DISSERTATION

THREE ESSAYS ON INSTITUTIONAL DESIGN FOR VOLUNTARY WATER CONSERVATION

Submitted by

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ABSTRACT

THREE ESSAYS ON INSTITUTIONAL DESIGN FOR VOLUNTARY WATER CONSERVATION

This dissertation is a compilation of three essays on institutional issues inherent in water conservation decision making by agricultural producers. Chapter 1 includes summaries of the three papers I intend to defend and introduces some ideas and concepts visited throughout the dissertation. Chapter 2 presents the results of a multidisciplinary study on managing selenium pollution in the Lower Arkansas River Basin in Southeastern Colorado titled, "Institutional Constraints on Cost-Effective Water Management: Selenium Contamination in Colorado's Lower Arkansas River Valley." The study presents the cost-effectiveness of various management practices to mitigate selenium pollution flows simulated over twenty years using regional scale groundwater and reactive solute transport models. Social institutions, such as rules on water conservation, serve to influence decision making and alter the economic feasibility of conservation efforts. The third chapter, "Uncertainty and Technology Adoption: Lessons from the Arkansas River Valley," extends the property rights institutional concerns introduced in chapter 2 and looks specifically to how use-based property rights influence decision making for conservation irrigation technology. When an irreversible investment is made under uncertainty, there is often a delay in investment that would not be seen under the traditional Marshallian framework for investment. This study advances the literature by exploring how property rights further exacerbate this option value hurdle which serves to further delay investment under uncertain water supplies. An empirical section explores how property rights are being applied in

the Arkansas River Basin and discusses the implications for future conservation efforts. Finally, the last chapter, "An Experimental Approach to Resolving Uncertainty in Water Quality Trading Markets," uses experimental economics to explore the impacts of resolving uncertainty in water quality trading market design. This paper looks at whether non-point sources would take an opportunity to resolve environmental uncertainty if there is a water quality trading market in place. Additionally, it explores the interactions between a pollution market and voluntary abatement with and without a voluntary-threat regulation.

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official polices, either expressed or implied, of the State of Colorado or U.S. Department of Agriculture Tables" section above.

DEDICATION

I dedicate this dissertation to my husband, Chris, and my children, Orion and Carinae, who all kept me sane throughout this grueling dissertating process.

TABLE OF CONTENTS

1. CHAPTER 1 - INTRODUCTION

Water resources are unique in that they are both renewable yet depletable, abundant yet scarce. Conservation concerns for water span the gamut of quantity related issues (is there sufficient supplies to meet demand?) and quality related issues (is water drinkable or swimmable?). Ultimately, these two issues are largely governed by absent or inadequate property rights assignments. Property rights, generally speaking, are rules governing the allocation and (sometimes) use of a given resource. In order for efficient allocation of a resource to occur, property rights must be well-defined such that the resource is divisible, transferable and enforceable. The three papers included in this dissertation are designed to advance conservation of water resources by identifying areas in which property rights could be improved.

1.1 Water Quality Related Issues and Solutions

To begin discussions about water quality, one must first identify sources of pollution in a given water system. Point sources (PS) of pollution are those that can easily be traced to the source, such as to a piped discharge into a water stream from a wastewater treatment plant (M. Ribaudo, Savage, and Talberth 2014). Other sources of pollution, which are not so easily traced, are known as non-point sources (NPS) of pollution and remain one of the largest contributors to water quality impairment today, largely due to an inability to hold polluters responsible for their discharges (Selman et al. 2009). As NPS dischargers (the focus in this dissertation is largely on the farming community) often do not have an obligation to resolve water pollution, most efforts are focused on requests for voluntary pollution control.

It is important to focus efforts on strategies that are 1) effective in mitigating pollution flows, and 2) economically and socially feasible. Groundwater, surface water and reactive transport modeling efforts have made great strides in tracing pollution flows attributable to NPS; many academic journals have even been dedicated only to these efforts. These models have recently been applied to the assessment of effectiveness of best management practices (BMPs) on pollution control. And economists have seized on this opportunity to improve our understanding about pollution control by using these model results to address important economic and policy questions.

