplied, debris-free water, which can be difficult to access for some less-senior water rights holders. In many cases, head stabilization ponds are installed to allow sediment to settle out, and surges of water to be temporarily stored. Sprinkler irrigation, especially surface water

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[16] Hereon referred to as sprinkler.

fed, has expanded significantly since the enactment of the Irrigation Improvement Rules (2010). Under sprinkler irrigation, water is pumped into the sprinkler system and applied from nozzles suspended above the crop. The system rotates around a center-pivot point, allowing for large areas to be irrigated, although this system may require field modifications to accompany a circular shape. The area under a center-pivot sprinkler irrigation system is often referred to as the footprint; footprints of 120, 90, and 60 acres are considered in this analysis. The efficiencies of sprinkler irrigation are expected to range between 75% and 95% (Irmak et al. 2011; Barta et al. 2007; Rodgers et al. 1997), depending primarily on management and nozzle height.

Drip irrigation is the other system included in the pressurized class. Drip irrigation systems deliver constant water directly to the crop root-zone in micro-sized volumes, through a perforated tubing referred to as drip tape. Drip tape can be installed above ground or subsurface, and requires close monitoring to ensure water is being emitted. A constant, reliable water source is paramount to drip irrigation systems, limiting their feasibility and applicability in the LARV because many irrigators receive sporadic deliveries throughout the season. However, expansion opportunities may exist along ditches with the most senior water rights. The expected efficiency of drip irrigation is the highest of all systems, ranging between 85% and 100% (Irmak et al. 2011; Barta et al. 2004).

Improvements in crop yields and/or quality are not uncommon when installing improved irrigation systems. These impacts played an important role in the adoption decision for ARMAC producers who reported adopting sprinklers or drip irrigation. While an efficiency improvement accompanied by proper reductions in applications should have no yield impact, many LARV producers report yield increases. In talking with Colorado State University Extension Irrigation Specialist, Joel Schneekloth, it is common for a 5%-15% increase to occur as a result of improved uniformity and better timing of application. Changes in yield resulting from decreased soil salinity will be addressed separately in later sections. For this thesis, I will assume a 12% yield increase in average per acre yields between the least and most efficient irrigation systems. Table 2 shows yield differences between the irrigation systems in this analysis.

Table 2. Per Acre Yield Differences between LARV Irrigation Systems

		Alfalfa	Corn	Wheat	Sorghum	Onion	Melon
Units	Yield	Tons	Bushels	Bushels	Bushels	CWT	CWT
LESA Center Pivot	100%	5.23	218.26	78.95	92.58	503.28	251.64
SDI	100%	5.23	218.26	78.95	92.58	503.28	251.64
Laser Leveling (Gated Pipe)	95%	4.96	207.34	75.00	87.95	478.12	239.06
Gated Pipe	92%	4.81	200.80	72.64	85.18	463.02	231.51
Siphon Tubes	88%	4.60	192.07	69.48	81.47	442.89	221.44

Given the performance of improved irrigation systems, it is suspected that adoption rates might be higher than currently exist. Figure 2 shows the irrigation mix in the LARV since 2004 and suggests significant growth in sprinkler and drip systems in recent years. As mentioned earlier, furrow systems require large river diversions and are associated with higher levels of irrigation return flows. These characteristics contribute to a series of water related concerns that are discussed in following sections.

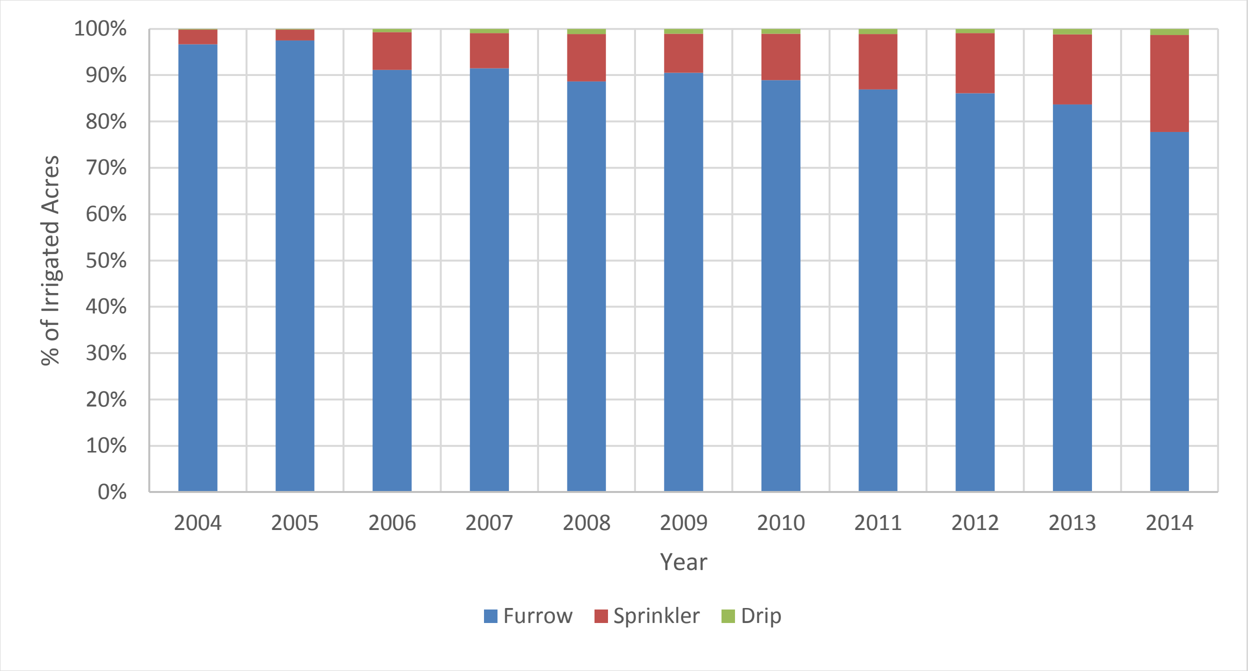

Figure 2. LARV Irrigated Acres by Irrigation System (2004-2014)
Notes: Data for Figure 2 was provided by the Colorado Division of Water Resources from the H-I Model used to maintain the Arkansas River Compact

1.4 Emerging Concerns Related to Arkansas River Water

As previously stated, the waters of the Arkansas River continue to be demanded at rates that far exceed availability. Water is demanded in all directions, for various uses, and with increasing intensity. Population steadily increased in the LARV's most urban county[17] (Pueblo) from 2002 to 2014, while steady declines have occurred over the same period in its more rural counties (Bent, Otero, Crowley, Prowers) as shown in Figure 3. Population forecasts for the year 2050 project continued decline or trivial growth in the rural counties, with significant population growth in Pueblo County, in the magnitude of a 40% increase. At daily per capita rates of 131 gallons in Pueblo County (Ivahnenko and Flynn 2010), 40% growth in population amounts to about an additional 9,100 ac. ft. of demand per year. Neighboring El Paso County also projects significant urban[18] population growth of about 60% by 2050.

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[17] 2010 estimates from the U.S. Census Bureau place about 86% of Pueblo County's population in urban areas

[18] 2010 estimates from the U.S. Census Bureau place about 90% of El Paso County's population in urban areas

Assuming equal per capita daily rates, this population growth will increase annual demand by about 60,800 ac. ft. Growth in El Paso County is relevant as it direct proximity to the LARV makes agricultural water a prime target to meet growing demands[19] Meeting this demand will likely require water transfers (temporary and permanent) from agricultural uses to municipal uses, which could have beneficial impacts on LARV water quality.

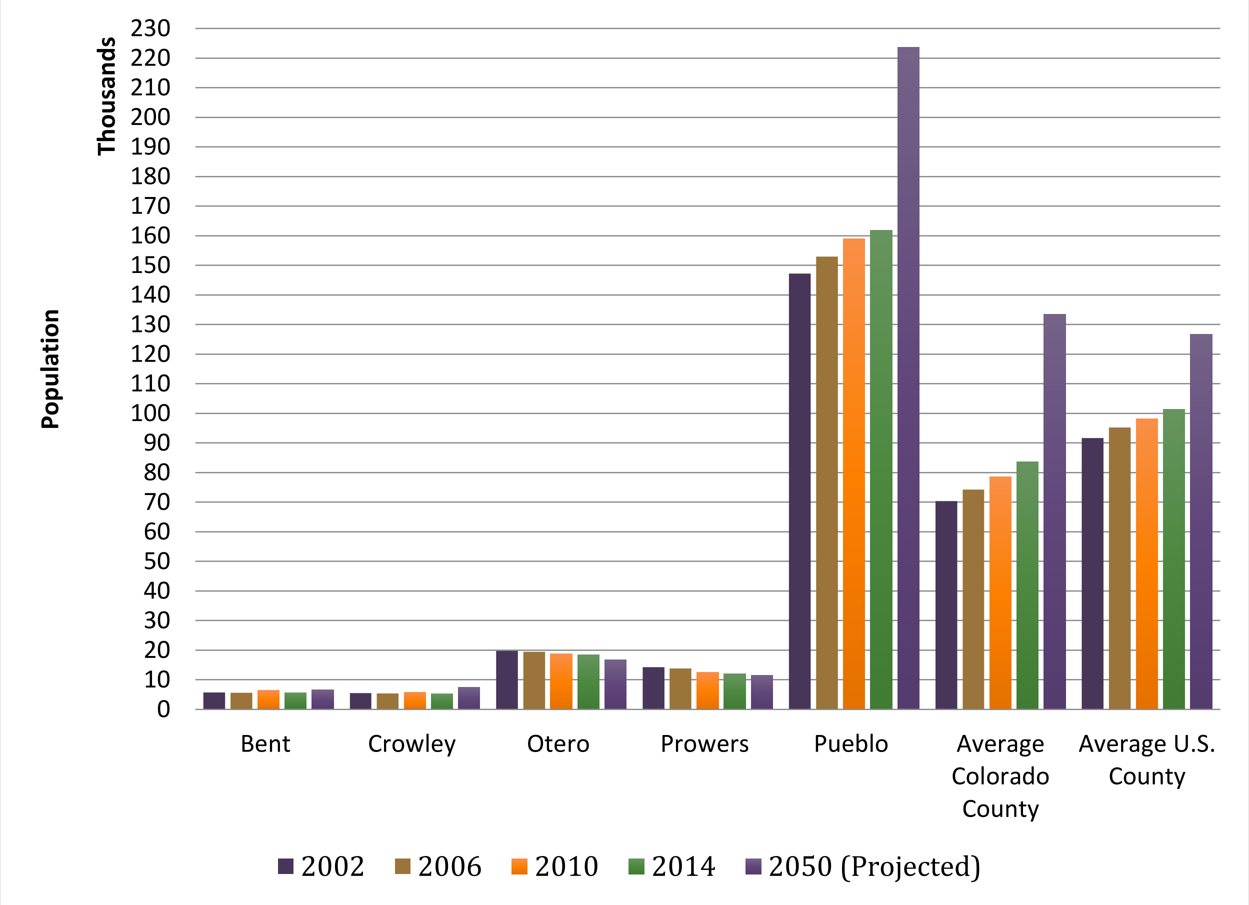

Figure 3. Population Trends in LARV Counties Compared to State and National Average
Notes: Data for Figure 3 was compiled from the U.S. Census Bureau and the Colorado State Demographer's Office

Concurrent to the water *quantity* issues, water *quality* measures in the Arkansas River reveal worrisome levels of a variety of pollutants including selenium, salts, nitrates, and uranium (Gates et al. 2002; Gates et al. 2009; Morway and Gates 2012, Gates et al 2016). The following subsections highlight

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[19] The City of Fountain, in El Paso County, was a participant in the 2015 Catlin Canal lease fallowing pilot project.

the emerging pollution concerns threatening the Arkansas River, agricultural producers, and LARV communities.

1.4.1 Water Quality Concerns

Selenium pollution is well documented in the LARV. Numerous studies have linked elevated selenium concentrations in the Arkansas River to the region's underlying shale bedrock, and the high volumes of irrigation return flows (Seiler, Skorupa and Peltz 1999; Gates et al. 2009, Miller et al. 2010, Gates et al. 2016). Selenium concentrations are found to exist far beyond the Colorado Department of Public Health's (CDPHE) chronic standard for aquatic life habitats of 85th percentile measure of 4.6 μL^{-1}. Gates et al. (2016) sampled two sub-regions in the LARV, an upstream study region (USR) and a downstream study region (DSR), and recorded 85th percentile measures of 13.5 μL^{-1} (USR) and 15.2 μL^{-1} (DSR). Eisler (1985) aggregated existing studies on selenium's environmental effects, and documented the impacts of high selenium concentrations on aquatic, bird, and mammal species including skeletal deformities, reproductive irregularities, and death. Bioaccumulation of selenium though the food chain intensifies the impacts of elevated stream concentrations as fish consume other aquatic species. Livestock populations in the LARV also risk exposure through locally grown feeds that are irrigated with selenium rich waters. Selenium exposure to livestock can result in acute selenium poisoning (short-term exposure), or a chronic condition known as alkali disease (long-term exposure), both of which can lead to hair-loss, hoof deformities, loss of appetite, lethargy, and death (Davis et al. 2000). Reducing selenium levels in the Arkansas River is thought to be achievable with the reduction in volume of irrigation return flows and leached nitrates associated with nitrogen fertilizer.

Elevated salinity represents another well documented pollutant that causes problems for the LARV in both the Arkansas River and the soils where agricultural production takes place. Salts build-up in LARV soils in two primary ways; irrigation water applications from the saline rich Arkansas River, and up-flux from shallow, saline water tables. Both of these processes introduce salt to the root-zone of a crop, and when water is consumed through evapotranspiration, salts are left behind. Salts are also dissolved and mobilized from the underlying shale formations and weathered residuum by irrigation return flows.

Shallow, saline water tables represent a persistent problem throughout the Lower Arkansas River Valley (Sutherland 2008, Gates et al. 2002). Morway and Gates (2012) investigated the relationship between soil salinity and depth to water table, identified an inverse non-linear relationship, and suggested that lowering water tables across the region could reduce negative crop yield impacts. Houk, Frasier and Schuck (2004) estimate that salinity build-up and waterlogging costs producers on average about $68 per acre in Otero County. The BMPs tested in this thesis aim to reduce losses to soil salinity by lowering regional saline water tables, and therefore reducing salinity levels in the crop root-zone.

Nitrogen enters the hydrologic system primarily by means of fertilizer applications for agricultural production. Nitrogen fertilizer applications that exceed crop uptake result in loading to the Arkansas River and leaching to subsurface aquifers, and is found to aid in selenium dissolution and mobilization (Bailey, Hunter and Gates 2012). Nitrogen generally exists in aquatic ecosystems as nitrate, nitrite, ammonium, and organic nitrogen. Elevated nitrogen concentrations can lead to eutrophic conditions, where rapid algae growth and decay consume dissolved oxygen and result in fish kills (Perlman 2017). Elevated nitrate levels also pose a threat to human health, primarily in infants, and can cause a condition known as “blue baby syndrome” (Perlman 2017). Halvorson, Schweissing and Reule (2002) and Halvorson et al. (2005) identified high residual soil nitrogen levels along the Rocky Ford Highline Canal, suggesting over application of nitrogen fertilizers.

1.5 Best Management Practices and Institutional Factors

This thesis investigates the cost effectiveness of a series of best management practices (BMPs) that are expected to improve environmental outcomes in the LARV. These BMPs have been identified by researchers in the CSU Dept. of Civil and Environmental Engineering, and have been approved by the ARMAC as realistic and reasonable. The BMPs, and application levels that I investigated, include:

- Reduced Irrigation Application (RI) (10%, 20%, 30%)
- Reduced Canal Seepage (CS) (20%, 40%, 60%, 80%)
- Reduced Nitrogen Fertilizer Application (RF) (10%, 20%, 30%)
- Increased Lease Fallowing Acreage (LF) (10%, 20%, 30%)

Along with single BMP analysis, combinations of these BMPs will be investigated. Combination scenarios will include all pairs of BMPs, combinations of three BMPs, and all four BMPs together. Including the baseline scenario, there are 15 possible BMP combinations, with 44 levels of analysis.

1.5.1 Reduced Irrigation

The reduced irrigation (RI) BMP is implemented by reducing the volume of irrigation water applied to fields across the Upstream Study Region (USR). Reduction in applied water does not necessarily constitute changes in consumptive use volumes. Reductions in applied irrigation water volumes are projected to be achievable through irrigation efficiency improvements throughout the USR given that, as application efficiency increases, less water needs to be applied to meet crop consumptive use requirements. Another method of achieving reduced irrigation water application volumes involves taking acres out of irrigation. A version of this method, lease fallowing, is presented and described in a later section. The final method of reducing irrigation application volumes is to reduce the volume of irrigation water applied to a crop. In many cases, this method is expected to have a negative yield impact and is not considered in this analysis. The levels of reduced applied irrigation water volumes tested in this thesis range from 10% to 30%, in 10% increments.

Reducing applied irrigation water volumes is expected to contribute to the improvement of a number of LARV environmental concerns. Reducing the volume of water applied to fields should directly result in increased flow volumes in the Arkansas River and decreased volume of irrigation return flows. Leaving water in the Arkansas River helps reduce the concentration of pollutants in the river and improves the habitat of aquatic species. Reducing irrigation return flow volumes is critical to minimizing soil waterlogging, mineral dissolution and transport, and non-beneficial consumptive use.

1.5.2 Canal Sealing

The canal sealing (CS) BMP is designed to reduce the volume seepage from canals. While there are numerous methods of stopping canal seepage, the focus in this thesis is on the application of granular linear anionic polyacrylamide (PAM). PAM is a water soluble polymer that, when applied in granular form to irrigation conveyance structures, has proven to be a cost-effective method of reducing seepage from the bottom and sides of unlined canals (Susfalk et al. 2008). Previous experiments of PAM applications in LARV canals found significant seepage reduction potential as shown in Table 3.

Table 3. Reported Impacts of PAM Application on LARV Canals

Canal[a]	Study Reach Length (km)	Average Pre-PAM Total Seepage ($m^3\ s^{-1}$)	Average Pre-PAM Seepage Rate ($m^3\ s^{-1}\ km^{-1}$)	PAM Application Rate (kg ha^{-1})	Average Seepage Reduction
Catlin-1	3.9	3.1	0.04	18.3	87%
Catlin-2	3.9	4	0.03	12.1	76%
Rocky Ford Highline-1	32	4.1	0.01	13.3	0%
Rocky Ford Highline-2	4	3.5	0.06	14.3	59%

Notes: Per Susfalk et al. (2008), [a]Includes only LARV canals in the Upstream Study Region (USR)

Susfalk et al. (2008) cites the existing low seepage rate and a lack of sufficient suspended sediment concentration as reasons to why no seepage reduction was recorded in the Rocky Ford Highline-1 trial. Based on these results, I assume that up to an 80% reduction in seepage is achievable under ideal conditions.

1.5.3 Reduced Nitrogen Fertilizer

The reduced nitrogen fertilizer (RF) BMP reduces the amount of applied nitrogen fertilizer on fields by up to 30%, in 10% increments. Nitrogen has been determined to be both a direct pollutant to the river, and an indirect pollutant, acting as a catalyst for selenium dissolution (Gates et al. 2009; Bailey, Hunter and Gates 2012). Furthermore, previous studies have suggested that nitrogen fertilizers are over applied in the LARV (Halvorson, Schweissing and Reule 2002; Halvorson et al. 2005). I project that managing nitrogen loading to waterways could have beneficial impacts on efforts to reduce selenium levels, while having a negligible impact on regional crop production.

1.5.4 Increase Lease Fallowing

The lease fallowing (LF) BMP takes land out of agricultural production, and makes water available for temporary transfers to local cities for municipal use. Lease fallow agreements are often executed for a single year, and are currently being tested as interest in alternative transfer methods in Colorado grows (Colorado Water Conservation Board 2015). Lease fallowing is currently only allowable under a State Engineer approved pilot projects per HB 16-1228. However, the Catlin Canal operated a successful lease fallowing project over the 2015 irrigation season, which may lead to more support of these projects.

Lease fallowing provides an alternative for what is generally referred to as permanent “buy and dry”, where water rights are sold and transferred to municipalities, and agricultural land is taken out of agricultural production, or “dried up. Permanent transfers of water from rural agricultural uses to urban municipal and industrial uses create three types of economic impacts; direct income impacts to sellers, indirect income impacts to local agriculture-dependent industries; and induced impacts in the form of population fluxes and local good and services consumption (Charney and Woodard 1990, National Research Council 1992). The degree to which these impacts negatively affect a community depends on the level of diversification in said local economy (Howe and Goemans 2003). The broad negative economic and social impacts on rural, undiversified communities when irrigation is no longer possible are evident in Crowley County (Sanchez 2014). However, the comprehensive impacts of temporary transfers are less well documented.

Lease fallowing is expected to provide two benefits; environmental and economic. Instead of irrigation water being applied to a field, the consumptive use portion of a water right is leased to a different user (generally a municipality). Therefore, we expect similar environmental impacts as the reduced irrigation BMP; that is, a drop in water tables, increased river flow volumes, decrease in mineral dissolution and transport loads, and decrease in non-beneficial consumptive use. Economically, lease fallowing offer an opportunity to directly exchange water for revenue, often at higher margins than under agricultural production; participants in the 2015 Catlin Pilot Project reported per acre returns on fallowed fields of $1031 (Lower Arkansas Valley Water Conservancy District 2015). It is also imperative to recall that under lease fallowing, the local agricultural producers maintain full ownership of the water right, allowing agriculture to maintain its role in the LARV economy in years where fields are not fallowed.