Chapter two of this dissertation looks to one such research effort that has been ongoing for over a decade regarding selenium pollution flows in the Lower Arkansas River Basin in Southeastern Colorado. These pollution flows have largely been attributable to irrigation water runoff (Gates et al. 2009; Morway, Gates, and Niswonger 2013). The efforts toward modeling pollution processes and their receptiveness of pollution control management strategies have resulted in various publications in peer-reviewed journals that give confidence to the knowledge of the pollution process itself as well as the receptiveness to management (Gates et al. 2009; Bailey, Gates, and Halvorson 2013; Bailey, Romero, and Gates 2015). Nevertheless, efforts to attribute pollution flows to an individual farmer still prove tricky; an inability to assign the burden of abatement to individuals results in calls for voluntary pollution control from all farmers within the basin. Over the last few decades various field trials have been implemented within the basin and results have been funneled back to the farmers during extension related events. In order for farmers to implement practices voluntarily, the burden of proof of feasibility is on government, non-governmental organizations and universities. Chapter two does that by exploring the cost feasibility and barriers to adoption of conservation technology in the Lower Arkansas River Basin. Without an assessment of the feasibility of various management options, pollution control from NPS remains a theoretical construct.

Efforts towards understanding voluntary pollution control and conservation have largely found that voluntary abatement is more the exception than the rule. Farmers are among the more elusive adopters in spite of many practices having positive on-farm net benefits (Knowler and Bradshaw 2007). Propensity to adopt practices depends on both characteristics of the practices and characteristics of the farmers (Greiner, Patterson, and Miller 2009). Those that do undertake voluntary pollution control tend to be well-informed (Knowler and Bradshaw 2007) with access to social and financial resources (Baumgart-Getz, Prokopy, and Floress 2012). Others have intrinsic (altruistic even) motivations for pollution control (Greiner and Gregg 2011; Knowler and Bradshaw 2007; Marc Ribaudo 2015; Howley 2015). Yet some researchers even warn that altruism can be "crowded out" with cost-share programs, market based instruments (Greiner and Gregg 2011). Additionally, nonpecuniary benefits, while good motivators for voluntary pollution control, are not good indicators of environmental benefit (Howley 2015).

Voluntary pollution control is not always in the best economic interest of an individual farmer. Farmers implementing practices sometimes spend significant amounts of money installing buffer zones or cover crops that may not lead a proportionate increase in on-farm productivity in future time periods (Ribaudo 2015). In these cases, the private accrual of net benefits is at odds with the social welfare of a given watershed (or other resource management unit) for a given management practice. Ribaudo (2015) finds that often those that implement practices voluntarily are not those on the most sensitive lands and thus the marginal benefit of the conservation activity is very low compared to if they had targeted conservation to more sensitive lands. A meta study also finds that the way intrinsic motivations and embedded ties have been loosely defined across various studies have also limited the capacity to really understand and effectively encourage non-economic motivations for pollution control (Baumgart-Getz, Prokopy, and Floress 2012).

Each group of people managing a common resource has their own characteristics and rules of operating which influence how they choose to manage a given resource (Ostrom 2011). Rules of the game matter when managing a common resource and institutional design is often the largest obstacle for engaging agricultural producers as institutions might just be at odds with each other (Sharp and Bromley 1979). Indeed, in the Arkansas River Basin in particular, one farmer anonymously told me in the summer of 2015:

> "We could fix the canal seepage problem in a weekend. Just let us at it, we are farmer's, we know how to get things done. The problem is, if we reduce canal seepage, we could be in violation of the [Arkansas River] compact."

In this case, management options that we were looking at, particularly that of canal sealing, were very feasible economically and physically but farmer's did not really see it as an option because they had previously violated the compact and did not want to repeat that again. Integrating the institutional analysis into the cost per unit of pollution framework in chapter two gives a much better picture regarding the perceived efficacy of each of the practices studied.

While institutional economics looks to rules for innovation, neoclassical schools of thought look to market based instruments to deal with pollution. An efficient market based instrument is one that maximizes net benefits of pollution control by setting the marginal cost of abatement equal to the marginal benefit. Often for pollution, the benefits of pollution reduction are not quantified, leading to a second best policy, which is one that minimizes costs by setting abatement costs equal across all firms given a constraint on pollution (M. Ribaudo, Savage, and Talberth 2014). One way to achieve pollution control at least cost is through the use of water quality trading markets where pollution is set to a fixed level and then firms can trade units of pollution control either between themselves or with an alternative source (Goulder 2013). While these markets are efficient in theory as all participants in the market have efficient property rights over allowable units of pollution, practices differ significantly in the real world. There are various impediments to an efficient market design including the following:

1. High transaction costs
2. Thin or lop-sided markets
3. Heterogeneous abatement costs
4. High costs of enforcement
5. Issues with finding the right trading ratio
6. Non-binding regulations (or caps)
7. Disparity among risk preferences for point sources and non-point sources

Due to the lack of success for these markets, many studies explore ways in which water quality trading went wrong after implementation (D. L. Hoag and Hughes-Popp 1997; D. Hoag and Motallebi 2017; Breetz et al. 2004; Selman et al. 2009). Others compare various water quality trading market designs to other market based instruments (Peterson et al. 2007; C. M. Smith et al. 2012; Nguyen et al. 2013; Colby 2000). These studies make inferences about how markets would work based on cost and return estimates; but the actual behavior of farmers is unknown. For example, how much more does a farmer have to receive compared to break even in order to adopt a conservation practice (Motallebi and Hoag, 2017)?   Experimental economics has provided a rich platform to test behavioral dimensions linked to these aforementioned bodies of research in a laboratory setting to determine over-arching behavioral incentives that distort otherwise straightforward economic theory (Jones and Vossler 2014; Suter, Spraggon, and Poe

2013; Cason and Gangadharan 2006; Stranlund 2008). It is within this body of literature that chapter four of this dissertation gets its inspiration.

The old adage, “dilution is the solution to pollution,” is not so easily applied in a state like Colorado where rainfall does not exceed twelve inches in a year in much of its most productive landscapes (Price and Gates 2008; Goemans and Pritchett 2014). A lack of mandatory NPS pollution control leads to attempts to engage these sources through voluntary mechanisms including voluntary threat regulations and water quality trading markets. Voluntary threat regulations ask farmers and other non-point sources, largely municipal developers through stormwater management, to engage in pollution control or they will, in the future, face a regulation. One example of this approach to pollution control in Colorado is Regulation #85, a policy implemented in the South Platte River Basin in Northeastern Colorado in order to mitigate nutrient pollution. This regulation places nutrient effluent limits on wastewater treatment plants (WWTPs) with voluntary management of agricultural run-off that will lead to regulation by May 31, 2022 if “sufficient progress has not been demonstrated in agricultural nonpoint source nutrient management” (5 CCR 1002-85, Regulation #85, adopted June 11, 2012). This policy also allows for trading between PS and NPS although the feasibility of such a program is in its preliminary stages.

A few urban areas near the urban Denver area feature water quality trading programs or pilot programs that have seen limited success including Bear Creek, Cherry Creek Reservoir Watershed Phosphorus trading program, Chatfield Reservoir Trading Program and the Colorado Pollutant Trading Program (Selman et al. 2009). It was from these policies that the ideas for the fourth chapter were wrought. More specifically, if NPS are not required to reduce pollution, will they? If firms have access to a water market, does that crowd out voluntary abatement? Would firms be willing to verify environmental outcomes if given the opportunity and the potential to garner benefit from a pollution market? While all of these questions directly relate back to the current experiences in Colorado, they are highly applicable to the larger debate occurring nationally and internationally about how to engage NPS in pollution control.

1.2 Water Quantity Related Issues and Solutions

Water quality and water quantity are strongly related. Too much nutrient rich water seeping into groundwater and reacting with naturally present underlying shale results in pollution loads of selenium in excess of EPA standards (Bailey, Gates, and Halvorson 2013). To the contrary, insufficient rains combined with low volume irrigation can lead to salt build up on fields (Morway, Gates, and Niswonger 2013). As such, there is a delicate balance between water quality concerns and water quantity concerns. Yet, reducing irrigation runoff also reduces return flows to downstream users. Any water not consumptively used by a plant or a process is returned to the ground or surface water, which is then used by a downstream user. This makes property right assignments very tricky. Increases in consumptive use of water or a decrease in runoff will both influence a downstream water user in such a system (Waskom et al. 2016).