1.5.5 Institutional Factors

Implementing BMPs is complicated by the institutions and rules that govern water use in the LARV. The objectives of maintaining Compact compliance by preventing changes to return flow patterns create extra costs for LARV growers and may also be slowing efforts improve water quality conditions in the region. All but the reduced fertilizer BMP require some form of state approval to implement. Rule 10 plans are required for both the canal sealing and reduced irrigation BMP, while currently lease fallowing is only permitted under a state engineer approved pilot project. These factors are considered in the analysis by including a cost to participate in a Rule 10 plan for all acres under sprinkler and drip irrigation, a cost of purchasing replacement water for any changes in canal seepage, and limiting the canals on which lease fallowing is allowed to occur. Furthermore, the subsequent economic modeling efforts capture the impacts of the priority water rights system by methods that are later discussed. For example, one of these impacts is the limitation of the lease fallowing to only the most senior canals in the USR (Catlin, Rocky Ford Highline, and Rocky Ford Ditch).

Chapter 2: Quantifying Economic and Environmental Trade-Offs Faced by LARV Irrigators

The purpose of this thesis is to estimate the economic and environmental trade-offs that are associated with a set of irrigation-related Best Management Practices (BMPs). For this portion of the research, an economic linear programming model is constructed to estimate optimized net returns from irrigated agricultural production in a LARV sub-region. This economic model is coupled with a series of regional water flow and reactive solute transport models that estimate changes in a series of water quality measures. A complete description of the environmental information provided by these models is presented later; a description of the water flow (MODFLOW-UZF1 and MODFLOW-SFR2) and solute transport (RT3D-OTIS) models are documented in Niswonger, Prudic, and Regan (2006), Niswonger and Prudic (2010), and Shultz (2017), respectively. This approach of modeling both economic and environmental outcomes is generally classified as hydro-economic modeling. The following sections outline the hydro-economic modeling framework, present the crop enterprise budgeting methods used in model development, describe the linear programming model, and preview the economic results.

2.1 Hydro-economic Modeling

Hydro-economic modeling is a method commonly employed to represent region-scale water systems by combining the physical, economic, and institutional characteristics of a region, and allowing for analysis of management, policy, and/or infrastructure changes. Modern hydro-economic models utilize the economic characteristics of water, such as scarcity and value-generating ability, to solve complex allocation problems, and are able to account for unique institutions, dynamic environments, and temporal changes (Clyde 1971, Harou et al. 2009). Clyde (1971) describes the use of operations research methods for water resource allocation and management, and provides one of the earlier applications of linear programming to a water resources problem. Clyde (1971) minimizes the cost of supplying water to ten hydrologic study units in Utah. In their review piece of hydro-economic modeling, Harou et al. (2009) describe the various forms these models determined by the objective (simulation/optimization), time variability (static/dynamic), approach (deterministic/probabilistic), and construct (modular/holistic). Each of these characteristics contributes to the complexity and uniqueness of the modeling effort.

Booker and Young (1994), Rosegrant et al. (2000), and Cai, McKinney, and Lasdon (2003) represent examples of integrated basin-scale hydrologic-economic models that account for diverse physical and institutional conditions in the Colorado, Maipo and Syr Darya River Basins respectively. Each model operates with an underlying economic optimization objective to maximize net economic returns from agricultural production, hydro-electric power generation, and municipal/industrial (Rosegrant et al. 2000) or ecological services (Cai, Mickinny, and Lasdon 2003). These models are applied to analyze water management strategies, salinity control measures, and in the cases of Booker and Young and Rosegrant et al., water trading programs. These models are holistic in that water availability and transportation, crop production levels and portfolios, and salinity balance equations are determined endogenously within a single model. While holistic models illustrate the vast capabilities of hydro-economic modeling, they often require years of data collection and model development, and therefore exceed the complexity of the modeling efforts presented in this thesis.

This thesis takes a modular approach where the economics of best management implementation are modeled independent of the physical water flows and impacts using a linear programming economic optimization model. Jacovkis et al. (1989) describes the linear programming (LP) framework for water resources management and planning as a computational exercise in optimizing the design and use of a multi-purpose water resource system. A static LP models assumes the hydrologic conditions of an average year, constant annual costs of operation, and a constant mix of various crops. Irrigation discharge for a given crop, in a given node, is determined by a known, constant parameter, which assures optimal crop yield. Jacovkis et al. (1989) also describes the use of constraints to bound upper and lower limits of crop production for physical, economical, and political reasons. The framework described closely resembles the model developed for this thesis. The flexibility of linear programming accommodates several dimensions at a time, and easily accounts for factors that are in discrete increments, which allowed me to consider economic, bio-physical and institutional dimensions simultaneously. A deeper exploration into the underlying economic theory and mechanics of liner programming follows.

Extensive applications of linear programming models to water resource planning exist throughout the literature. Applications include water quality management, water allocation, crop production and trade, and analysis of best management practices for pollution loading. Loucks, Revelle, and Lynn (1967) used linear programming in identifying the least-cost scenarios to meet in-stream dissolved oxygen standards. Pearson and McRoberts (2011) identify optimal levels of crop production and trade in Germany in the context of virtual water.[20] In this context, the trade value in Germany is maximized subject to water and land constraints, and agricultural output (virtual water) can be both imported and exported. Alminagorta, Tesfatsion, Rosenberg, and Neilson (2012) use an LP model to minimize phosphorus removal costs for a set of BMPs, subject to meeting proposed Total Daily Maximum Loads (TMDL) limits to the Echo Reservoir, and along the Webb River in northeastern Utah. This model uses BMP specific phosphorus reduction estimates to calculate changes in reservoir loads from a series of sub-watersheds along the Webb River. Alminagota et al. (2012) describe the simplicity and generality of linear programming as significant benefits that allow for a broader and more flexible application of the model. Common between these models is the application of economic optimization to a constrained water-resource allocation problem; be it water quality or water quantity. However, the linking of a mathematical programming model to an independent water flow and solute transport model

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[20] Virtual water refers to water used in production agricultural products that is ultimately consumed, exported, or in imported

for trade-off analysis is unique to a smaller number of studies. Along with linear programming, the coupled model approach has also been employed. Attwood et al. (2000) applied this method on a national scale using a mathematical programming Agricultural Sector Model (ASM) and the water-flow modeling Soil and Water Assessment Tool (SWAT). Attwood et al. (2000) addresses the challenges in regional modeling of economic and environmental changes which are often being limited: (1) to analysis of edge of field or crop root-zone movements of sediments pesticides, and nutrients, and (2) by the exclusion of changes in land uses and crop management and in differing physical boundaries/level of data aggregation (i.e. watershed vs. counties vs. state). The linking of their models is based on the ASM feeding an optimal crop mix into the SWAT model, which generates water flow and quality impacts. Cools et al. (2011) also employ the coupled model method to identify cost effective pollution abatement sets that conform to an in-stream concentration standard. The economic component minimizes abatement costs using a mixed-integer programming approach.

2.2 Crop Enterprise Budgeting

Crop enterprise budgets are a common tool used in farm planning and analysis. Crop enterprise budgets present the operating and equipment ownership costs of crop production, along with output levels and prices to allow for an estimation of per acre costs and returns. Crop enterprise budgets generally present estimates for a typical farm, and a series of blank lines for customization. Colorado State University publishes annual budgets for the various crop producing regions throughout the state, including Southeastern Colorado. Colorado State University's published budgets[21] for Southeastern Colorado were utilized when available to estimate costs and returns, but the irrigation costs and yields were modified to more accurately account the irrigation scenarios examined in this case study (See

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[21] CSU Extension crop enterprise budgets can be found at: http://wr.colostate.edu/ABM/cropbudgets.shtml

Appendix 1 for example). All inputs that are independent of irrigation system are assumed constant. This process is described in the following sections.

2.2.1 Irrigation System Operating Cost Estimates

Five irrigation systems are considered in this thesis; siphon-tube furrow, gated-pipe, laser-leveled gated pipe, center-pivot sprinkler, and drip. These previously described systems present some general trends in there cost structure that become important. Less efficient systems (surface) tend to be more labor intensive, requiring more irrigation labor and field preparation. Improved efficiency systems on the other hand favor capital in place of labor with more, and more expensive, equipment.

The annual operating costs estimates are derived from a combination of published reports and interactions with the ARMAC, LARV producers, and CSU Irrigation experts. Based on the many variables that impact irrigation system operating costs, these estimates are assumed to be representative of a typical LARV operation for a given irrigation system, producing a given crop. Total operating costs associated with an irrigation system include labor, pumping, fieldwork, and replacement water. Rule 10 applications are presented for improved efficiency practices (sprinkler and drip) as an operating cost; although this cost is fixed in the short-run, it is a variable cost in the long-run consideration of sprinkler adoption.

Labor costs are assumed to be a function of the number of irrigators required to operate a system, the number of hours required per irrigation, and the total number of irrigations per season. In general, these costs decrease as more efficient irrigation practices are adopted. Wage rates were taken from the Bureau of Labor Statistics (2015) and local producers on the ARMAC were consulted with in determining labor requirements. A significant benefit of sprinkler irrigation is the reduction in the number of laborers required to irrigate. However, it is often the case that the labor required to operate sprinkler is of the management variety, and therefore a bit more expensive. The breakdown of labor costs between systems is shown below in Table 4.

Table 4. Estimated Labor Usage and Costs across Irrigation Systems

	Furrow (60 ac.)	Gated Pipe/ Laser Level (60 ac.)	Sprinkler (120 ac.)	Sprinkler (90 ac.)	Sprinkler (60 ac.)	Drip (60 ac.)
Labor Type	General	General	General/ Management	General / Management	General / Management	General / Management
Laborers (#)	3	2	1/1	1/1	1/1	1/1
Hours/ Irrigation	8	8	6/10	2/5	2/5	10/10
Rate ($/Hour)	12.31	12.31	12.31/21	12.31/21	12.31/21	12.31/21
Irrigations	8	8	8	8	8	8
Total Annual Irrigation Labor Cost	$2,363.52	$1,575.68	$2,270.88	$1,036.96	$1,036.96	$2,664.80
Per Acre Labor Cost	$39.39	$26.26	$18.92	$11.52	$17.28	$44.41

Notes: Values for labor usage and hours were estimated from conversation with local producers

Pumping costs are determined by the pumping-plant's fuel source and the water requirement of the crop; for this analysis, the focus is on low elevation spray application (LESA) sprinklers, operating with electricity.[22] More water intensive crops (alfalfa) tend to have higher pumping costs than crops with lower water requirements (melons). Fieldwork costs are associated with the hours and fuel required to prepare a field for production. The rates of these operations were obtained from Colorado State University Extension (Russell et al. 2015). It is common practice for a reduction in the number of field operations, primarily tillage and furrowing, to accompany adoption of sprinkler irrigation per communications with LARV producers.

Rule 10 costs and replacement water costs are also included in the calculation of operating costs. Rule 10 of the Irrigation Improvement Rules for Colorado allows for the joint-application for an irrigation efficiency improvement. The Lower Arkansas Valley Water Conservancy District (LAVWCD) operates a single Rule 10 plan for all producers in the five-county region. LAVWCD charges a $300 administrative fee to LARV farmers who are interested in participating in a Rule 10 plan, which includes

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[22] While the costing has also been conducted for diesel powers sprinklers, conversations with growers suggest that electricity is primary source of energy for sprinkler systems. The electrical rate structure use to calculate pumping costs was taken from the Southeast Colorado Power Association, and is available at: http://secpa.com/wp-content/uploads/2016/05/Schedule-ID.pdf

an engineering analysis of how improving on-farm irrigation efficiency affects future return flows. This analysis also provides both the state of Colorado and the individual producer with a detailed record of the producer's water use and irrigation system, which serves to benefit the producer in future water rights change cases. By conducting a single analysis for multiple LARV farmers at a time, the LAVWCD can significantly bring down the price of a typically expensive[23] analysis, which is required by the Irrigation Improvement Rules. Replacement water needs for each irrigated field are also computed in the Rule 10 planning process. Depletions or accretions are estimated for the planned irrigation change. If there are depletions, return flows are reduced, that farmer must buy replacement water to make up the difference. In some cases there are accretions, an increase in return flow volumes, primarily from the addition of head stabilization ponds, which seep to the groundwater. While an individual farmer cannot get credit for these accretions, they can be used to offset other farmers depletions, thereby lowering the costs for replacement water overall. An example of this is presented below.

Table 5 illustrates the impact of Rule 10 plan return flow accounting. Based on the 2016 Rule 10 plan, USR producers who adopted sprinkler or drip irrigation faced average depletions as large as 33 acre feet, and accretions up to 23 acre feet on the Rocky Ford Highline and Catlin Canal respectively. However, the total change in return flows summed across USR canals was positive, meaning that accretion volumes were greater than depletion volumes, and no farmers had to purchase replacement water.[24] Estimates for changes in return flows are based on a ten-year average, and depending on the location of depletions and accretions, this may not always be the case zero replacement water is required.

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[23] Estimates from LAVWCD engineers suggest that an engineering analysis as required by the Irrigation Improvement Rules could cost in the $10,000-$15,000 range for a single farm.

[24] While Table 9 shows only return flow change estimates for USR canals, the 2016 Rule 10 plan includes other canals outside of the USR. For the entire plan, it was also the case that accretions were greater than depletions, and replacement water was not purchased.

Table 5. Changes in USR Return Flows per 2016 Rule 10 Filings

Canal	Average Annual Δ in Return Flows (ac. ft./farm)	Total Δ in Return Flows (ac. ft.)
Rocky Ford Highline	-33.26	-299.30
Holbrook	2.40	24.00
Ft. Lyon	-10.20	-30.60
Catlin	20.11	422.30
Rocky Ford Ditch	-7.65	-15.30
Total USR	2.93	131.70

Notes: Negative and positive values represent depletions and accretions respectively

Table 6 below shows the estimated annual operating costs for the five irrigation systems. Costs presented in Table 6 include only those operating costs that are directly related to the irrigation system. Total operating costs are better represented in the crop budgets in Appendix 1. Notably absent from the operating costs are replacement water costs for improved irrigation systems (sprinkler and drip). Based on the water accounting practices used in the Rule 10 planning process, it is assumed that accretions will be sufficient to overcome depletions, and farmers will not have to purchase replacement water when installing sprinklers or drip irrigation. Table 6 generally shows that operating costs for irrigation are decreasing with the adoption of improved irrigation practices. This effect is driven primarily by the decreasing labor and field work costs associated with improved irrigation practices. This is not true for drip irrigation, which is estimated to increase labor costs.

Table 6. Per Acre Operating Costs for Suite of Irrigation Systems

	Acres	Labor	Pumping						Field Work (Tillage)	Rule 10 Costs	Total Operating Costs ($/acre)
			Alfalfa	Corn	Wheat	Onion	Sorghum	Melon			
Furrow (Baseline)	60	$39.39	$-	$-	$-	$-	$-	$-	$92.00	$-	$131.39
Gated Pipe	60	$26.26	$-	$-	$-	$-	$-	$-	$92.00	$-	$118.26
Laser-leveled Gated Pipe	60	$26.26	$-	$-	$-	$-	$-	$-	$92.00	$-	$118.26
LESA Center-pivot (Electric) (L)	120	$18.92	$26.48	$22.03	$20.69	$22.80	$22.10	$20.85	$35.00	$2.50	$78.91
LESA Center-pivot (Electric) (M)	90	$11.52	$31.60	$27.53	$26.31	$28.23	$27.60	$26.45	$ 35.00	$3.33	$77.80
LESA Center-pivot (Electric) (S)	60	$17.28	$42.74	$38.97	$37.85	$39.63	$39.04	$37.97	$35.00	$5.00	$96.65
SDI (Electric)	60	$44.41	$52.15	$43.65	$38.34	$40.46	$39.76	$41.39	$35.00	$5.00	$127.04

Notes: (1) Per acre operation costs are calculated based on the assumed field sizes for the analyzed irrigation systems

(2) Replacement water costs for on-farm irrigation efficiency improvements are assumed as zero under current LARV water accounting practices

(3) Total operating costs presented for pressurized irrigation systems assume an average pumping costs across all crops

2.2.2 Irrigation System Annual Ownership Cost Estimates

Irrigation system annual ownership costs are estimated assuming straight-line depreciation of a typical scenario, as described by the USDA Natural Resources Conservation Service (NRCS)[25]. Annual ownership costs are assumed to be paid over the life of an irrigation system, and are calculated as the sum of depreciation, interest, taxes, insurance, housing, and repairs and maintenance.

Interest is assumed at a real rate of 4%, and represents the opportunity cost of making an irrigation investment. Taxes, insurance, and housing costs (TIH) are assumed at 0.5% of the average between the initial investment costs and salvage value. Repairs and maintenance costs are estimated at 2% of the initial investment. Straight-line depreciation ($/yr.) is calculated as:

$$\text{Depreciation} = \frac{\text{Initial Investment} - \text{Salvage Value}}{\text{Expected Useful Life}} \tag{3}$$

Typical irrigation scenarios that were developed by the NRCS for the purpose of computing cost sharing were used to compute costs here. Table 7 presents per acre ownership cost estimates for these irrigation systems, including the complementary equipment required to operate the systems using surface water from the Arkansas River. Center-pivot sprinkler scenarios are considered for small, medium, and large sized fields measuring 60, 90, and 120 acres, respectively. While sprinklers were found to exist on fields as small as 30 acres, these situations are rare. The ownership costs for furrow irrigation, which dominates the region, are only about $5/acre compared to $97 for a center pivot irrigation system when including the costs to convey water to the system. The total cost of these two systems, when including operating costs from Table 6, are $135.39 and $175.91 respectively.

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[25] A description of the Colorado scenarios and payment schedule are available at: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/programs/financial/?cid=nrcseprd1328229

Table 7. Ownership Costs for LARV Irrigation Systems

Practice	Acres	Useful Life (Years)	Gross Investment Cost ($)	Salvage Value (PV $)	Depreciation ($/yr)	Interest ($/yr)	Taxes, insurance, housing ($/yr)	Repairs and Maintenance	Total Ownership Costs (TOC)	TOC/ Acre
Furrow	60	15	$3,038	$64	$198	$59	$8	$61	$326	$5
PVC Gated Pipe	60	15	$6,866	$762	$407	$122	$19	$137	$685	$11
Laser-leveling (Gated Pipe)	60	60	$98,238	$762	$1,625	$1,950	$248	$1,965	$5,786	$96
Center Pivot (MESA & LESA) (Large)	120	20	$98,144	$8,958	$4,459	$1,784	$268	$1,963	$8,474	$71
Head Stabilization Pond (Large)	120	20	$9,500	$-	$475	$190	$24	$190	$879	$7
Electric Pumping Plant (Large)	120	15	$12,215	$1,357	$724	$217	$34	$244	$1,219	$10
PVC Pipeline (1800 ft.)	120	25	$14,551	$1,092	$538	$269	$39	$291	$1,138	$9
Center Pivot (Medium)	90	20	$85,799	$7,832	$3,898	$1,559	$234	$1,716	$7,408	$82
Head Stabilization Pond (Medium)	90	20	$9,500	$-	$475	$190	$24	$190	$879	$10
Electric Pumping Plant (Medium)	90	15	$12,215	$1,357	$724	$217	$34	$244	$1,219	$14
PVC Pipeline (1600 ft.)	90	25	$12,934	$970	$479	$239	$35	$259	$1,011	$11
Center Pivot (MESA & LESA) (Small)	60	20	$71,691	$6,544	$3,257	$1,303	$196	$1,434	$6,190	$103
Head Stabilization Pond (Small)	60	20	$9,500	$-	$475	$190	$24	$190	$879	$15
Electric Pumping Plant(Small)	60	15	$12,215	$1,357	$724	$217	$34	$244	$1,219	$20
PVC Pipeline (900 ft.)	60	25	$7,276	$546	$269	$135	$20	$146	$569	$9
SDI	60	15	$120,777	$13,413	$7,158	$2,147	$335	$2,416	$12,056	$201

2.2.3 Canal Sealing Costs

Canal sealing costs are incurred in two ways; a per-mile material and application cost of linear anionic polyacrylamide sealant (PAM), and a replacement water cost resulting from reduced seepage. The costs of the applying PAM at the different BMP levels are based on the findings from Susfalk et al (2008), and assume a linear relationship between the amount of PAM applied and the reduction in canal seepage. As previously discussed, an 80% reduction in seepage was found to be achievable under ideal PAM application conditions in experiments conducted along the Catlin and Rocky Ford Canals in the LARV. The average application costs between the two canals is assumed to account for differences in canal width, application accessibility, and PAM effectiveness across the LARV. The cost per mile parameters used in the LP are presented below in Table 8.

Table 8. Per Mile Costs of PAM Application in the LARV

Seepage Reduction Scenario	20%		40%		60%		80%	
Canal	Catlin	Rocky Ford Highline	Catlin	Rocky Ford Highline	Catlin	Rocky Ford Highline	Catlin	Rocky Ford Highline
PAM Material Cost	$23.54	$32.95	$35.31	$49.43	$47.08	$65.90	$58.84	$82.38
Labor	$25.88	$25.88	$25.88	$25.88	$25.88	$25.88	$25.88	$25.88
Vehicle Use	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19
Fuel	$0.76	$0.76	$0.76	$0.76	$0.76	$0.76	$0.76	$0.76
Total Average Cost	$50.37	$59.78	$62.14	$76.26	$73.91	$92.73	$85.67	$109.21
Scenario Average Cost ($/mile)	$55.08		$69.20		$83.32		$97.44	

Notes: Values are based on the findings of Susfalk et al (2008). Costs have been averaged across experimental scenarios (application rate and application method) and converted to $/mile from $/km.

Another important note about the canal sealing BMP is in regards to the implementation is that it is assumed that all canal miles in the model are sealed. This leads to the cost of sealing canals being higher on longer canals, and does not account for those canals with higher seepage rates or which are proximate to selenium-containing shale formations.

2.3 Summary of Modeling

As previously described, the comprehensive modeling conducted in this thesis requires two separate modeling frameworks; the estimation of water flows and reactive transport impacts, and the estimation of economic outcomes. The basic interactions between the models are shown below in Figure 4. The linear programming model used in the economic analysis requires the same inputs as the water flow and reactive transport models, plus additional information on crop production costs, irrigation systems, and salinity distribution. The outputs from the water flow and transport models involve environmental factors, such as in-stream and groundwater flow, pollutant concentrations and water table. The economic model adds net returns and includes outputs from the other models for reference.

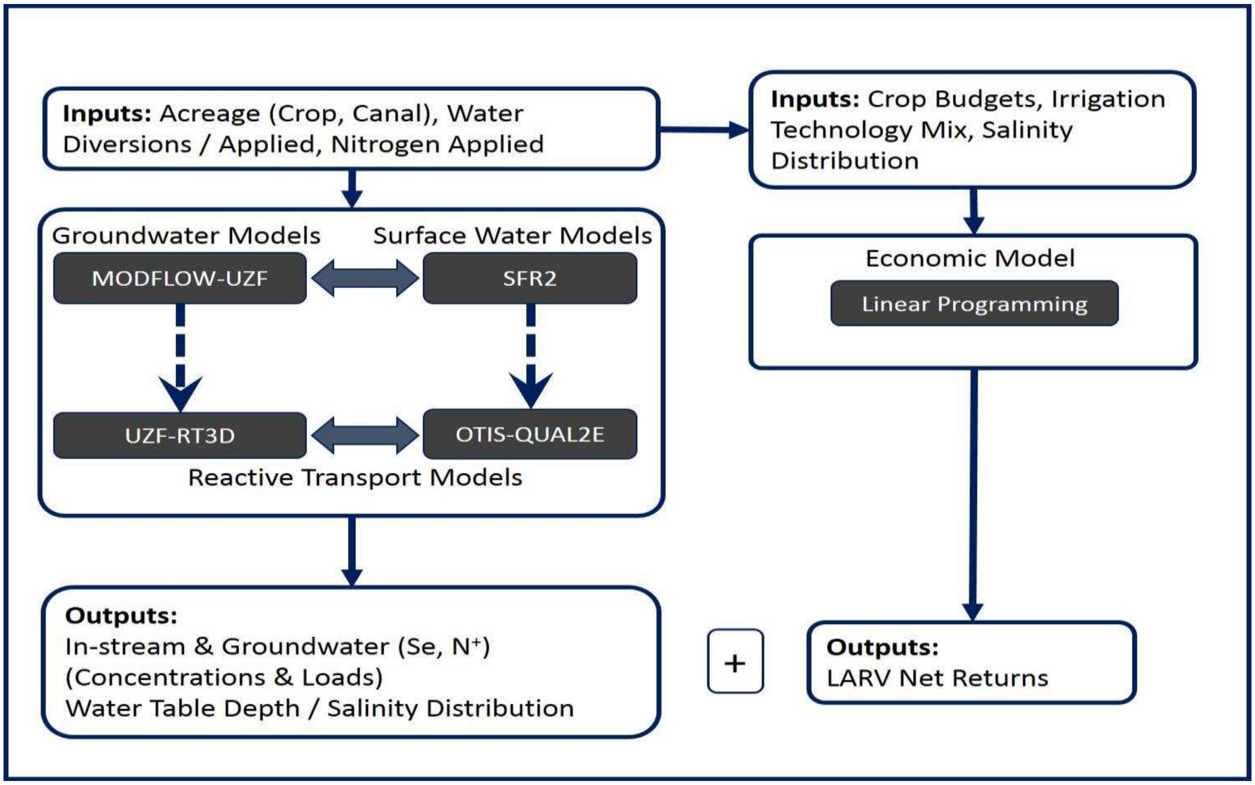

Figure 4. Overview and Interactions between Economic and Environmental Models

The basic structure of the LP model used for economic analysis is presented below as a stylized tableau. This illustration shows the components that drive the LP model in a clear, concise manner.

Table 9 is simplified to represent the important components of the model and intentionally omits the full crop set and irrigation technology sets. The stylized tableau clearly represents the decision variables, objective function, land and water constraints, and salinity and nitrogen impacts.

A title for the model's decision variables, those that determine the objective value, are represented across Row 1. The primary decision variable in the model is x_{ink}, which represents acres of crop *i*, under irrigation system *n*, on canal *k*. Row 2 represents the objective function coefficients that are multiplied by the respective variable in Row 1 to achieve the largest value in the Net Returns cell. The objective is to maximize net returns, which is the crops sold, less their production costs, plus an adjustment for the cost of purchasing replacement water when there is canal sealing or the reduced cost of nitrogen fertilizer when that input is reduced. Rows 3-7 represent land constraints for irrigation technology, crop, and total area, and are all set less than or equal to their respective limits. Notice that the drip irrigation column takes a value of zero in row 6 and a value of one in row 7. This is because the model is prevented from producing corn with drip irrigation[26], yet it does allow melons to be produced with drip. Rows 8-9 are inventory constraints that prevent the model from selling more that it produces by making the crop sales variable no larger than the total yield (acres*per acre yield). Rows 10 and 11 are used to track the applied water across the USR and by canal and implement the canal sealing BMP. By fixing the number of unsealed miles at zero, the model must select treated miles to equal the total canal mileage (seal all miles). Therefore, canal sealing depends on the amount applied per mile for all miles. Row 12 calculates seepage by canal, and is also used to implement the canal sealing BMP by limiting the right hand side value. Row 13 tracks salinity yield impacts, and transfers those values into the $\tilde{y}_{inS}$ cell where it is converted to a cost. Lastly, Row 14 is used to calculate the opportunity cost of a

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[26] Combinations of crop and irrigation systems were chosen based on conversations with the ARMAC committee, and are meant to be representative of common combinations in the region. In the model, corn, wheat, alfalfa, and sorghum are prevented from being produced with drip irrigation, while onions and melons are not. Melons and onions however, are not assumed to be produced using center pivot sprinklers, while remaining crops are. All crops can be produced with the suite of furrow systems.

reduced fertilizer scenario. The function of these constraints will be discussed in further detail in the coming sections.

Table 9. Stylized Tableau Representation of Linear Programming Model

1	Decision Variables	x_{ink}	…	x_{ink}	$\widehat{y}_{ink}$	$\widehat{y}_{ink}$	Untreated Miles (k)	Treated Miles (k)	$\widetilde{y}_{inS}$	ρ_{iN}	$\widetilde{y}_{inF}$		Right Hand Side
2	Objective	$-PC_{in}$	…	$-PC_{in}$	MP_i	MP_i		-CSC	$-\phi_S MP_i$		$-MP_i$	=	USR Net Returns
3	Siphon tube	1										≤	USR Land in Furrow
	⋮	⋮		⋮								⋮	⋮
4	Drip			1								≤	USR Land in Drip
5	Total Land Area	1	…	1								≤	USR Land Area (Total)
6	Corn	1	…	0								≤	USR Land in Corn
	⋮	⋮		⋮								⋮	⋮
7	Melon	1	…	1								≤	USR Land in Melon
8	Corn Inv.	y_{in}	…	0	-1							≥	0
	⋮				⋮	⋮						⋮	⋮
9	Melon Inv.	y_{in}	…	y_{in}		-1						≥	0
10	Applied Water (k)	A_{ink}	…	A_{ink}								=	Baseline Applied Water (k)
11	Canal Miles (k)						1	1				=	Total Canal Miles
12	Total Seepage (k)						δ_k^0	δ_k^1				≤	Baseline Seepage
13	Salinity Yield Impact (i,SL)	$\psi_{iS} y_{in}$	…	$\psi_{iS} y_{in}$					-1			=	0
14	Nitrogen Yield Impact	$\psi_{iF} y_{in}$	…	$\psi_{iF} y_{in}$						$\psi_{iF} y_{in}$	-1	=	0

Symbol Key

x	Acres indexed over *i,n,k*	y_{in}	Per acre yield of crop *i*, with irrigation technology *n*
i	Set of crops (including Lease Fallow)	$\widetilde{y}_{in(S,F)}$	Total yield losses attributed to crop *i,* resulting from soil salinity *S*, and Reduced Fertilizer level *F*
n	Set of irrigation technologies	A_{ink}	Applied water to crop *i*, with irrigation technology *n*, on canal *k*
k	Set of canals	δ_k^0	Untreated per mile seepage on canal *k*, as calculated from MODFLOW
S	Set of Salinity Levels ranging from Low to Severe	δ_k^1	Treated per mile seepage on canal *k*
F	Set of Nitrogen Fertilizer Reduction Level (10%, 20%, 30%)	$\psi_{i(S,F)}$	Per acre salinity yield impact on crop i, of salinity level S or yield impact of Reduced Fertilizer on crop i, by reduction level *F*
PC_{in}	Per acre production costs associated with crop *i*, with irrigation technology *n*	ϕ_S	Coefficient representing % of acres affected by salinity level *S*
MP_i	Market price of crop *i*	ρ_{iF}	Accounting variable for crop *i,* and reduction in fertilizer level *F*

2.4 Model Domain

This thesis focuses on a reach of the Arkansas River stretching from Manzanola, CO to Las Animas, CO, ending at the John Martin Reservoir (See Purple outline in Figure 5). This region is called the upstream study region (USR) of the overall CSU LARV analysis. Future efforts will include the downstream region (DSR), and coupling of the two study regions.

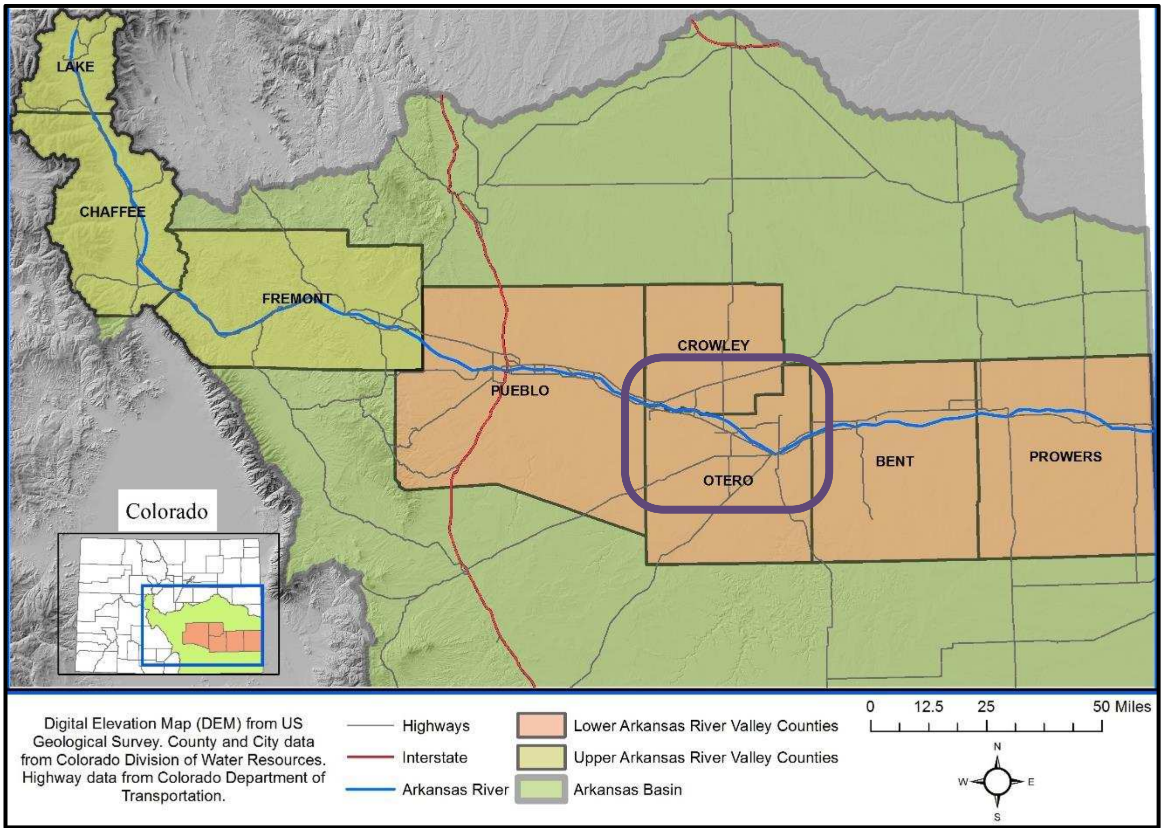

Figure 5. Map of Arkansas River Basin with Highlighted Upstream Study Region
Note: Map obtained from Blake Osborn, Colorado Water Institute

Baseline conditions for economic analysis are analyzed based average USR field conditions between 1999 and 2009. The region contains 71,065 irrigable acres, across six canals. Over the eleven-year study period, the USR averaged 52,518 irrigated acres.[27] With the assistance of the ARMAC,

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[27] Irrigated acres are calculated as the total land area less the average annual fallowed and unallocated acreage. Unallocated land is land in which cropping data was unavailable or not reported, and averaged 2,859 acres annually over the calibration period.

economically important crops were identified for the region. Irrigation application volumes are bounded as calculated from historical diversion data with MODFLOW, using the UZF1 (Niswonger, Prudic, and Regan 2006) and SRF2 (Niswonger and Prudic 2010) packages. The irrigation technology mix serves to combine information on water required and water applied by employing irrigation efficiency-adjusted water requirements for crops in the LARV. A discussion on these aspects and there relevance to the economic model follows.

2.4.1 Crop Mix

Economically important crops to the LARV include alfalfa, corn, wheat, sorghum, onions, and melons. The respective average annual acreages, percentage of average irrigated acreage, and coefficient of variation (CV) are presented in Table 10.

Table 10. USR Crop Mix for Economic Analysis (1999-2009)

Crop	Average Acres	% of Average Irrigated Land	CV
Alfalfa	22,984.64	44%	9%
Corn	8,662.82	16%	79%
Wheat	3493	7%	56%
Sorghum	3,493.45	7%	54%
Onions	470.91	1%	98%
Melons	763.55	1%	111%
Economic Crop Acres	39,868.36	76%	9.13%
Total Irrigated Acres	52518	100%	21.97%

As shown, these crops account for about 76% of total irrigated acreage. Much of the remaining acreage resides as pasture/grassland. It is assumed that irrigated acres of the listed crops remains constant at 76% throughout this analysis. Table 4 shows that alfalfa is both the most abundant (high average acres) and consistently produced (low CV[28]) crop. The relatively high volatility of crop acreages could be attributed to crop rotations and the relative uncertainty of water irrigation water deliveries, especially during the extreme drought conditions experienced in the 2002 and 2003 growing seasons, which left some farmers without any water for irrigation. Regardless of crop specific volatility, the average acres of the six crops analyzed remains consistent with a CV of 9.13% overall. Applied water volume for the baseline scenario, calculated using the Colorado Division of Water Resources (DWR) historical diversion data[29] and used in MODFLOW-SFR2, is presented in Table 11. The average proportion of total water applied in the model across the USR to the six economic crops is 84%.

Table 11. Irrigation Water Volumes Applied to Economic Crops by Canal (1999-2009)

	Catlin	**Fort Lyon**	**Holbrook**	**Otero**	**Rocky Ford Ditch**	**Rocky Ford Highline**	**Total**
Average Applied Water Volume (ac. ft.)	66,176	27,061	25,520	4,671	15,290	36,950	175,668
CV	38%	43%	41%	94%	55%	28%	33%

Notes: Applied water volumes exclude the 2008 year where data was irregular

Modeling applied irrigation water by canal allows for the implicit impacts of the priority water rights system. The canal specific CV measure, presented in Table 11, illustrates the impacts of canal seniority, where more senior-water-rights canals have lower CV measures than those more junior-right canals. The lower CV values for economic crop acres (Table 10) and total irrigation water applied volume show relatively low volatility between seasons.

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[28] Coefficient of variation (CV) describes the variation of an element around its mean. In this application, the CV of average acres provides us with information about how crop acreages change from year to year. Low CV values suggest that in given year, the acreage of a given crop will be close to its mean value. High CV values suggest there is more volatility in the annual acreage.

[29] Historical diversion data is available from the Colorado DWR for the structures in this analysis at: http://cdss.state.co.us/onlineTools/Pages/StructuresDiversions.aspx

2.4.2 Irrigation Technology Mix

Another relevant characteristic of this region is the irrigation technology portfolio. Information regarding the LARV's historic irrigation technology portfolio was extracted from the input data used in the Hydrologic-Institutional (H-I)[30] model. This model was approved by the Supreme Court appointed Special Master, along with Colorado and Kansas, to predict Stateline flow volumes and maintain the Arkansas River Compact. This data tracks annual changes in the LARV irrigation technology mix and suggests growth in sprinkler irrigated acreage in the LARV across time, with most of the rapid growth occurring below John Martin Reservoir. However, a positive trend in sprinkler-irrigated acreage is observed from 2004-2014 in the upstream study region as well. Figure 6 displays growth in total (surface and groundwater) sprinkler acreage in the USR, DSR, and LARV per data from the H-I model. More specific acreage for surface water-fed sprinklers on USR canals is extracted from Rule 10 application filings from 2016, and represents the baseline sprinkler acreage (5158 acres).

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[30] Documentation of the H-I model is available at: https://www.supremecourt.gov/specmastrpt/Amended_Appendix_C-1_9_2011.pdf

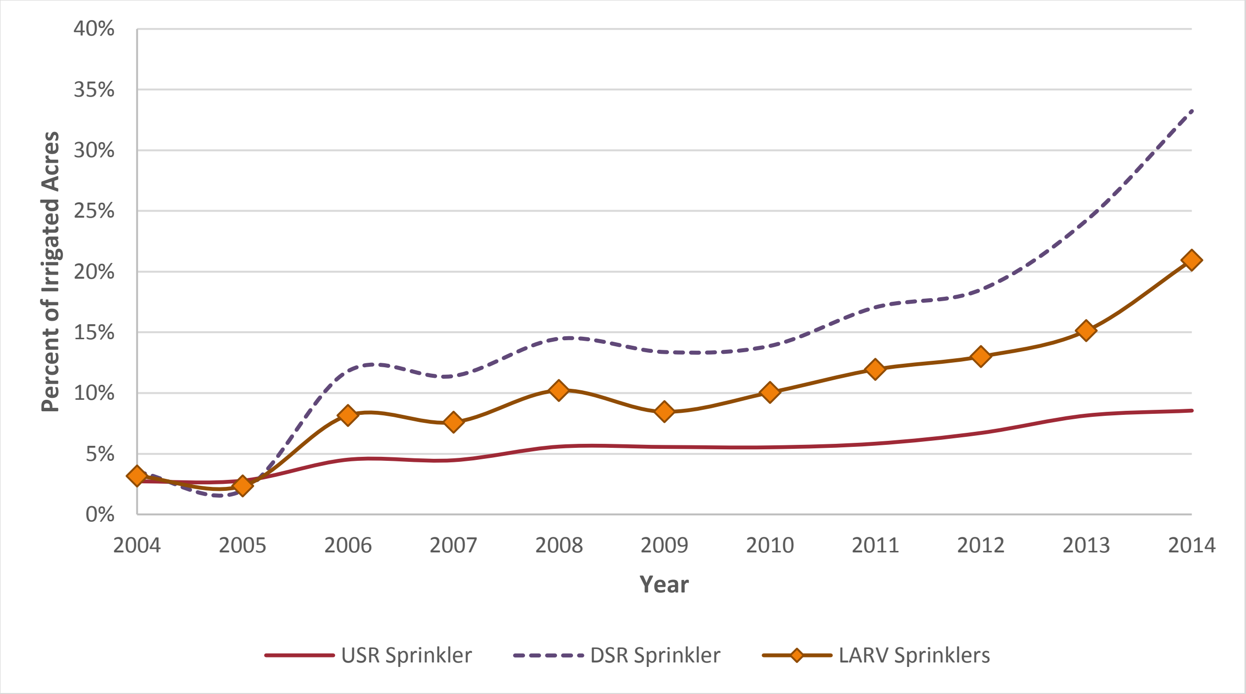

Figure 6. Sprinkler Irrigation Acreage across the LARV
Note: Based on acreage data used in H-I Model, collected from Colorado Division of Water Resources

Sprinkler acreage is further disaggregated into levels based on field size as shown in Table 12. Possible field sizes for sprinkler systems in this analysis include 60, 90, and 120 acres; the ratio of these systems is applied in the economic analysis is 20%, 20%, and 60% respectively. Many farms in the LARV consist of multiple smaller, fragmented fields, and cannot accompany the standard 120 acre pivot. The sizes chosen were based on interactions with the ARMAC and local producers.