Conservation irrigation, such as sprinkler irrigation, can be a very effective tool for managing water run-off and can help achieve greater yield with less water. However, in a system that depends on return flows, conservation must be very strict to protect historical downstream users (Anderson 2013). Kansas successfully sued Colorado for insufficient return flows in 1985 leading to new rules being implemented in the basin to protect return flows to downstream users. Chapter three looks at how these rules and property rights restrictions on the resource influence conservation adoption. I show that the feasibility of adoption depends on how the property right is enforced and on the perception of that property right.

1.3 How to Read the Dissertation

Each chapter of the dissertation is a stand-alone paper with its own introduction, background, methodology, results, conclusion, references and appendices. Each of these papers relate back to the issues discussed above and thus there is a great deal of overlap between the three papers. Nevertheless, each of the three papers apply different methodologies to the problems stated for each essay. Empirical information for chapters two and three overlap in some cases as chapter three is really an extension of chapter two. Nevertheless, chapter two is not needed to understand the scenario in chapter three and chapter three does not alter the findings from chapter two. Additionally, chapter two has already been published in JAWRA.

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2. CHAPTER 2 - INSTITUTIONAL CONSTRAINTS ON COST-EFFECTIVE WATER MANAGEMENT: SELENIUM CONTAMINATION IN COLORADO'S LOWER ARKANSAS RIVER VALLEY[1]

2.1 Introduction

The Lower Arkansas River Valley (LARV) in Colorado is designated an impaired watershed by the Environmental Protection Agency due to high levels of selenium (Se) and uranium, endangering aquatic life and impairing domestic water sources (EPA, 2010). Samples gathered in groundwater over 2006 – 2011 within the study region described in this paper reveal an average concentration of 53.4 μg/L of Se, exceeding the livestock water guideline of 50 μg/L while samples gathered from the Arkansas River over this same period indicate an 85th percentile concentration of 13.5 μg/L, substantially higher than the aquatic life criterion (85th percentile) of 4.6 μg/L (Gates et al., 2009; Gates et al., 2015). Leached irrigation water reacts with naturally present Se-bearing shale formations and seleniforous soils to mobilize soluble Se, which is concentrated by evapotranspiration, then flows through the aquifer and discharges to the river (Gates et al., 2009). This process has been confirmed in other stream-aquifer systems underlain by shale formations (Presser et al., 1994; Lemly, 2002; Seiler et al., 2003). The link of water contamination to agriculture provides an impetus to develop mitigating policies; yet, nonpoint sources are not currently regulated, leaving solutions to voluntary programs that can reduce Se contamination in a cost-effective manner.

[1] This paper has been published in JAWRA with the following citation: "Sharp, Misti D., Dana L.K. Hoag, Ryan T. Bailey, Erica C. Romero, and Timothy K. Gates. 2016. Institutional Constraints on Cost-Effective Water Management: Selenium Contamination in Colorado's Lower Arkansas River Valley. Journal of the American Water Resources Association (JAWRA(52(6): 1420-1432. DOI: 10.1111/1752-1688.12463."