Table 12. Sprinkler Field Size

Sprinkler Field Size (Acres)	Count	Percent of Total Sprinkler Acres
<60	7	18%
60<Acres<90	6	16%
>90	25	66%

Note: Field size counts were extracted from 2016 Lower Arkansas Valley Water Conservancy District Rule 10 filings

The irrigation technology mix plays an important part in the economic modeling of water applied. As mentioned earlier, LARV-specific crop water requirements are derived from Schneekloth and Andales (2017), and modified to account for irrigation technology specific application efficiencies by dividing the per acre crop water requirement by the irrigation system application efficiency. The results of this are shown below in Table13.

Table 13. Estimated Irrigation Efficiencies and Irrigation Requirements by Crop and System

	Estimated Efficiency	**Alfalfa**	**Corn**	**Wheat**	**Sorghum**	**Onion**	**Melon**
Gross Irrigation Requirement[a] (ac. ft.)		3.44	1.71	1.13	1.64	1.90	1.25
Sub-Surface Drip	95%	3.62	1.80	1.18	1.73	2.00	1.32
Low-Elevation Spray Application Center Pivot	90%	3.82	1.90	1.25	1.82	2.11	1.39
Laser Leveling (Gated Pipe)	80%	4.30	2.14	1.41	2.05	2.37	1.56
Gated Pipe	65%	5.29	2.63	1.73	2.53	2.92	1.92
Siphon Tubes	55%	6.25	3.11	2.05	2.98	3.45	2.27

Notes: [a]Gross irrigation requirements, per Schneekloth and Andales (2017), reflect the volume of water required by a crop, less annual effective precipitation.

Irrigation system mix plays another key role in this analysis in terms of the annual economic operating costs. The following section introduces crop enterprise budgeting and the process of calculating per acre costs by crop and irrigation system.

2.5 Empirical Linear Programming Model

The construct of the linear programming (LP) problem aligns with economic theory, and allows for the incorporation of physical and institutional constraints that bind real-world water resource systems (McCarl and Spreen 1996). The objective, presented below in Equation 4, is to maximize net profit generated throughout the region, which is a function of net revenues generated from crop production, the cost associated with PAM application, and the cost of meeting return flow requirements. The model is bound by a series of physical and institutional constraints, presented in a later section.

$$\max_{x_{ink}} \Omega = \pi(x_{ink}, S, F) - \theta C_P - \sum_k p_w D_k \tag{4}$$

Where the variables in Equation 4 are defined as $\pi(x_{ink}, S, F)$ denotes the per acre profit generated from irrigation of crop i, using irrigation technology n, on ditch k, and any losses to salinity (S) or reduced nitrogen fertilizers (F). θ is a zero-one variable denoting whether or not PAM has been applied to canals throughout the region, and C_P corresponds to the cost of reducing seepage. D_k is the quantity of replacement water that must be purchased under a given scenario to maintain historical return flows. P_w is the cost of replacement water. A more extensive explanation of the objective follows.

The model is solved under existing conditions to arrive at a baseline profit crop production pattern. This baseline is compared to a series of model runs where a portfolio of BMPs are introduced at different levels. These include exogenous reductions in irrigation water volumes applied, the amount of fertilizer applied, and canal seepage, as well as, an increase in the use of lease-fallow contracts. This model estimates at the regional level, leading to a few important notes. First, total net returns (Ω) are aggregated to the basin level, meaning that the model cannot be directly applied to any individual farm due to the unique characteristics of each farm. Secondly, this model is designed to represent a long-run estimate of economic impacts, and does not accurately model short run decision making due to the exclusion of any in-season decision making that could occur. Finally, the model indirectly captures the effects of the priority water rights system by limiting the water availability for each canal to the average water applied over the calibration period of 1999-2009, where more senior canals receive larger volumes of water than canals with more junior rights.

2.5.1 Objective Details

The objective is presented above in Equation 4. The objective function consists of three components; net returns from crop production, canal sealing costs, and replacement water costs. These components require further discussion about the inputs and parameters used in their development.

Net returns from crop production across all acres in the USR were presented in Equation 4 as $\sum_{ink} \pi_{ink}$, and are formulated as shown in Equation 5.

$$\pi_{ink}(x_{ink}, S, F) = \Sigma_{ink}(y_{in} x_{ink} p_i) - (c_{in} x_{ink}) - \tilde{y}_{in} p_i x_{ink} + \omega_i \qquad (5)$$

Where total revenue is presented in the expression $(y_{in}x_{ink}p_i)$, and y_{in} is the per-acre yield of crop *i*, under irrigation technology *n*, x_{ink} is the number of acres producing crop *i*, under irrigation technology *n*, on canal *k*, and p_i is the per unit price crop *i*, based on a five-year average from 2010-2014. Production costs are the product of c_{in} and x_{ink}, where c_{in} is the per acre production costs of crop *i* under irrigation technology *n*. $\tilde{y}_{in}$ represents a loss in per acre yields resulting from either soil salinity (*S*), or reducing nitrogen fertilizer applications (*F*). ω_i is an adjustment factor for changes in input use with BMP adoption. A further explanation of $\tilde{y}_{in}$ follows.

In Equation 5, I presented the term $\tilde{y}_{in}$ as a loss in per acre yield resulting from soil salinity (*S*) or reducing nitrogen fertilizer applications (*F)*. The formulation of $\tilde{y}_{in}$ for soil salinity (*S*) is as follows.

$$\tilde{y}_{inS} = \phi_S \psi_{iS} y_{in} x_{ink} \tag{6}$$

Where in equation 6, ϕ_S represents the percentage of acres affected by salinity level S, ψ_{iS} is the yield reduction factor ($0<\psi_{iS}<1$) for crop *i*, with salinity level *S*, and y_{in} is the per-acre yield of crop *i*, under irrigation technology *n*. Parameters for ϕ_S and ψ_{iS} are determined using the relationship identified in the LARV by Morway and Gates (2012) between the simulated water table depth across the USR and electrical conductivity (EC) measures in the soil. Electrical conductivity is a measure of soil salinity, and can be used to estimate crop specific yield losses resulting from salty soils.

The relationship between crop yields and EC is represented by a two-piece linear response function described by Maas and Hoffman (1977):

$$\mathbf{Y_i = 100 - s_i(EC_e - \boldsymbol{\alpha}_i)} \tag{7}$$

Where Y_i is the relative yield (%) of crop *i*, s_i is the percent change in yield per dS/m, EC_e is the mean electrical conductivity estimate in the crop root-zone (dS/m), and α_i is the salinity threshold (dS/m). At EC_e measures greater than the threshold (α_i), crop yields are reduced by the slope percentage (s_i). Parameter estimates for α_i and s_i are taken from Hanson, Grattan and Fulton (2006). Threshold parameters (α_i) required modification to account for the gypsum salt species that exist throughout the LARV (Cooper, Cardon, and Davis 2006). Maas and Grattan (1999) recommend a two-unit increase in threshold EC (α_i) measures to account for the gypsiferous soils that exist in the LARV. This adjustment was verified for the LARV by Gates et al. (2012). The soil salinity cost is broken into groups based on the estimated average measure of soil salinity (EC). Information on the distribution of salinity (ϕ_S) was calculated based on the depth to water output from the MODFLOW-SFR2 model, which is then converted to a soil EC estimate. The total yield loss is calculated by multiplying the percent of acres in each classification, by the crop-specific yield loss per acre, across all crops. Soil salinity classifications constructed for this analysis are based on the mix of crops analyzed, and designed to capture the impact of salinity on sensitive crops such as onions and corn. Soil salinity classifications for this analysis include *None (EC<3), Low (3<EC<4), Medium (4<EC<5), High (5<EC<7) and Severe (7<EC<10)*. The respective yield impact estimates (ψ_{iS}) of the soil salinity classification are presented in Table 14.

Table 14. Percent Reduction in Yield Associated with Soil Salinity

Crop	EC<3	3<EC<4	4<EC<5	5<EC<7	7<EC<10
Alfalfa	0%	0%	4%	15%	33%
Corn	0%	2%	10%	28%	-
Wheat	0%	0%	0%	0%	7%
Sorghum	0%	0%	0%	0%	10%
Onion	0%	6%	21%	45%	-
Melon	0%	4%	13%	25%	46%
Average	0%	2%	8%	19%	39%

Notes: Calculated per Hanson, Grattan and Fulton (2006), Corn and Onions are excluded from severe salinity (7<EC<10) impacts because they will not produce profitable yields in such conditions.

As BMPs are implemented, the percentage of fields (ϕ_S) affected by each salinity classification is adjusted accordingly. Calculating the adjusted yield of the reduced nitrogen fertilizer BMP follows a similar process and is described next.

The reduced nitrogen fertilizer imposes an opportunity cost on farmers by reducing per acre yields of some crops in the model. The adjusted yield resulting from the reduced fertilizer BMP is calculated as follows.

$$\tilde{y}_{inF} = \psi_{iN} y_{in} \tag{8}$$

Where ψ_{iN} represents the yield reduction factor (0<ψ_{iF}<1) for crop *i*, with nitrogen reduction level *F*, and y_{in} is the per-acre yield of crop *i*, under irrigation technology *n*. Nitrogen reduction induced yield impacts (ψ_{iF}) estimates are based on a series of studies, mostly focused on production in the LARV (Halvorson et al. 2008, Halvorson and Bartolo 2014, Johnson, Dreier and Grabouski 1973, Mahama et al. 2016). Using the nitrogen response functions developed in these studies, estimates of yield impacts from reducing nitrogen are presented in Table 15.

Table 15. Percent Reduction in Yield Associated with Reduced Nitrogen Fertilizer

Crop	RF10	RF20	RF30
Alfalfa	0%	0%	0%
Corn[a]	0%	8%	20%
Wheat[b]	8%	16%	23%
Sorghum[c]	2%	5%	8%
Onion[d]	7%	14%	20%
Melon	0%	0%	0%
Average	3%	7%	12%

Notes: [a] Halvorson and Bartolo 2014, [b] Johnson, Dreier and Grabouski 1973,
[c] Mahama et al. 2016, [d] Halvorson et al. 2008

Yield impacts presented in Table 15 make an important assumption regarding residual soil nitrogen levels. Notice that alfalfa and melons are not impacted by the RF BMP. In the case of alfalfa, nitrogen applications are minimal, and generally occur only in year one of an alfalfa crop. In the case of melons, it is assumed that producers would not reduce applications to such an economically important crop. Therefore, nitrogen reductions must come from corn, wheat, sorghum, and onions. Halvorson et al. (2002) described high residual nitrogen in the soils near Rocky Ford, CO. Residual soil nitrogen plays an important role in nitrogen management as it becomes available for use by future crops, and reduces the amount of nitrogen fertilizer that needs to be applied to a field. This analysis assumes that 20% of residual soil nitrogen is available for the next season's crop. These relationships suggest that nitrogen fertilizers are over-applied in the region, and better management could occur with relatively small opportunity costs. Accounting for over applications of nitrogen fertilizers is captured in the yield response functions. The response functions chosen for this analysis vary in functional form, but all functions have an upper limit as to the amount of beneficial nitrogen each respective crop can use. The difference between functional forms is whether or not, at nitrogen applications above the upper limit, yields are constant or declining. Therefore, in the instance of corn, a 10% reduction in nitrogen fertilizer applications has no impact on crop yield, suggesting current application rates exceed what the crop can use (See Table 15). Over application of fertilizers increases the likelihood of elevated nitrogen measures in the river.

Included in nitrogen cost, is a cost savings adjustment for the amount of fertilizer that does not need to be purchased at the different levels of reduced fertilizer BMP. Nitrogen fertilizers are priced volumetrically, and therefore the cost savings are assumed to accrue proportionally to the reduction in fertilizer applied. The total opportunity cost of the reduced fertilizer BMP is the net of yield losses and fertilizer application savings. This adjustment factor appears in Equation 4 as ω_i.

The last two components in the objective function (Eq. 4) relate to the canal sealing BMP. The first expression, θC_P, represents the total cost of applying PAM across the region. In this expression, θ is a binary variable taking on the values of zero, or the sum of canal miles across the USR, and C_p is the per mile cost of applying linear anionic polyacrylamide (PAM) to achieve seepage level p. The second component from Equation 4 consists of D_k, which represents the reduction in seepage on canal k, and p_w, the price of replacement water per acre foot The resulting reduction in seepage volumes, and subsequent change in return flows, requires the purchase and release of additional water to off-set these changes in return flows. Therefore, D_k is multiplied by p_w to compute the total cost of replacement water. Reduction in seepage and per mile PAM application cost are assumed to be constant between all canals.

2.5.2 Constraints

Constraints are critical to LP modeling in that they communicate to the model the rules of operation. For the agricultural production model, constraints are required to ensure that the physical limits on acreage are not exceeded. Since acres of production are the primary decision variables, a series of limits are imposed on crop, irrigation system, and canal acreage. Constraints are presented below in Equations 9 – 13:

$$\Sigma_i \Sigma_n \Sigma_k x_{ink} \ \leq Total\ Acreage\ \forall\ i, n, k \tag{9}$$

Where x_{ink} represents the number of acres of crop *i*, under irrigation technology *n*, on canal *k*. These acres must be less than or equal to the Total Acreage (*i*) representing the total acreage available for crop *i*; the Total Acreage (*n*) representing the total acreage available for irrigation technology *n*; and the Total Acreage (k) representing the total acreage available for canal *k*.

For this model, it is also critical to constrain the amount of water applied to crops in the USR. The economic model applies water based the gross irrigation requirement crop *i* (Schneekloth and Andales 2017), and the estimated efficiency of irrigation technology *n*. This results in the following constraint:

$$\Sigma_i \Sigma_n \Sigma_k A_{in} x_{ink} \ \leq Total\ Applied\ Water\ \forall\ k \tag{10}$$

Where A_{in} represents the per acre application of water (ft.) to crop *i*, under irrigation technology *n*, and must be less than or equal to the Total Applied Water (*k*), which represents the average total annual surface water application volume in acre ft. along canal *k*. Indexing this constraint by canal captures the impacts of the priority rights system given that more senior canals are expected to receive more water in a given year, especially in severe drought years such as 2002-2003.

This model also employs a series of linking constraints that are used for crop inventory, and calculating reduced nitrogen yield impacts. The first of these, crop inventory, serves to convert the primary decision variable x_{ink} measure from acres into marketable yield units (bu., tons, CWT). The crop inventory equation is:

$$\sum_i \sum_n \sum_k y_{in} x_{ink} - \sum_i I_i \hat{y}_{in} \geq 0 \tag{11}$$

Where y_{in} represents the per acre yield (bu., tons, or CWT) of crop *i*, under irrigation technology *n,* and x_{ink} again represents acres of crop *i*, under irrigation technology *n*, on canal *k*; I is an identity matrix; and $\hat{y}_{in}$ is an accounting variable the transfers the amount of *total* yield of crop *i* ($y_{in}x_{ink}$) into the objective function where it is multiplied by the per unit price of crop *i* (p_i) to get total revenue. This expression is set to be greater than zero, which prevents the model from allowing more crops than are produced to be sold.

Costs incurred as a result of reduced nitrogen require another layer of complexity because it must first be communicated to the model the level of reduced nitrogen prior to computing the yield impact of the targeted nitrogen reduction. Below is the basic structure of these constraints:

$$\Sigma_i \Sigma_n \tilde{y}_{in} x_{ink} - \Sigma_i \Sigma_n \tilde{y}_{in} \rho_{iF} - \Sigma_i \Sigma_n I_i \tilde{y}_{in} x_{ink} = 0 \tag{12}$$

Where $\tilde{y}_{in}$ represents the nitrogen adjusted yield as previously defined, ρ_{iF} represents one of the previously defined accounting variables that communicates to the model the level of nitrogen reduction, $I_i$is an identity matrix, and $\tilde{y}_{inF}$ is a variable the transfers the total yield impacts associated with a given level of reduced nitrogen (F) on crop *i* into the objective function. The actual operation of these constraints require some further explanation. Because crop production is a net return generating activity, the LP model wants to choose as many x_{ink} units as are available. However, because of the reduced fertilizer (RF) BMP, returns are reduced depending on the RF level (*F*). To convey to the model which RF Level (*F*) we are modeling, we fix the accounting variable ρ_{iF}at zero. By doing this, the only way for the constraint to be met (equal zero), is for $I_i\tilde{y}_{in}x\_ink$ to take on non-zero values. When an accounting variable ρ_{iF} is fixed at zero for a given *F*, the remaining accounting variables take on positive values. However, these non-zero variables have no impact on the objective, and serve only to balance the constraint equation.

The crop yield losses associated with the different levels of soil salinity are calculated as follows:

$$\sum_i \sum_n \sum_k \psi_{iS} y_{in}\, x_{ink} - \sum_i \sum_S I_{iS} \tilde{y}_{iS} = 0 \tag{13}$$

Where ψ_{iS} is a vector of yield reduction factors for crop *i* and salinity level *S*, y_{in} represents the per acre yield (bu., tons, or CWT) of crop *i*, under irrigation technology *n, I_{iS}* is an identity matrix; and $\tilde{y}_{iS}$ is the total yield losses associated with salinity level *S*. Because soil salinity is a function of water table depth, and water tables transcend individual property boundaries, the cost of salinity therefore can be an external cost borne by those that take action, and those that fail to take action. BMP implementation causes the percentages of acre affected by each salinity classification to change, generally reducing the total cost of salinity.

2.6 LP Results

The following sections outline the results of the economic modeling. It is important to note that the modular structure of this analysis means that the economic (LP) and environmental (water and pollution flow) models are run independently of one another. Therefore, these models must be calibrated to ensure a representative portfolio of crops and irrigation technologies are analyzed. I use crop acreage and the volume of water applied to check consistency between the models. Beyond the calibration, the economic model is further adjusted to represent irrigation technology changes that have occurred since 2009, primarily the advent of Rule 10 and subsequent growth in sprinkler irrigation. The implications of these changes will be later addressed. The basic structure of the LP solutions tend to favor lease fallowing, melons, and onions.

2.6.1 Calibration

A simplified version of the economic model focusing on the physical characteristics of the model domain, the applied water volume, and canal seepage volumes is run for comparison against the baseline levels in the water flow model. Table 16 shows this calibration.

Table 16. Calibration of Baseline Scenario for Independent Models

	Engineering[1]	Economic	Economic Percent Difference From Engineering
Water Applied (ac. ft.)	175718	173790	-1.11%
Canal Seepage (ac. ft.)	42468	42468	0.00%
Alfalfa (ac.)	39868	39868	0.00%
Corn	22985	22985	0.00%
Wheat	8663	8663	0.00%
Sorghum	3493	3492	-0.03%
Onion	3493	3493	-0.01%
Melon	471	471	0.02%
Total Acres	764	764	0.06%

Note: [1]Engineering model values represent the average levels across the calibration period of 1999-2009. Levels of water applied, canal seepage, and acreage occurs at the region level.

The engineering models (water flow and solute transport) are calibrated to *replicate* producers' decisions over the years 1999-2009, while the economic LP model *optimizes* decisions in an average year scenario. Constraints limiting crop and irrigation technology acreage, and water volume application (Eq.20) are used to calibrate the economic and engineering models as shown in Table 16. The remaining differences reflect information lacking from the model, which prevents perfectly reproducing the observed conditions. The difference in water applied can primarily be attributed the combination of irrigation efficiencies, and acreages for each irrigation system, both of which were estimated with available data. Beyond the calibration, the economic model is further adjusted to represent irrigation technology changes that have occurred since 2009, primarily the advent of Rule 10 and subsequent growth in sprinkler irrigation. Based on this adjustment, the baseline scenario suggests that current LARV irrigation application volumes are 15% below 1999-2009 levels.

2.6.2 LP Results

The baseline net returns for producers in the USR are estimated at $18,855,850. The baseline levels for acreage and irrigation volumes are estimated at 37,304 acres and 149,013 acre feet of water, respectively. Table 17 shows the baseline crop and irrigation mix. This mix of crops and irrigation systems is determined to maximize regional net returns given baseline conditions, based on estimated per acre net returns and per acre water requirements of available crops. About 94% of total available acres (See Table 17) and 99%of available water is accounted for, supporting my previous claim that the baseline scenario is a representative portfolio of crops and irrigation technologies. Economically, per acre net returns are generally higher for increased efficiency systems, driven by the increased yields under these systems. These systems also reduce water application volumes, making more water available to irrigate additional acres, which ultimately results in increase net returns. The baseline scenario accounts for about 94% of available acres, leaving 5% of alfalfa, 16% of wheat, and 25% of sorghum acres out of production. These unplanted, and therefore unirrigated acres, coupled with updating the baseline sprinkler acreage to levels reported in the LAVWCD Rule 10 plan results in about a 15% difference of water applied in the baseline between the engineering and economic models.

Table 17. Economic LP Optimization Model Crop and Irrigation Mix for Baseline Scenario (Acres)

	Furrow	Gated Pipe	Laser-Leveled Gated Pipe	Sprinkler	Drip	Total	LP Allowance	Percent of Available Acres
Alfalfa		16238	781	4834		21853	22985	95%
Corn	4854	3485		324		8663	8663	100%
Wheat	2920					2920	3493	84%
Sorghum	2356	277				2633	3493	75%
Onion	471					471	471	100%
Melon			299		465	764	764	100%
Total	10601	20000	1080	5158	465	37304	39869	94%

The applied water constraints for the Otero and Holbrook canal are binding. This suggests the annual average amount of water is insufficient to irrigate all the acreage under these canals. This is likely a direct impact of the priority water rights system, given that these are two of the more junior canals in the USR. Analysis of the shadow prices for these constraints suggest that adding an acre-foot of water to either the Otero or Holbrook canal would increase the USR net returns by $61 or $103 respectively. Other notable shadow prices are those of melon and onion land. Increasing allowable acres in melons results in an increase in total USR net returns ranging from $2,955 to $3,183, depending on what canal the additional acre is added to. An acre of onion land increases USR net returns by $1,693, regardless of the canal. These large increases result from changes in the optimal allocation of water and crop mix.

BMP implementation levels are 10%, 20%, 30% for the reduced irrigation (RI), reduced fertilizer (RF), and lease fallow (LF), and 20%, 40%, 60%, 80% for canal sealing (CS). These implementation levels are normalized for between 0% and 100% such that 0% represents the baseline scenario and 100% represents the most aggressive scenario of a given BMP; 30% for RI, RF, and LF, and 80% for CS. This normalization allows for a cleaner graphical presentation. Figure 7 and Figure 8 show the results of the economic optimization LP model for the normalized single and combination BMP scenarios respectively.

From an economic perspective, the lease fallow (LF) BMP appears to dominate other single BMPs as it has a positive impact on regional net returns at increasing levels of implementation (See Figure 7). This is because introducing a lease fallow option into the model has the same effect as introducing a new, more valuable crop to the region. Therefore, we fully expect producers to lease fallow the maximum number of acres in a given year. The LF BMP also has the effect of applying zero water to fields, which even when restricted in concert with the RI BMP, allows for production on all acres. The limits of the LF BMP will be discussed in later sections. Also of note, the RI BMP shows a slight positive impact on USR net returns at the 10% and 20% (shown as 33% and 66% in Figure 7) levels. This is explained primarily by the expansion of allowable sprinkler acres in the region, and the drop in soil salinity yield losses of up to 16% for RI20, which are enough to offset the costs of reducing applied water.

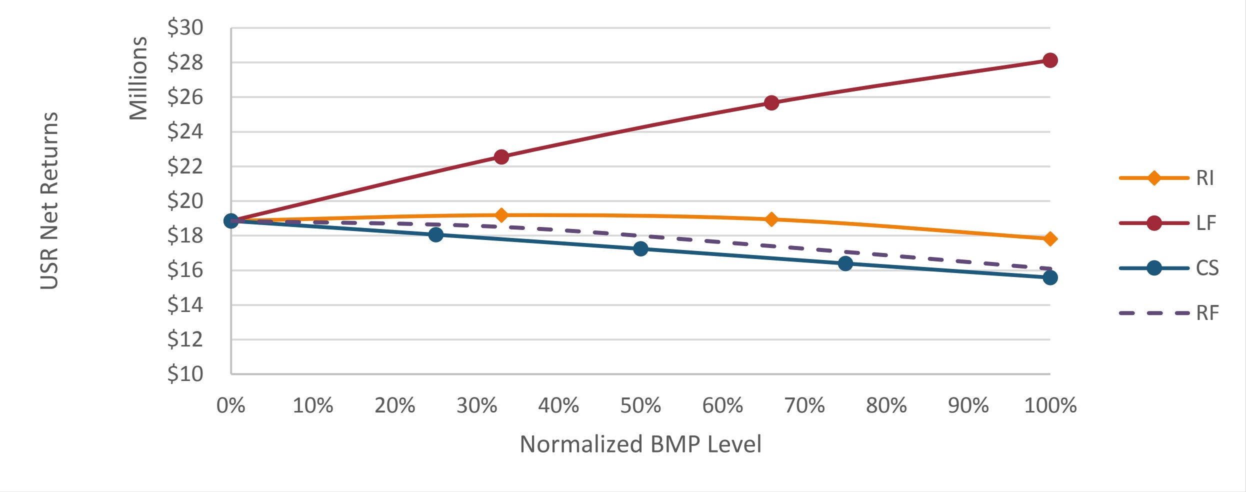

Figure 7. USR Net Returns at Normalized Single BMP Levels

Notes: Normalized BMP levels are equivalent to 10%, 20%, and 30% for Reduced Irrigation (RI), Reduced Fertilizer (RF) and Lease Fallow (LF), and 20%, 40%, 60%, and 80% for Canal Sealing (CS)

It also becomes evident that canal sealing (CS) appears to be the most expensive single BMP. The current legal requirement of purchasing replacement water for all seepage volumes that are reduced as a result of an efficiency improvement drives this outcome. At its highest level of seepage reduction, CS results in 33,972 ac. ft. of seepage reduction, costing an estimated $3,397,199.

Figure 8 shows the economic results for the combination BMP scenarios. The economic performance of BMPs is significantly improved when combined with lease fallowing. All combination scenarios with the LF BMP result in net returns above the baseline; the highest of these being the RI30+LF30 scenario, which results in a 50% increase in net returns or a $9.5 million. The most expensive combination scenario is RI30+RF30+CS80, which lessens regional net returns by an estimated 35% or $6.5 million. Overall, there seem to significant opportunities using the lease fallow BMP to implement BMPs at minimal to no cost throughout the USR. Another factor driving the economic performance of these BMPs is the large reductions in salinity-related yield losses across the region due to dropping water tables. Salinity-related yield losses are reduced by up to 65% or $855,000 in the most aggressive

BMP ALLCOMBO (RI30+RF30+LF30+CS80). The impact of these practices on selenium and nitrates will be discussed in later sections.

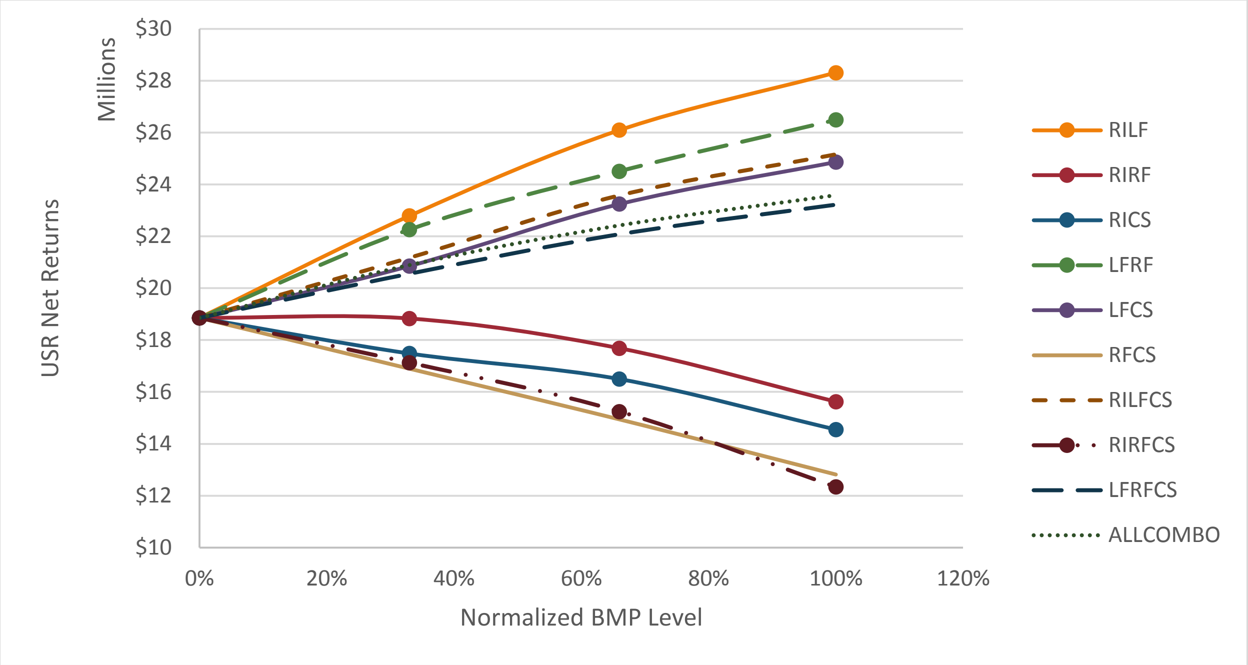

Figure 8. USR Net Returns at Normalized Combination BMP Levels

Notes: Normalized BMP levels are equivalent to 10%, 20%, and 30% for Reduced Irrigation (RI), Reduced Fertilizer (RF) and Lease Fallow (LF), and 20%, 40%, 60%, and 80% for Canal Sealing (CS)

The deterministic nature of LP modeling results in solutions that are highly dependent on the input parameters of the model. Varying these input parameter levels serves as a robustness check on the model, and allows for situational analysis. In the following sections, I conduct sensitivity analysis on crop prices, analyze the impacts of NRCS cost-sharing programs, and simulate a reservoir storage scenario.

2.6.3 Cost-Sharing

The USDA NRCS provides considerable cost-sharing opportunities for LARV producers through the Environmental Quality Incentives Program (EQIP). These programs are designed to encourage the adoption of technologies and practices that are recognized to mitigate the negative environmental impacts of agriculture. Cost-sharing opportunities exist for all irrigation systems analyzed in this thesis, aside from standard siphon-tube irrigation. NRCS cost-shares at three levels designed to maximize the impact of EQIP; standard east-slope rate, historically underserved/disadvantaged rate, and a special initiatives rate. For this analysis, the average of these rates is used. A significant portion of the existing center-pivot sprinklers and drip irrigation systems currently existing in the LARV received some amount of cost-sharing, and many of the member of the ARMAC committee stated that the cost-sharing is necessary to make adoption affordable. Table 18 shows the reduction in annual per acre ownership costs for the irrigation systems included in this analysis. Reductions in per acre ownership costs range from 22% for laser-leveled gated pipe, to 60% for gated pipe.

Table 18. Change in Per Acre Costs with NRCS EQIP Cost-sharing

Irrigation Technology	Per Acre Ownership Cost Adjustment	Per Acre Change in Ownership Costs
Furrow (Baseline)	N/a	0%
Gated Pipe	- $10.05	-60%
Laser-leveling (Gated Pipe)	- $22.26	-22%
LESA Center-pivot (Electric) (L)	- $48.01	-40%
LESA Center-pivot (Electric) (M)	- $63.02	-44%
LESA Center-pivot (Electric) (S)	- $113.65	-49%
SDI (Electric)	- $100.13	-37%

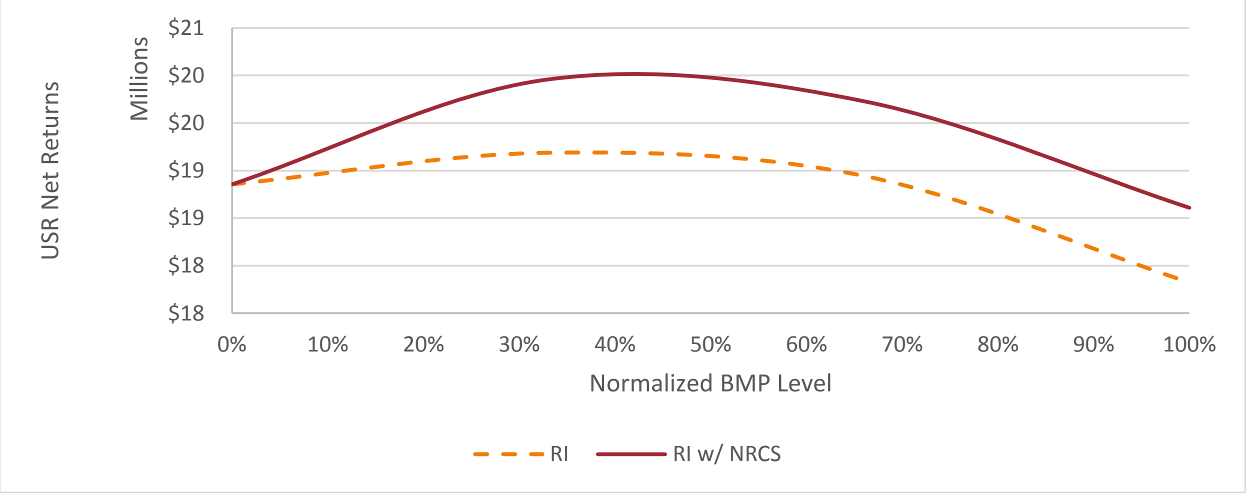

Figure 9. Change in USR Net Returns with NRCS Cost Sharing

The relationships between LARV net returns ($), and BMP implementation level change as shown in Figure 9 for the reduced irrigation scenario. Reduced irrigation (RI) application scenarios were re-analyzed using the cost-sharing adjusted values. Because of the pressure applied by the RI BMP on water-application volumes, increased efficiency systems like sprinklers, gated pipe, and drip become critical to minimizing the cost of the RI BMP, and avoid simply taking acre out of production. Wheat in particular has relatively low per acre returns, and in the case of the 60-acre sprinkler, even negative per acre returns. Cost-sharing programs greatly improve the margin on these lands, and increase USR net returns by an estimated $800,000 at the RI30 level. Another significant factor in determining the results of the economic model are the crop price parameters. A look at the impact of changing crop prices follows.

2.6.4 Price Adjustments

The baseline analysis assumes the five-year average prices for the included crops (alfalfa, corn, wheat, sorghum, onion, and melon) from 2010-2014 per the Colorado Agricultural Statistics 2015 (Meyer et al. 2016). Recent trends in USDA's Agricultural Price Index suggest agriculture product prices are in a decline. The API is calculated by the USDA National Agricultural Statistics Service and is constructed using reported prices received for 48 commodities. The parity base period (1910-1914) is used for the reported data below, meaning that prices from the parity base period would be equivalent to a value of 100 on the index. Figure 10 shows the API from 2005 to 2016, along with the API during the five- and ten-year periods of prices used in the LP.

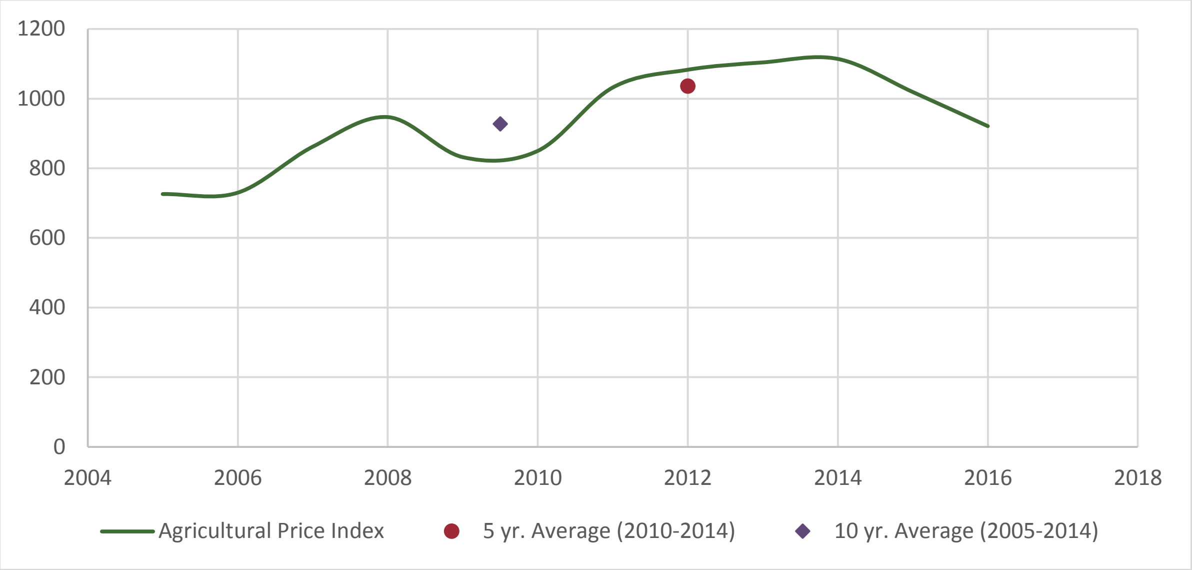

Figure 10. USDA Agricultural Price Index Trends (2005-2016)
Notes: Agricultural Price Index data is taken from the USDA National Agricultural Statistic Service

As illustrated above, the ten-year API is about equal to the 2016 API index value. Adjusting crop prices to the ten-year average (2005-2014) shows the impact prices have on the optimal crop-mix and acreage for the reduced irrigation and reduced fertilizer scenarios. The ten-year average price was used to capture heterogeneity in crop specific prices, which should better illustrate producer's decisions[31]. Table 19 shows the 10-yr. average prices and percent change in prices for the included crops between the 5-yr. and 10-yr average prices.

Table 19. Percent Change in Crop Prices from Five Year Averages

	Alfalfa (tons)	**Corn (bu.)**	**Wheat (bu.)**	**Sorghum (bu.)**	**Onion (CWT)**	**Melon (CWT)**
10-yr. Price	$169.2	$4.37	$5.78	$4.12	$16.23	$24.13
% Change from 5-yr. Price	-17%	-18%	-12%	-21%	-6%	-21%

Using the lower, ten-year average prices in the LP model results in a 38% decrease in baseline net returns, or $7,118,480 less than with the five-year average prices. The impacts of these price

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[31] An alternative would be to reduce all crop prices by some constant reduction factor. The approach of using crop specific price changes better illustrates the resiliency and stability of some crops such as onions.

changes in the reduced irrigation and reduced fertilizer BMPs are shown in Figure 11. The reduction in crop prices generally makes BMP implementation more expensive, increasing the cost of RF30 by as much as 3%.

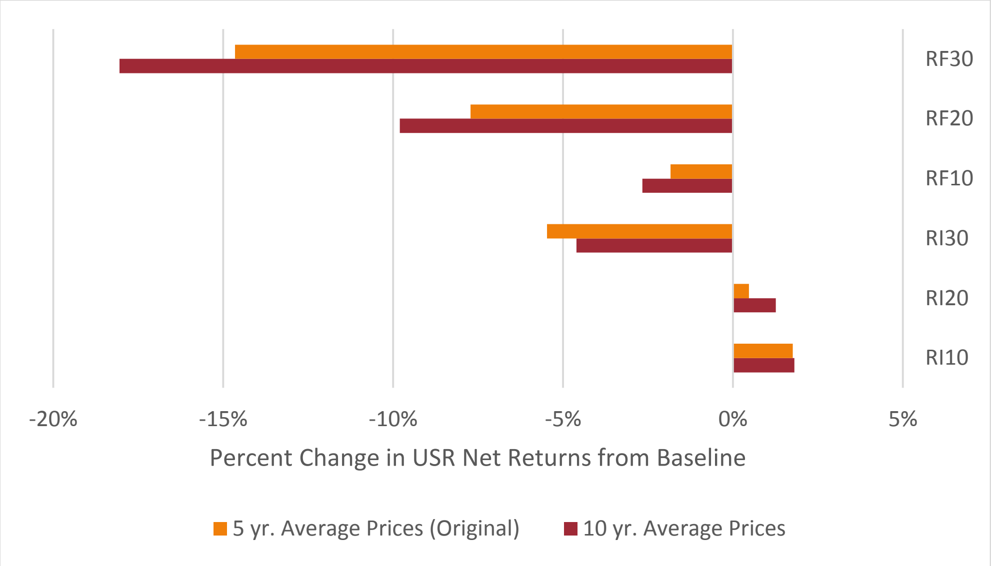

Figure 11. Impacts of Crop Price Changes for RI and RF BMPs

2.6.5 Reservoir Storage

Reservoir storage options in the LARV are understood to be necessary in order to truly improve water quality outcomes. Efficiency improvements to on-farm and canal level operations result in decreased levels of river diversions. Forgone diversions represent water that would have been applied to fields prior to the efficiency improvement, some of which would have acted as return flows. Under Colorado water law and the Arkansas River Compact, these flows are owed to the river in an equal time and location, which can only occur with properly timed storage and release from reservoirs. The LARV has two major reservoirs, Pueblo and John Martin, which could be used to manage exchange of these return flows. Return flow management using the reservoirs negates the requirement of purchasing replacement water, significantly reducing the cost of the canal sealing BMP. Before I discuss the impacts of eliminating replacement water costs, it is important to note that there are expected costs related to reservoir capacity and operation of such a program. These costs have not been estimated for this analysis, but should be further investigated in future analyses.

The cost savings of eliminating replacement water costs, by using reservoirs to store and release return flows, are shown in Table 20. The cost savings shown below occur for all scenarios that include the canal sealing BMP, as reduced seepage volumes are the same for any BMP combination with canal sealing. As shown, costs could be reduced by over $800,000 and as much as $3.4 million. That is, the net returns to the region could be increased by something around $1-3 million with the reservoir option (less costs to operationalize the accounting).

Table 20. Cost Savings of Elimination of Replacement Water Requirement

	CS20	**CS40**	**CS60**	**CS80**
Reduced Seepage (ac. ft.)	8493	16986	25479	33972
Cost Savings	$849,299.70	$1,698,599.30	$2,547,899.00	$3,397,198.60

Note: Cost saving assume a replacement water price of $100 per acre-foot

Chapter 3: Trade-off Analysis

The goal of modeling BMP adoption is to identify changes in economic and environmental outcomes, and any trade-offs that occur when economic and environmental measure change in opposing directions. Understanding the trade-offs is critical to analyzing the economic efficiency[32] of BMPS, and allows for informed policy and decision making where trade-offs are between different goals are unavoidable.

The focus of the trade-off analysis will be on USR net returns, in-stream concentrations for selenium and nitrates, and costs of soil salinity. Selenium measures are presented as the 85th percentile measure of selenium concentration in micrograms per liter (μL^{-1}), consistent with the chronic standard. Median nitrate concentrations are presented as milligram per liter (mg L^{-1}) nitrate as nitrogen (NO_3-N); a measure that represents the percentage of total nitrogen attributed to nitrates. Salinity losses are presented in dollars ($). The baseline measurements are presented below in Table 21.

Table 21. Baseline Scenario Measures

Measure	Level
85th Percentile In-stream Selenium Concentration (µ L^{-1})	13.38
Net Returns	$18,850,855
Median In-stream NO_3-N (mg L^{-1})	1.82
Total Soil Salinity Losses	$1,309,510

Table 22 shows the ranges in economic and environmental measures compared to the baseline, and the respective practices that result in those changes. Changes in environmental measures are presented as the spatio-temporal averages over a 40 year simulation period. As shown, the largest reduction of in-stream selenium and nitrate concentrations is estimated at 27% and 13% respectively. The most effective BMP for reducing selenium is also the most expensive, RI30+RF30+CS80, which is

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[32] Economic efficiency refers to an outcome in which no criterion can be made better off, without make another criterion worse off.

reduced irrigation, reduced fertilizer, and canal sealing at their maximum levels of 30%, 30% and 80% respectively. Almost all BMPs decrease crop yield losses to soil salinity, aside from RF10 and RF20 which have no estimated impact.

Table 22. Extremum Values of Change in Economic and Environmental Measures

	% Change	Practice
Max Net Returns	50%	RI30+LF30
Min Net Returns	-35%	RI30+RF30+CS80
Max Salinity Costs	0%	RF10,RF20
Min Salinity Costs	-65%	RI30+RF30+LF30+CS80 (ALLCOMBO)
Max Se	7%	RI30+LF30
Min Se	-27%	RI30+RF30+CS80
Max N	17%	RI30+LF30+CS80
Min N	-13%	RF30

Also of importance is the impact of combining BMPs. Table 23 shows that combinations of BMPs perform significantly better than single BMPs in managing surface-water selenium concentrations and soil salinity costs. Nitrates show an increase in surface water concentrations, an effect that is thought to occur because of decreased return flow volumes; which in the baseline scenario, have a dilution effect resulting from denitrification processes in the riparian zones adjacent to the streams. Ongoing research not considered here suggests that an additional BMP, an enhanced riparian buffer zone, could serve to enhance chemical reduction in the riparian zone and increase the effectiveness of other BMPs.

Table 23. Change in Economic and Environmental Measures by Number of BMPs

	Average Change Single BMPs	Average Change 2 BMP Combination	Average Change 3 and 4 BMP Combination
Selenium	-4%	-8%	-18%
Nitrates	1%	3%	6%
Salinity Costs	-11%	-22%	-35%

Since the outcomes vary so much, choosing BMPs to implement will require comparing the resulting outcomes for economic and environmental measures in some meaningful way. The nature of this analysis results in a multi-dimensional output with trade-offs occurring between economic-environmental measures and environmental-environmental measures. Therefore, three approaches have been chosen, each with their own strengths and weaknesses. The following sections discuss a trade-off table, trade-off frontiers, and radar charts.

3.1. Trade-off Table

The trade-off diagram in Table 24 houses the modeling output for the various BMP scenarios, and uses a transitional red-green color scheme to identify desirable changes in economic and environmental measures. The measures in the trade-off table are expressed in percent changes from baseline, taking advantage of the unit-less-ness of percentages. For net returns, increases are a desirable outcome (green), while decreases are undesirable (red). For in-stream selenium and nitrate concentrations, and soil salinity costs, decreases are desirable (green) and increases are undesirable (red). The baseline is represented by yellow, while the magnitude of change is represented by the intensity of color (red to green). Because the color intensity is relative to each respective baseline, and the respective extremum values, color intensity is not consistent across magnitudes and measures (i.e. 25% reduction in selenium appears much darker than a 25% reduction in salinity costs).

Table 24. Trade-off Table Presented with Transitional Color Scheme

BMP Scenario	Change in Estimated Net Returns	% Change in Selenium (85th percentile surface concentration) (µg/L)	% Change in Nitrate as Nitrogen (median surface concentration) (mg/L)	% Changes in Soil Salinity Costs (Total)
Baseline	0%	0%	0%	0%
RI10	2%	1%	3%	-7%
RI20	0%	1%	7%	-16%
RI30	-5%	2%	10%	-28%
LF10	20%	0%	-1%	-14%
LF20	36%	2%	1%	-15%
LF30	49%	3%	5%	-33%
RF10	-2%	-3%	-5%	0%
RF20	-8%	-6%	-9%	0%
RF30	-15%	-8%	-13%	-3%
CS20	-4%	-4%	1%	-5%
CS40	-9%	-10%	2%	-7%

CS60	-13%	-14%	3%	-8%
CS80	-17%	-19%	5%	-11%
RILF10	21%	1%	3%	-16%
RILF20	38%	5%	8%	-34%
RILF30	50%	7%	13%	-43%
RIRF10	0%	-2%	-1%	-7%
RIRF20	-6%	-4%	-1%	-16%
RIRF30	-17%	-5%	1%	-35%
RI10CS40	-7%	-9%	5%	-7%
RI10CS60	-12%	-16%	10%	-25%
RI10CS80	-23%	-22%	15%	-39%
LFRF10	18%	-3%	-4%	-14%
LFRF20	30%	-1%	-3%	-17%
LFRF30	40%	-2%	1%	-34%
LF10CS40	11%	-10%	2%	-14%
LF20CS60	23%	-13%	5%	-25%
LF30CS80	32%	-21%	9%	-44%
RF10CS40	-10%	-12%	-3%	-7%
RF20CS60	-21%	-19%	-6%	-8%
RF30CS80	-32%	-25%	-7%	-13%
RILF10CS40	12%	-11%	6%	-23%
RILF20CS60	25%	-14%	11%	-38%
RILF30CS80	33%	-22%	17%	-63%
RIRF10CS40	-9%	-12%	1%	-7%
RIRF20CS60	-19%	-20%	3%	-25%
RIRF30CS80	-35%	-27%	7%	-45%
LFRF10CS40	9%	-12%	-1%	-14%
LFRF20CS60	17%	-17%	2%	-27%
LFRF30CS80	23%	-24%	5%	-46%
RIRFLF10CS40	11%	-12%	3%	-23%
RIRFLF20CS60	19%	-17%	8%	-40%
RIRFLF30CS80	25%	-24%	14%	-65%

The trade-off table provides some useful aesthetic insights. BMPs with multiple red criterion can easily be identified and disregarded. Alternatively, BMPs with multiple green criterion, should be further considered. A person could apply a standard that they will not consider any row with a red or dark orange outcome, for example, which eliminates 14 of the 44 practices. If they wanted some green in all of the columns, no practice would suffice. Or finally, by way of example, if someone wanted to see some green and not red or orange, only 11 practices (25%) would be considered. While this presentation represents an effective first step in BMP analysis because users can narrow the field of consideration easily, it fails to allow for a thorough comparison between those BMPs that have moderate impacts across the board. To better illustrate the performance of these BMPs, it is necessary to introduce a trade-off frontier.

3.2 Trade-off Frontier

Trade-off frontiers are an in important tool in analyzing the changes in economic and environmental measures and have been used extensively throughout the literature for analyzing similar problems of non-point source pollution (Maringanti, Chaubey and Popp 2009; Panagopoulos, Makropoulos and Mimikou 2012; Sharp el al. 2016B). Outputs from the economic and environmental modeling are plotted in two-dimensional space, and the efficient frontier is identified. Points on the frontier represent the efficient BMP practice at each level of pollution reduction, meaning that in order to improve in one the criterion, there must be some worsening of another criterion. These two-dimensional plots have four quadrants of possible scenarios. Figure 12 depicts the possible scenarios that occur in two-dimensional space.

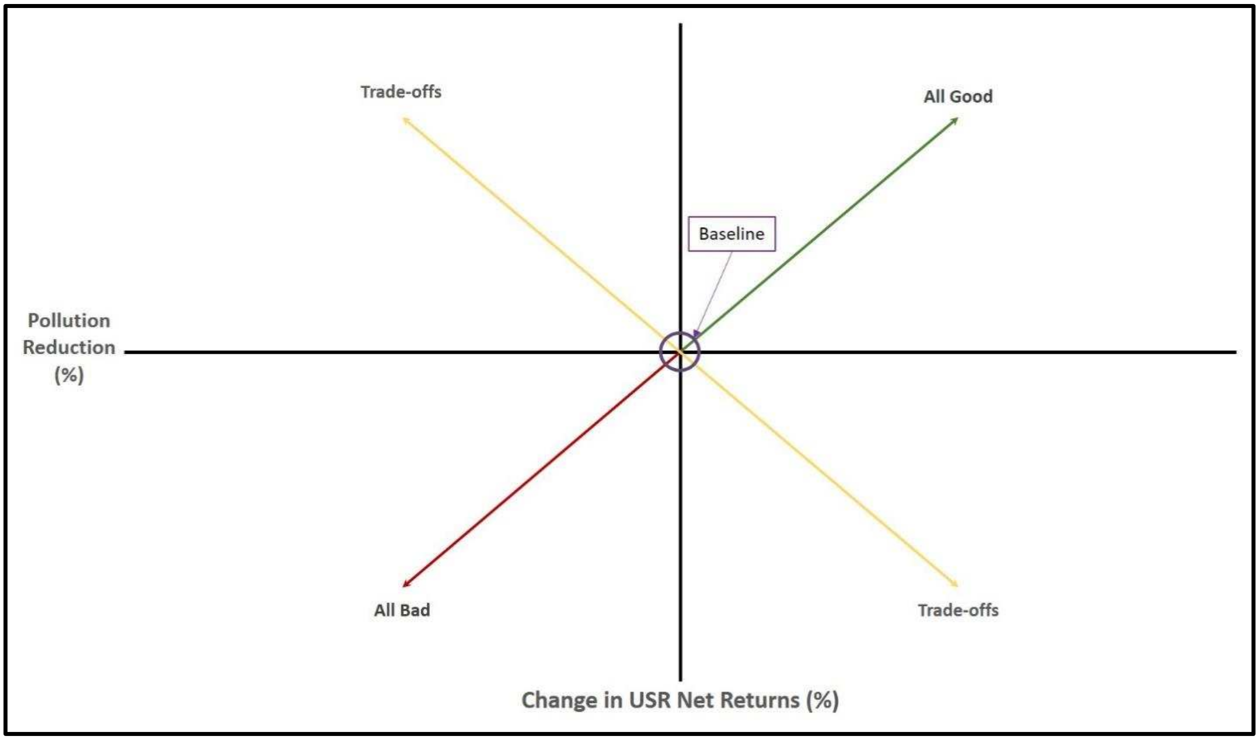

Figure 12. Trade-off Scenarios

Possible scenarios associated with BMP adoption include "All Good," in which both economic and environmental measures improve; "All Bad," in which both economic and environmental measures are made worse; and "Trade-offs," in which one measure improves, and one measure worsens. In two-dimensional space, these diagrams provide important information with regard to the economically optimal BMP to employ for a given level of pollution reduction. Solutions that exist in the upper-right hand quadrant ("All Good") convey important economic information and are of particular interest. Based on our profit maximization assumption, these solutions suggest a market-failure[33] in the baseline scenario, in which opportunities exist to improve USR net return outcomes without making pollution worse. This is explained by the introduction of lease fallow BMP, where lease fallow acts as new economically superior cropping option. Mapping percent change in USR Net Returns against percentage

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[33] The term market failure suggests an inefficient allocation of resources where an opportunity to improve one measure without negatively affecting other exists. In this scenario, we assume that pollution is undesirable and the existence of solutions with less or equal pollution, and higher profits means that baseline decisions are inefficient.

pollution reduction allows for the identification of an efficiency frontier; a collection of points where Net returns cannot be improved without making pollution outcomes worse. I consider three frontiers below, economic returns compared to selenium, then nitrogen, then salinity.

3.2.1 Selenium

The relationship between in LARV regional net returns ($), and 85th percentile in-stream selenium concentrations ($\mu\ L^{-1}$) are presented in Figure 13. It is important to note that even under the most effective BMP scenario for selenium (RIRF30CS80), in-stream selenium concentrations remain significantly above the Colorado Department of Public Health and Environment (CDPHE) chronic standard for aquatic habitats (4.6 $\mu\ L^{-1}$). The 27% reduction is equivalent to an in-stream concentration of 9.812 $\mu\ L^{-1}$ (85th percentile). Concurrent to its impacts on selenium, the RI30+RF30+CS80 BMP is also the most expensive BMP scenario, costing an estimated $6.5 million loss in USR net returns. While the in-stream concentration is reduced at most by 27%, reductions in mass loading to streams is reduced on average by 26%, with a maximum reduction of 61%. These reductions in mass loading could be a positive for the long-term health of the LARV ecosystem if concentrations are also decreased.

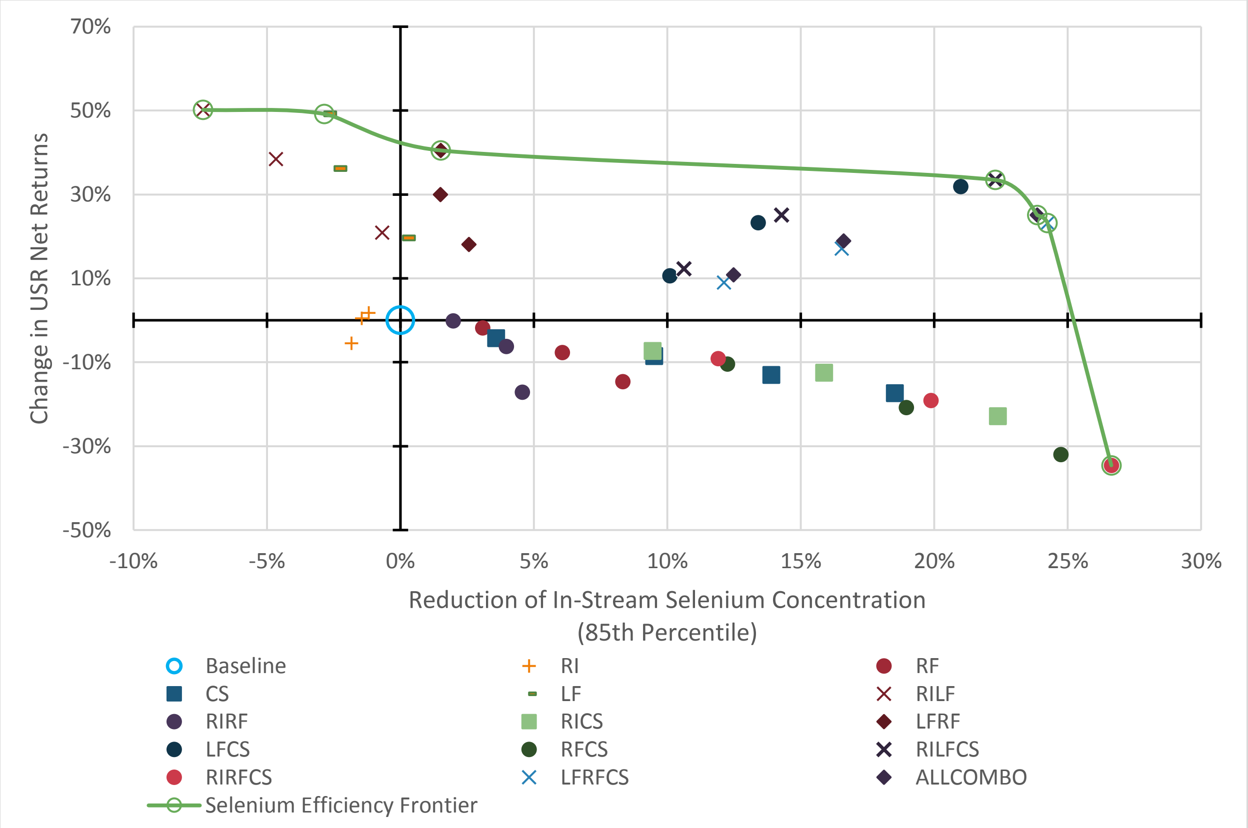

Figure 13. Trade-offs Between USR Net Returns and 85th Percentile In-stream Selenium Concentration

Plotting all BMP scenarios and their respective impacts on net returns and selenium concentrations allows for the identification of the efficient frontier of BMPs. Points along this frontier represent the highest net returns at each level of selenium reduction. The efficient frontier is represented with a green line (BMP scenarios in green circles) in Figure 13. A majority of the frontier lies above of the baseline net return amount, a result driven by the lease fallow (LF) BMP. Several points also exist to the left of the X-axis, suggesting increases in in-stream selenium concentrations resulting from the reduced irrigation (RI), lease fallow, and RILF combination BMPs. These points are not desirable from an environmental perspective, but are efficient in that no improvement in environmental conditions can occur without a decrease in net returns. Focusing on those scenarios that decrease selenium concentrations (right of the X-axis), the frontier is relatively flat until it takes a dramatic fall when only scenarios that do not include the LF BMP remain. This fall exists around the 24% reduction in selenium concentrations, where an additional 3% reduction requires a significant reduction in net returns, suggesting a high marginal cost for the last 3% of selenium reduction.

3.2.2 Nitrates

The relationship between USR Net Returns ($), and median in-stream nitrate as nitrogen (NO_3-N) concentrations (mg L^{-1}) are presented in Figure 14. Median in-stream NO_3-N concentrations are used here because of their significance to the Colorado Department of Health and Environment's (CDPHE) Regulation 31[34], which sets an interim standard for median total nitrogen of 2.15 mg L^{-1}. It should be acknowledged that while this analysis focuses only on nitrates, other species of nitrogen are included in the total nitrogen measure. However, it is understood that a majority of total nitrogen can be attributed to nitrates. While baseline estimates of NO_3-N (1.815 mg L^{-1}) are currently below the Regulation 31 standard for *total* nitrogen, CDPHE is also in charge of administering a separate nutrient management rule, Regulation 85. Regulation 85 encourages voluntary nitrogen management BMP adoption and reserves the right review and adjust total nitrogen standards if conditions do not show signs of improvement.[35] Of the tested BMPs, the most effective at reducing median NO_3-N concentrations is the RF30, which results in a 13% reduction in concentrations. Similar to selenium, the analyzed BMPs result in marked average reductions in surface-water loading (17%) and groundwater concentrations (13%), both of which bode well for long-term water quality goals.

Analyzing Figure 14, we see that a significant number of the BMPs increase in-stream nitrogen concentrations, with three points from the efficiency frontier showing this effect. The explanation for

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[34] Interim standards took effect on May 31, 2017, and reported standards apply to warm-bodied lakes and rivers. More information on these standards is available at: https://www.colorado.gov/pacific/sites/default/files/31_2017-03.pdf

[35] Per Regulation 85, "If voluntary nonpoint source BMPs are not effective in managing nutrients by May 31, 2022, the Commission may consider the adoption of prohibitions or precautionary measures to further limit nutrient concentrations." Full text available at: https://www.colorado.gov/pacific/sites/default/files/85_2012%2809%29hdr.pdf

this increase was discussed in previous sections, but is related to chemical reactions that occur in the riparian buffer zones along the stream. The remaining frontier points include LF10+RF10, LF20+RF20, and RF10, RF20, and RF30. Only one BMP that did not include RF resulted in nitrate concentration reductions (LF10).

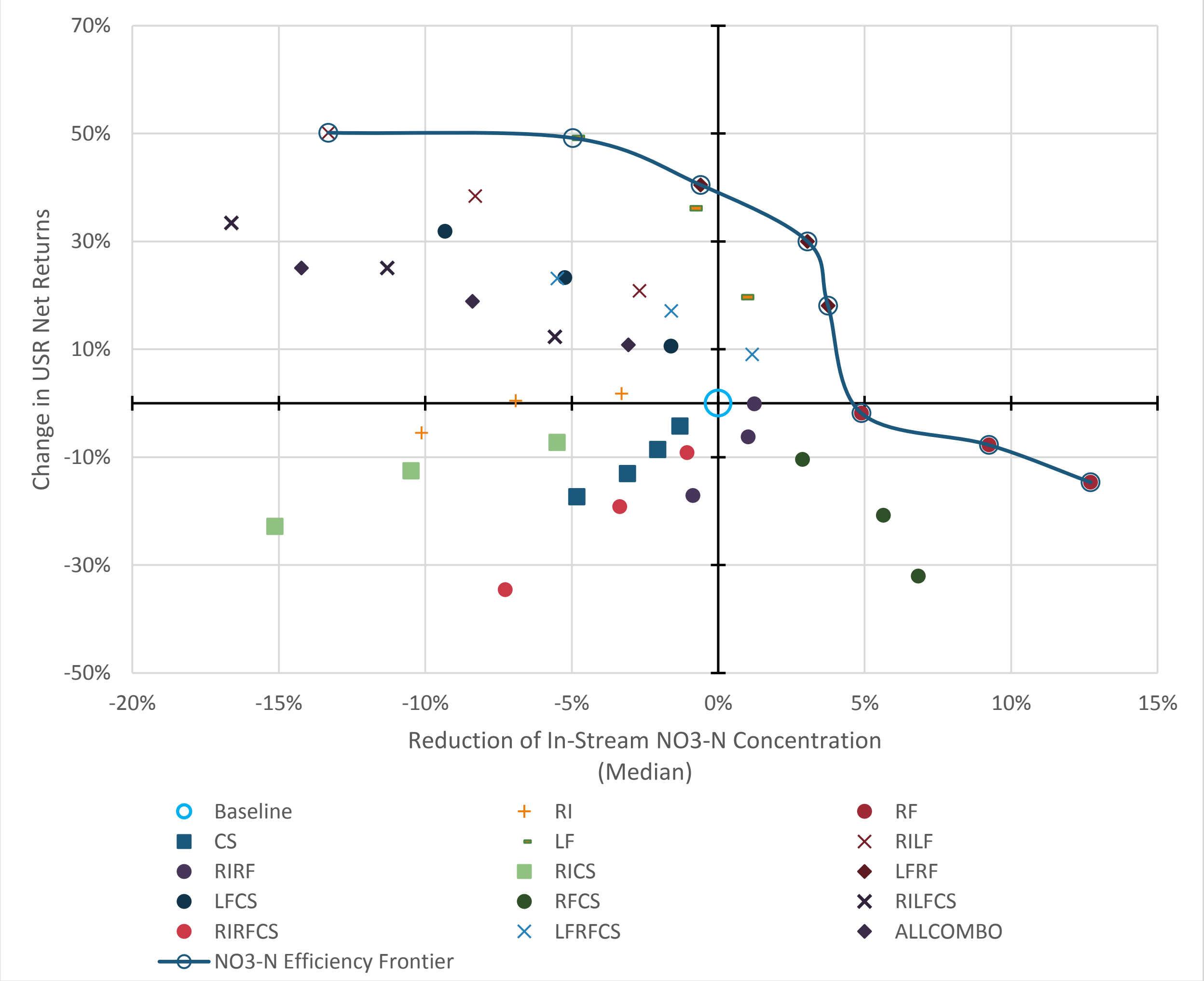

Figure 14. Trade-offs Between USR Net Returns and Median In-Stream Nitrate Concentration

3.2.3 Salinity

The relationship between LARV regional net returns ($), and estimated soil salinity costs ($) are presented in Figure 15. Here, it is shown that aside from two BMPs that have no impact, all BMPs decrease the cost of salinity across the region. Intuitively this makes sense as salinity costs are assumed to be a directly related to water table depth from ground surface, levels of which are increased in three of the four BMPs. The largest reduction in costs resulting from soil salinity is achieved with the RI30+RF30+LF30+CS80 (ALLCOMBO) BMP, which reduces costs by 65% or about $796,000. As previously mentioned, this cost may not be avoidable for individual farmers given that shallow water tables transcend both property lines and canal boundaries, imposing an external cost on some farmers. It should be noted that the distribution of costs will vary significantly across farms, irrigation systems, and irrigation practices.

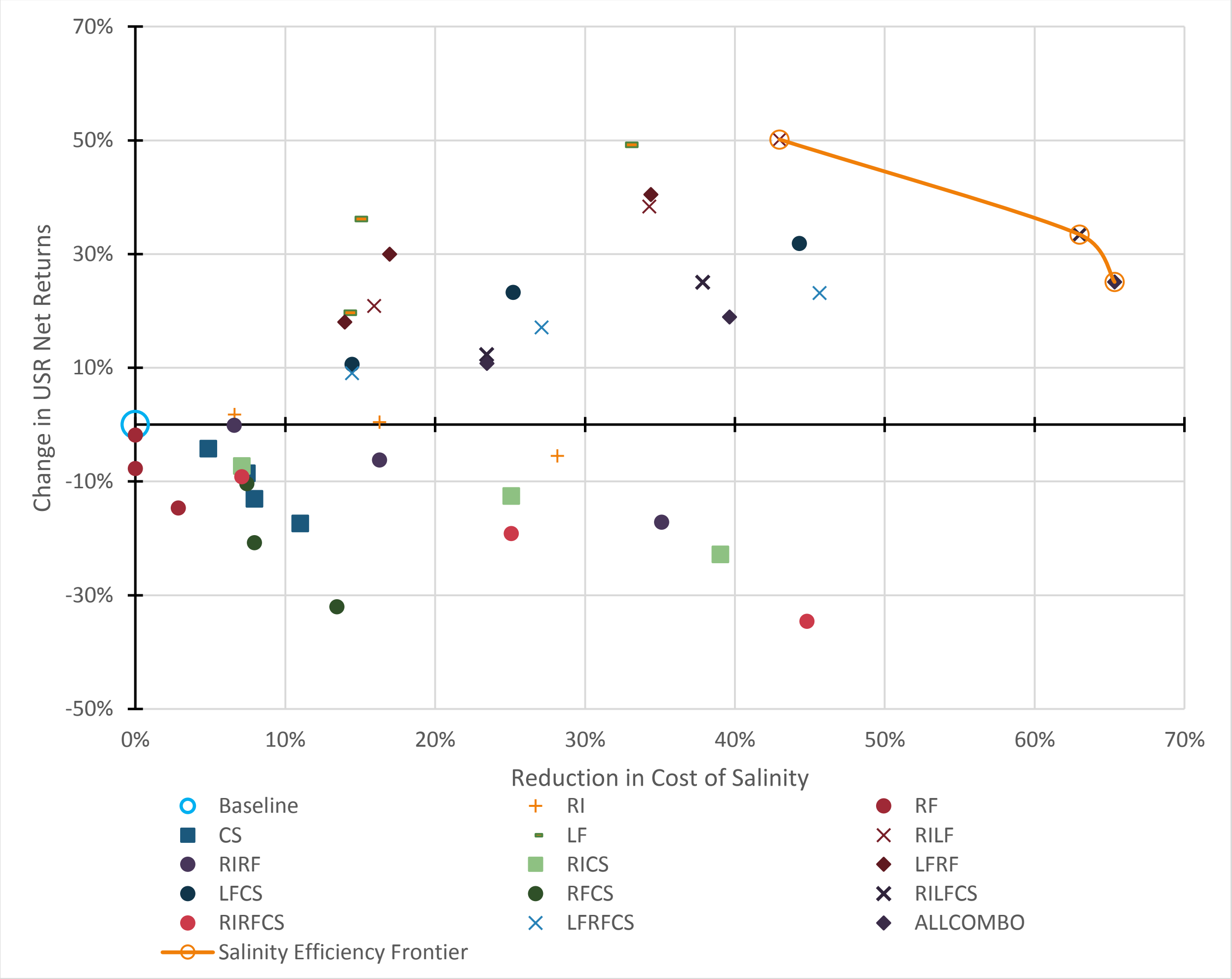

Figure 15. Trade-offs Between USR Net Returns and Costs of Salinity

The salinity efficiency frontier, shown in orange, consists of only three points, and lies above and to the right of the baseline scenario. This positon suggests opportunities for win-win BMPs which improve both economic and environmental outcomes. While many of the BMPs produce win-win situations, only those that meet the criteria for efficiency (no points above and to the right) exist on the frontier. The three BMP scenarios on the efficiency frontier include LF30+RF30, RI30+LF30+CS80, and the ALLCOMBO, and reduce the cost of soil salinity by 43%, 63%, and 65% respectively.

3.2.4 Trade-off Frontier Discussion

Looking across the three trade-off graphs, a few important characteristics are found to exist. First, win-win situations exist for selenium, nitrates, and salinity costs. Most of these win-wins involve the lease fallow BMP in combination with other practices. This is promising for improving environmental outcomes. Recall also, the driver of the canal sealing BMP expenses being the replacement water costs. When we consider the use of storage and release of reservoir storage accounts, the cost of the canal sealing BMP is significantly decreased; bumping some points closer to the win-win scenario, and potentially pushing the frontier upward. Secondly, the efficiency frontiers for all three measures are downward sloping, with selenium showing increasing marginal costs of controlling pollution suggested by the drastic drop in net returns. Thirdly, nitrates appear to be the most difficult pollutant to control, and are primarily reliant on the RF BMP. This is interesting because the RF BMP imposes a very direct cost to individual farmers who may have to accept lower per acre yields as a result of the BMP. Lastly, both selenium and nitrates have scenarios which increase respective concentrations. This reinforces the idea that complicated trade-offs exist, and suggests further investigation is required.

3.2.5 Modified Trade-off Frontiers

The trade-offs presented in the previous section provide important information, but are limited to illustrating the two-dimensional relationships between USR net returns and a single environmental measure. Mapping the all frontier points in a single space increases the usefulness of this analysis, and helps to better inform LARV water policymakers and stakeholders.

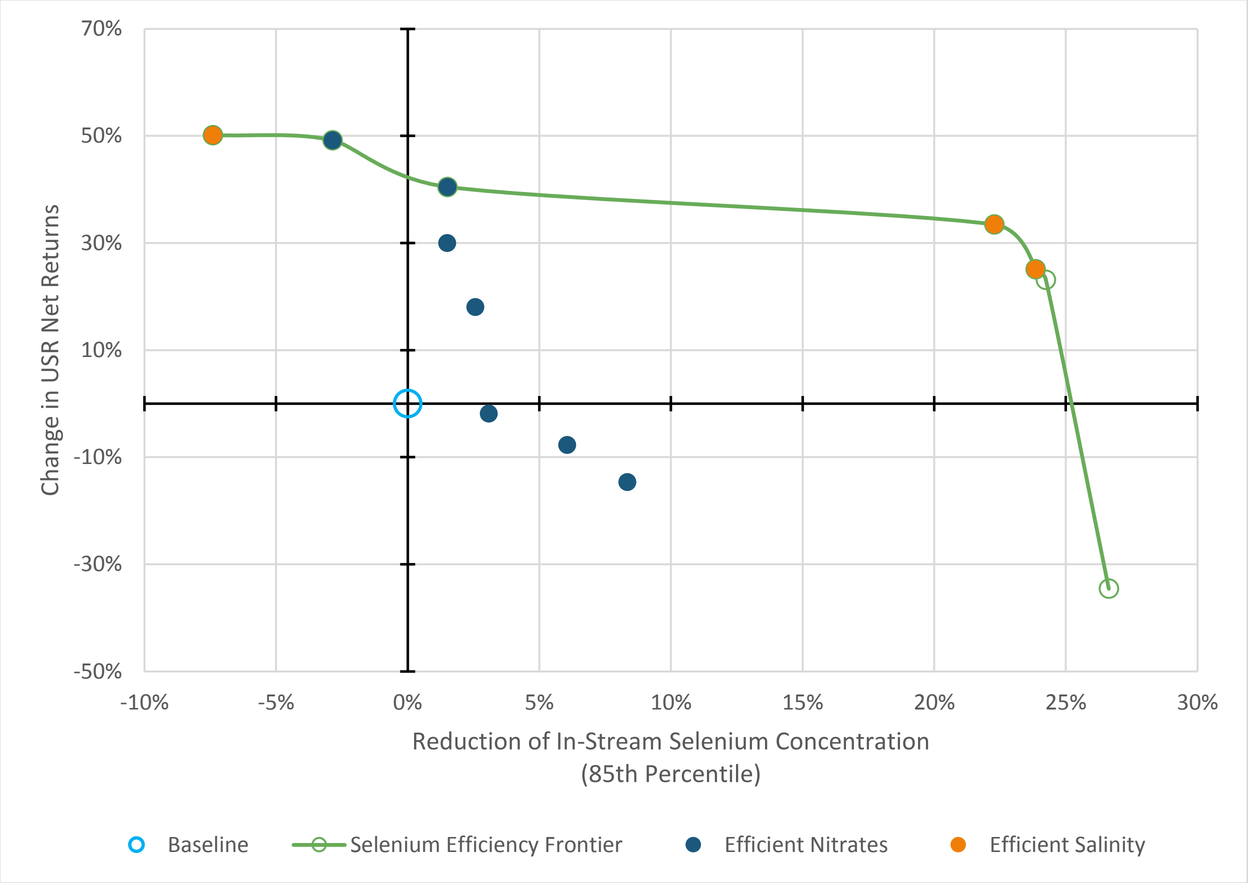

Figure 16. Efficient BMPS Mapped in Selenium Space

Figure 16 illustrates the selenium efficiency frontier (green), as shown before, but adds the selenium impacts of the efficient nitrate frontier (blue) and efficient salinity frontier (orange), mapped in selenium space. It can be seen that all three points from the salinity frontier, and two from the nitrate frontier, fall on the selenium frontier. Two BMP scenarios that fall on multiple frontiers increase selenium concentrations (RI30+LF30, LF30). A majority of the efficient nitrate frontier also has positive selenium impacts, a development that supports the previously identified link between nitrates and selenium dissolution (Bailey, Hunter and Gates 2012). This illustration conveys important information about the impacts on selenium that would occur if policy focused on reducing either nitrogen concentrations or losses to soil salinity. The same charts for the nitrate concentration and soil salinity losses are presented below.

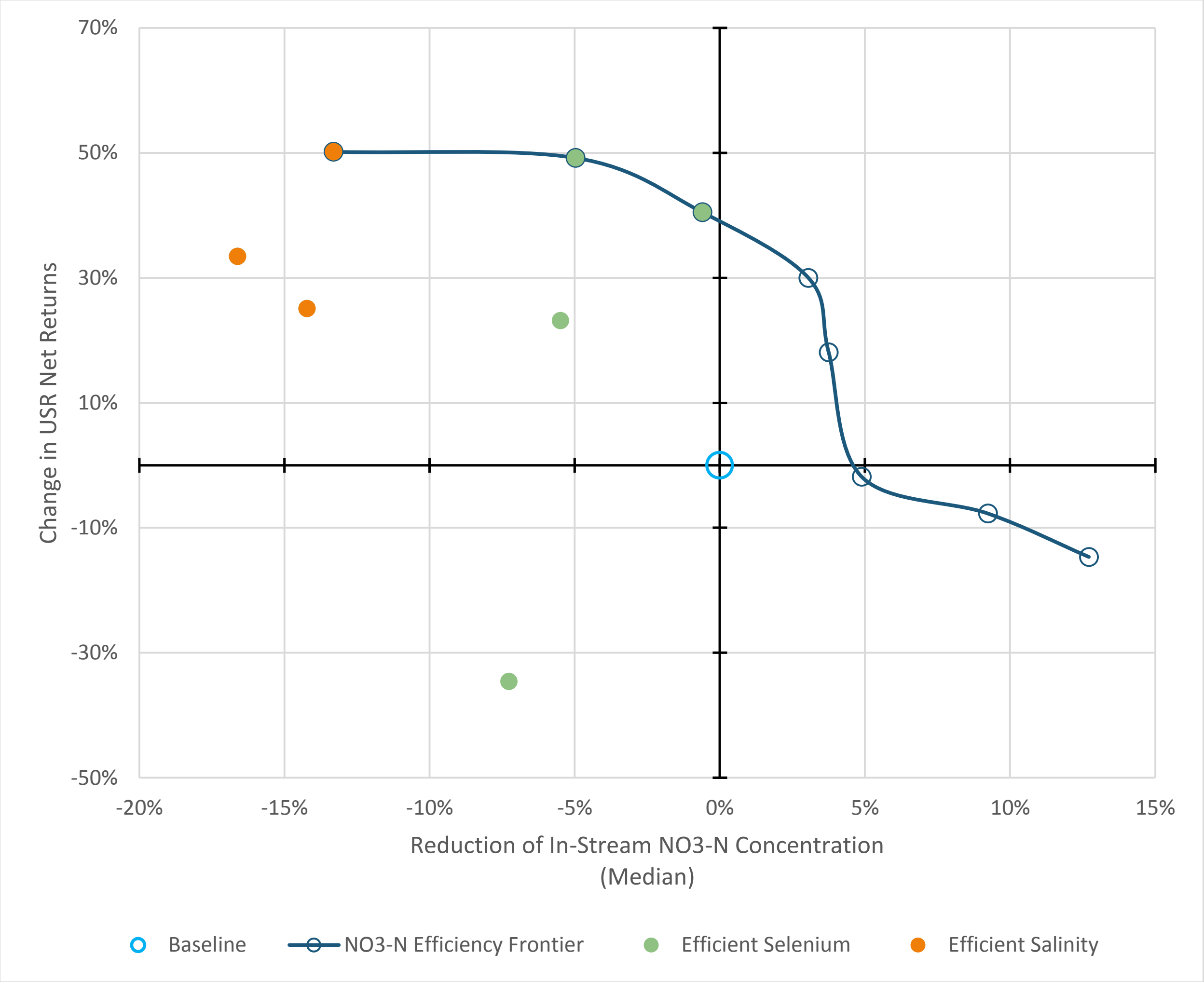

Figure 17. Efficient BMPS Mapped in Nitrate Space

If policy were focused on selenium or salinity, the impacts on nitrogen would be as shown in Figure 17. Plotting the efficient selenium and salinity frontiers in nitrate space (Figure 17), we see that the efficient selenium and salinity points all have a negative impact (increase concentrations) on nitrates. The most effective BMP for selenium management (RI30+RF30+CS80), has the opposite effect on nitrates, increasing in-stream concentrations by 7%. Those BMPs that fall on the salinity frontier have more significant negative impacts on nitrates, increasing in-stream concentrations from 13% to 17%.

Finally, policy could be focused on selenium or nitrates, and the resulting salinity impacts are shown below in Figure 18. As shown, there are no BMPs that worsen soil salinity conditions, and both efficient selenium and nitrate points fall on the salinity frontier. It is notable that the two BMPs that result in no changes to soil salinity losses (RF10 and RF20) fall on the nitrates efficiency frontier. The BMPs from the selenium frontier appear to have superior impact on salinity when compared to the nitrate frontier BMPs.

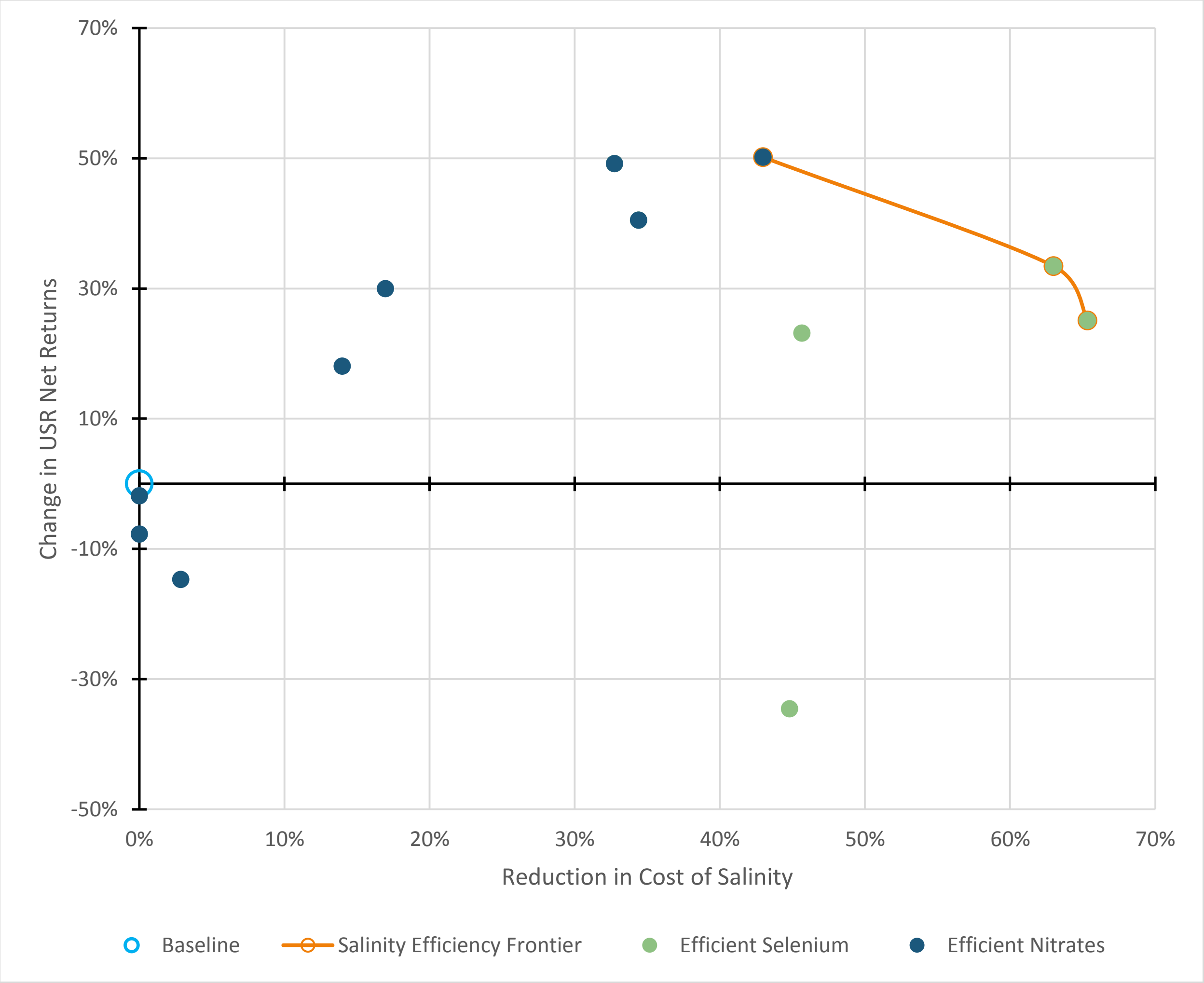

Figure 18. Efficient BMPS Mapped in Salinity Space

3.3 Radar Charts

The last method used to compare the multiple outcomes is radar or spider charts. Radar charts provide a depiction of the multi-dimensional analysis needed to accurately assess the total impact of a BMP scenario by plotting *n*-criterion in a unit-less space. Presented in Figure 19 are those BMPs that fall on at least one of the efficiency frontiers, with the exception of BMPs that increase selenium concentrations. BMPs that increase nitrogen concentrations up to the interim standard for total nitrogen are included.

The radar chart consists of four criterion (USR net returns, in-stream selenium and nitrogen concentrations, and soil salinity costs), plotted as a percentage of each respective baseline measure (Baseline = 100%). The chart ranges from 0% in the center to 150% on outer bounds (representing a 50% increase). For economic measures, desirable outcomes exist above the baseline measure (increase in net returns). For environmental measures, movement in toward zero is the preferred outcome (decrease in pollution and soil salinity losses).

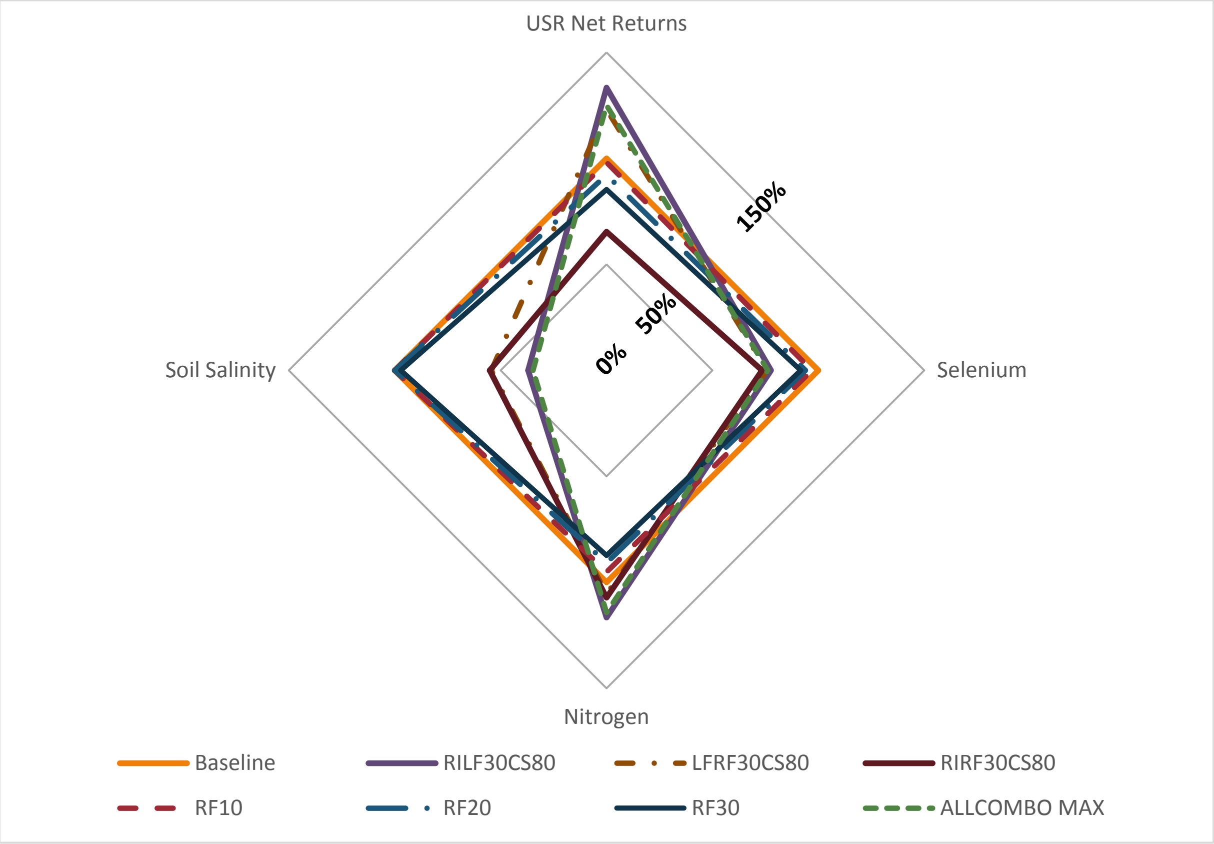

Figure 19. Radar Chart Showing Trade-offs of Efficient BMPs

Figure 19 shows that there is no single BMP nor combination BMP, which outperforms all others. An "ideal" BMP would lie outside all of the others on the net returns axis, and inside all of the others on the environmental axis. This supports the notion that LARV producers and water quality policymakers face trade-offs when deciding on how to improve water quality outcomes. Choosing how to manage trade-offs depends on the weights placed on each respective measure. This thesis has avoided the use of weights due to the intense data requirements and inherent heterogeneity across stakeholders. However, we may be able to use other qualitative information to make recommendations.

3.3.1 Choosing BMPs

As previously mentioned, the "ideal" BMP scenario would strictly dominate all other scenarios, meaning it would be superior in all measures to other outcomes (highest profits, lowest pollution). It ends up being the case that none of the investigated BMP scenarios strictly dominate all others. Therefore in deciding which of the above BMPs to implement, LARV producers and policymakers must face some trade-offs. This thesis presented three methods of illustrating trade-offs; trade-off table, trade-off frontiers, and radar charts. Using these illustrations, we can begin the process of eliminating inferior BMP scenarios. As described in earlier sections, decision makers could utilize trade-off tables and frontiers to eliminate very poor performing BMPs, and identifying efficient BMPs scenarios for a respective environmental measure. Radar charts then can be used to compare the efficient scenarios across all measures. Further comparison becomes dependent on how decision makers value each of these measures.

Based on the assumption of the profit maximizing producer, we can reasonably suggest that lease fallowing, and combination scenarios that include lease fallowing, will be highly desired by LARV producers. Ranking BMPs on their environmental performance requires some information on how LARV producers value selenium, nitrate, and salinity pollution. Using the results of a survey conducted over the summer of 2016[36] (Hoag, Smith and Gates 2016), we can gain insights into the measures that local

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[36] The term salinity was used in a water quality context in the 2016 survey. However, due to the exchange between soil salinity and in-stream salinity, it is reasonable to relate the results of the survey to the results of this thesis. The full results of Hoag, Smith, and Gates survey are available on the ARMAC website at: https://www.coloradoarmac.org/survery-results

producers are most concerned with and use that information to formulate recommendations. Based on the results of the LARV producer survey, salinity was identified as the highest concern for producers with about 55% of respondents citing it as a problem. This is not an unexpected result in that salinity contributes to direct economic losses for LARV producers. Selenium was found to be the second most measure of concern with 35% responding it is a problem. These responses would suggest that the RI30+LF30+CS80, RF30+LF30+CS80, RI30+RF30+CS80, and ALLCOMBO MAX would be among the favorite BMPS to implement, and thus recommend.

3.4 Shortcomings

While the results of this exercise are useful, they are far from flawless. Models are representations of reality, but fail to capture the vast heterogeneity that truly exists in the real world. Besides any shortcomings from the environmental modelling effort that was not part of this analysis, the shortcomings of this modeling effort are primarily driven by the assumptions that exist within linear programming, the limitations of data, and future uncertainty.

3.4.1 Linear Programming Limits

McCarl and Spreen (1996), describe the assumptions of the LP model as objective function appropriateness, decision variable appropriateness, constraint appropriateness, proportionality, additivity, divisibility, and certainty. This section will explore four of these; objective function appropriateness, decision variable appropriateness, additivity, and certainty.

The objective function of this model is based on the neoclassical assumption that the primary objective of LARV producers is to maximize the net returns of agricultural production. This age old assumption, revered for its consistence with the norm of economic efficiency, where resources are put to use such that value generated is maximized (Koplin 1963), has been challenged on numerous grounds. Simon (1959) discuss some of the concerns with the net return maximizing assumption. Among those relevant to this thesis are the ambiguity between short-run and long-run net return maximization and the possible existence of non-monetary benefits. This model does not include any short-run decision making, which is incredibly complex for LARV producers whose water supply is often very uncertain and can include various in-season decisions. The existence of non-monetary benefits to operation, often referred to as utility, would introduce significant bias into these findings. If producers engage in agricultural production for reasons than other making net returns, this model becomes obsolete. There is also evidence emerging from ongoing research at CSU that LARV producers may be treating their water rights as a legacy asset. Legacy assets are described as an asset that has been owned for a long period of time, whose value is depressed or stagnant, but may have a new, increased value in the future. It is reasonably presumed that the value of the right will be worth more in the future than today, however, water must be put to a beneficial use in order to maintain a water right. If this is the case, the more accurate objective may be to minimize the costs of maintaining a water right, and might partially explain why producers choose not to adopt new technology. Ongoing research at CSU also suggests the existence of an option-value associated with the future sale of water.

While there are a various variables included in this model, the primary decision variable that drives all outcomes (aside from canal seepage related outcomes) is acres of production. This variable is indexed across three levels including crop, irrigation technology, and canal. Two of these indices are actual choices a producer can make; crop and irrigation technology. The third is an exogenous decision that, for all intents and purposes, cannot be easily changed. This model allows producers to make a single planting, irrigating, and harvesting decision. It could be, and likely is, the case that these decisions are not made simultaneously at the beginning of the season, but instead at stages throughout the season. It is possible that in any given year, water is traded among growers on a common ditch. These trades could have significant impact on the solution, but are difficult to capture the regional level.

Inconsistencies across seasons complicate the modeling efforts, and modelers are often lacking sufficient data to accurately represent this temporal decision making.

The assumption of additivity could be another area where this model is weak. This assumption implies a constant, and additive relationship between coefficients and variables. The coefficients used throughout the model are based on averages across the study region; implying that each acre of land growing crop *i*, under irrigation technology *n*, requires the same amount of water and produces the same level of yield. In reality, there is vast heterogeneity among these coefficients, and implementing BMPs could have significantly different outcomes through targeting the least inefficient producers. Targeting pollution hot-spots, and/or those irrigators with the most inefficient practices for BMP implementation is the most efficient approach. However, the existence of sufficient information regarding on-field irrigation practices and efficiencies limits this analysis. Pollution hot-spots are in the process of being identified and analyzed, but are not included in this thesis.

The assumption of certainty in regards to the perfect knowledge of all coefficient values in the model is what make this model deterministic; these constant, known coefficients are what determine the solution of the model. If these parameters are incorrect, the solution of the model is incorrect. However in reality, it is impossible to parameterize the model with 100% accuracy. Estimations of future scenarios based on historical data are employed to test BMP implementation, which can create significant error if the future varies from the past. An attempt to address this error is made by running the model with a series of crop prices, varying the cost parameters to account for EQIP cost-sharing, and modifying the replacement water structure.

3.4.2 Data Limitations

There are also assumptions in the model that result from limited data and regional aggregation. This model treats all acres as homogeneous, interchangeable, and separable; where in reality, acres vary significantly in a series of characteristics including underlying soil, topography, existing infrastructure, and decreed water. These characteristics may limit the applicability of laser-land leveling or high efficiency irrigation systems such as sprinkler or drip irrigation. Underlying soil and topography may also drive water table depth, mineral dissolution, and pollution loading to the river. Analyzing potential "hot-spots" for pollution would further improve the efficiency of BMP implementation.

The model also treats production activities, and the ability of producers as homogenous on each farm. In reality, farms are in unique in their production methods and operations, their aversion to risk, and possibly in their objectives. Crop production often represents one aspect of a farmers operations. Cattle and dairy operations play a significant role in farm enterprises that is not included in this analysis, and if producers are growing feed for their cattle operations, the optimal crop-mix cold look significantly different.

3.4.3 Future Uncertainty

Inherent error exists in the model based largely on our assumption that the future will mimic certain aspects of the past. There is an obvious level of uncertainty with all models that project into the future. This model is not immune. Policies that change the way water is allocated or water quality is regulated, lawsuits from neighboring Kansas, unforeseen changes in technological capabilities, and shifts in commodity markets could all have significant impacts on the results of this modeling. This is addressed in part by including analysis of reservoir storage option and varying crop prices. This analysis shows that managing return flows at the regional level, as opposed to on farm, could add significant cost saving to the canal sealing BMP; one of the better environmentally performing BMPs.

Conclusion and Future Work

This thesis set out to describe the institutional system in which LARV water decisions are made, to quantify the economic cost of BMP adoption, and to identify efficient BMPs and implementation levels by comparing economic and environmental measures in a sub-region of the LARV. A few major takeaways standout from this analysis. First, implementing BMPs across the upstream study region results in trade-offs between economic and environmental measures. From this analysis, there is not found to be a single BMP scenario that strictly dominates all others. Therefore, the optimal BMP for the USR will depend on how stakeholders and policymakers value economic and water quality measures. Sharing the findings of this thesis to the ARMAC and garnering their input will represent a step in the right direction, but continued information sharing is key to identifying the best way forward for the LARV.

Secondly, lease fallowing would appear to be the economically optimal BMP for LARV agricultural producers, generating increases in regional net returns from 20% to 49%. Temporary transfers appear to be the most lucrative option for individual farmers in the LARV. As previously discussed, it is possible that local agricultural input and equipment suppliers, could be negatively impacted in years when land is fallowed. A more comprehensive analysis of the regional economic impacts of lease fallowing in the LARV should be further examined. There also needs to be a more complete analysis of the lease fallowing potential of individual canals. It may be the case that lease fallowing is an option in the water-long upstream region, but it may be less feasible in the downstream region. Due to the marginal increase of in-stream selenium and nitrate concentrations, any expansion of lease fallowing should also be accompanied by some other BMP and careful monitoring to ensure that implementation results in environmental improvements to the region.

Thirdly, combining BMPs seems to result in higher levels of pollution reduction than single practices alone. The lease fallow BMP plays another important role here by offsetting some of the economic losses associated with implementing BMPS. BMPs such as reduced nitrogen fertilizer and canal sealing are in general the most effective in reducing both in-stream selenium and nitrogen concentrations, and the impacts of soil salinity. However, these BMPs are also among the more expensive and difficult to implement. Reducing nitrogen application occurs at the farm level and would be incredibly challenging to monitor and regulate, let alone the added risk of reduced crop yields. Canal sealing is a BMP that requires broad collaboration and agreement among a canal's owners/operators and may require a canal-specific Rule 10 plan[37]. This coordination may result in additional transactions costs and complicate the process of implementation.

Lastly, this approach is a region-wide evaluation of BMP implementation and the associated changes in economic and environmental changes. The findings indicate that many of these BMPs could be regionally implemented at a relatively low cost. However, the findings do not speak to the distribution of losses, which could reasonably be expected to impact junior rights canals more than senior rights canals. Future analysis should look at the distribution of costs and benefits, and how these BMPs impact the broader regional economy.

The focus of recommendations for future analysis can be broken into three categories; depth, breadth, and additions. Future analysis should look at specific pieces of this analysis in more depth. A deeper understanding of lease fallowing feasibility, reservoir storage accounts, and sprinkler expansion potential are critical. A wider breadth of analysis including the DSR, and the combined (USR and DSR) basin is required to fully understand the impact of practices on water quality and quantity. In terms of

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[37] When asked about this scenario, engineers at the LAVWCD said it would depend on the canal and degree of changes in return flows as to whether a new Rule 10 plan was necessary.

additions, analysis of the riparian buffer zone expansion BMP, uranium, and non-market benefits of improving ecosystem health would significantly add to the findings of this thesis.

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Appendix 1: Example of Crop Enterprise Budgets

Corn - Furrow Irrigation (Siphon Tube)

Adapted from Colorado State University Extension (2015, Southeastern Colorado)

Gross Receipts	**Price**	**Yield (Bushels)**	**$/Acre**
Corn	5.34	196.43	1048.94
Net Gov. Payments			0.00
Total Receipts			**1048.94**
Direct Costs	**Cost/Unit**	**Quantity**	**Cost/Acre**
Pre-harvest Operating			
Seed	$360.00	0.40	$144.00
Fertilizer (Nitrogen & Phosphorus)	$110.00	1.00	$110.00
Herbicide	$22.00	1.00	$22.00
Insecticide/Fungicide	$0.00	0.00	$0.00
Field Preparation			
Disk	$10.00	4.00	$40.00
Level	$15.00	1.00	$15.00
Plow	$22.00	1.00	$22.00
Furrow	$15.00	1.00	$15.00
Custom Planting	$12.00	1.00	$12.00
Irrigation			
Water Assessment (surface)	$7.52	1.00	$7.52
Energy/Pumping[1]	$0.00	0.00	$0.00
Rule 10	$0.00	0.00	$0.00
Labor	$39.39	1.00	$39.39
Crop Insurance	$35.00	1.00	$35.00
Interest Expense (6 mths @ 6%)	$12.26	1.00	$12.26
Total Pre-harvest Cost			$474.17
Harvest Cost			
Custom Harvest ($0.25/Bushel)	$0.25	196.43	$49.11
Hauling ($0.24/Bushel)	$0.24	196.43	$47.14
Total Harvest Cost			$96.25
Total Operating Cost			**$570.42**
Property and Ownership Costs			
General Farm Overhead	$65.00	1.00	$65.00
Siphon Tubes	$5.44	1.00	$5.44
Depreciation	$10.00	1.00	$10.00
Real Estate Taxes	$23.00	1.00	$23.00
Total Ownership Cost			**$103.44**
Total Direct Cost			**$673.86**
Net Receipts Before Factor Payments			**$375.08**
Factor Payments			
Land			$200.00
RETURN TO MANAGEMENT & RISK			**$175.08**

Corn - Sprinkler Irrigation (Large, Medium, Small)

Adapted from Colorado State University Extension (2015, Southeastern Colorado)

Gross Receipts	**Price**	**Yield (Bushels)**	**$/Acre (Large)**	**$/Acre (Medium)**	**$/Acre (Small)**
Corn	$5.34	218.26	$1,165.49	$1,165.49	$1,165.49
Net Gov. Payments			$48.01	$63.02	$89.53
Total Receipts			**$1,213.51**	**$1,228.51**	**$1,255.02**
Direct Costs	**Cost/Unit**	**Quantity**	**Cost/Acre**		
Pre-harvest Operating					
Seed	$360.00	0.40	$144.00		
Fertilizer (Nitrogen & Phosphorus)	$110.00	1.00	$110.00		
Herbicide	$22.00	1.00	$22.00		
Insecticide/Fungicide	$0.00	0.00	$0.00		
Field Preparation					
Disk	$10.00	2.00	$20.00		
Level	$15.00	1.00	$15.00		
Custom Planting	$12.00	1.00	$12.00		
Irrigation (Large)				Medium	Small
Water Assessment (surface)	$7.52	1.00	$7.52		
Energy/Pumping[1]	$22.03	1.00	$22.03	$27.53	$38.97
Rule 10	$2.50	1.00	$2.50		
Labor	$18.92	1.00	$18.92	$11.52	$17.28
Crop Insurance	$35.00	1.00	$35.00		
Interest Expense (6 mths @ 6%)	$12.26	1.00	$12.26		
Total Pre-harvest Cost			$421.23		
Harvest Cost					
Custom Harvest ($0.25/Bushel)	$0.25	218.26	$54.56		
Hauling ($0.24/Bushel)	$0.24	218.26	$52.38		
Total Harvest Cost			$106.95		
Total Operating Cost			**$528.18**	**$526.27**	**$543.48**
Property and Ownership Costs				Medium	Small
General Farm Overhead	65.00	1.00	$65.00	$65.00	$65.00
Pumping Plant	10.10	1.00	$10.10	$13.47	$20.21
Stabilization Pond	7.32	1.00	$7.32	$9.76	$14.65
Pipeline	9.44	1.00	$9.44	$11.18	$9.44
Sprinkler	70.24	1.00	$70.24	$81.87	$102.62
Depreciation	10.00	1.00	$10.00	$10.00	$10.00
Real Estate Taxes	23.00	1.00	$23.00	$23.00	$23.00
Total Ownership Cost			**$195.10**	**$214.29**	**$244.91**
Total Direct Cost			**$723.27**	**$740.57**	**$788.39**
Net Receipts Before Factor Payments			**$490.23**	**$487.95**	**$466.63**
Factor Payments					
Land @ 4%			$200.00	$200.00	$200.00
RETURN TO MANAGEMENT & RISK			**$290.23**	**$287.95**	**$266.63**