The purpose of this study is to search for cost-effective conservation practices, while accounting for institutional constraints that affect a producer's ability to adopt the most cost-effective practice. Studies that compare economic and environmental tradeoffs are common (Braden et al., 1989; Taylor et al., 1992) and are often represented in a trade-off frontier that shows only the most efficient combinations of cost and environmental outcomes. While these frontiers effectively reveal the environmental and economic consequences of different practices, they only tell part of the story because they do not include institutional constraints. Engineering approaches to estimate environmental outcomes, pollution from Se in this case, utilize field studies to determine impacts of implemented practices and employ models to project relative cost-efficiency for pollution abatement strategies (Collins and Gillies, 2014; Triana et al., 2010a). Economic approaches model costs by taking into account shadow prices or resource rents and opportunity costs associated with each engineering practice (Bond and Farzin, 2007; Liu and Sumaila, 2010). Approaches that depict these economic and environmental values in a frontier imply there is continuity from one level of implementation to the next when moving along the frontier. Research in integrated resource management and institutional economics illustrate, however, management of a common resource is rarely so easily modeled. Indeed, pollution control often depends much more on the rules of the game in place than on the physical environment or monetary costs, which often are given so much emphasis in a frontier (Ostrom, 2009; Grigg, 1999). These rules can make moving from one practice to another along the frontier infeasible and therefore must be considered in any policy or analysis about why farmers adopt, or do not adopt irrigation management practices.

Identification of mitigation strategies to address water quality and their associated cost-effectiveness is an important first step in creating policy programs that address one of the foremost problems facing water systems today. The LARV historically has experienced problems with waterlogging and salinity such that the ground is over-saturated with irrigation water and high in dissolved salts due to seeping earthen canals and the dominant irrigation method, flood irrigation, leading to decreased yields on agricultural lands. Using a regional-scale modeling approach with the MODFLOW-UZF1 groundwater flow model (Niswonger et al., 2006), Morway et al. (2013) found there are several best management practices (BMPs) that, if implemented in the LARV, may help ameliorate waterlogging and salinization conditions, decrease non-beneficial consumptive use of water, and lower excessive return flows. These BMPs include canal sealing, increased irrigation efficiency, land fallowing, and combinations of these three options. The flow model has also been used in conjunction with the groundwater reactive solute transport model UZF-RT3D for Se species (Bailey et al., 2014), which has been used to assess decreased Se groundwater concentration and mass loading to the Arkansas River under various hydrological and management scenarios (Bailey et al., 2015). Although only practices deemed feasible were investigated, the economic costs/benefits were not analyzed. This study links the results of these simulation models with economic and institutional information to examine the problem of Se in the LARV.

The objectives and contribution of this work include: 1) to provide a metric for cost effectiveness to simulated BMPs in the LARV as described in Bailey et al. (2015) and to build associated Pareto frontiers for these BMPs that map economic and environmental trade-offs, 2) to identify a set of major institutional constraints to local farmers in the LARV, and 3) to determine how institutional constraints related to western water management influence the frontiers. This paper differs from previously-published studies in that it integrates physical, environmental, social and political environments in its recommendations for policy in the future.

We use a traditional modelling and budgeting approach to estimate contamination and costs related to different types and intensities of irrigation management, and to map these trade-offs in a Pareto frontier. We then ask farmers through an in-person qualitative survey to identify institutional constraints that affect how they are able to manage their irrigation systems, or to change them. Finally, we examine how the institutional constraints that farmers identified affect feasible solutions along the Pareto frontiers. The work has implications for managing water quality under western water institutions as well as paving a way forward to better understand processes and solutions for pollution from non-point sources.

2.2 Background

The LARV is home to about 270,000 acres of irrigated agriculture, mostly consisting of corn, alfalfa, onions and melons. As much as 80 to 90% of farmers use surface (flood) irrigation (Gates et al., 2012), and only about one-fourth employ any nutrient management practices (Bauder et al., 2012). In addition the LARV is inflicted with shallow groundwater tables and high salinity, which results in reduced crop yields (Morway and Gates, 2012; Gates et al. 2012). On top of reduced farm yields, livestock, fish and wildlife are impacted by deep percolation as excessive irrigation water, rich in nutrients and trace elements, seeps down into the groundwater and reacts with naturally present shale, discharging Se and other soluble forms of pollutants to the river (Gates et al., 2009). Even without agricultural production, background levels of Se would be problematic in the LARV due to the presence of underlying cretaceous shale. Irrigation exacerbates this problem and current levels exceed concentrations considered safe for aquatic life and livestock (Lemly, 2002). Figure 2.1 illustrates the current distribution of Se in a baseline scenario under current practices; this study considers voluntary management practices that reduce runoff of nutrient-rich irrigation water in order to mitigate Se loadings to the river.

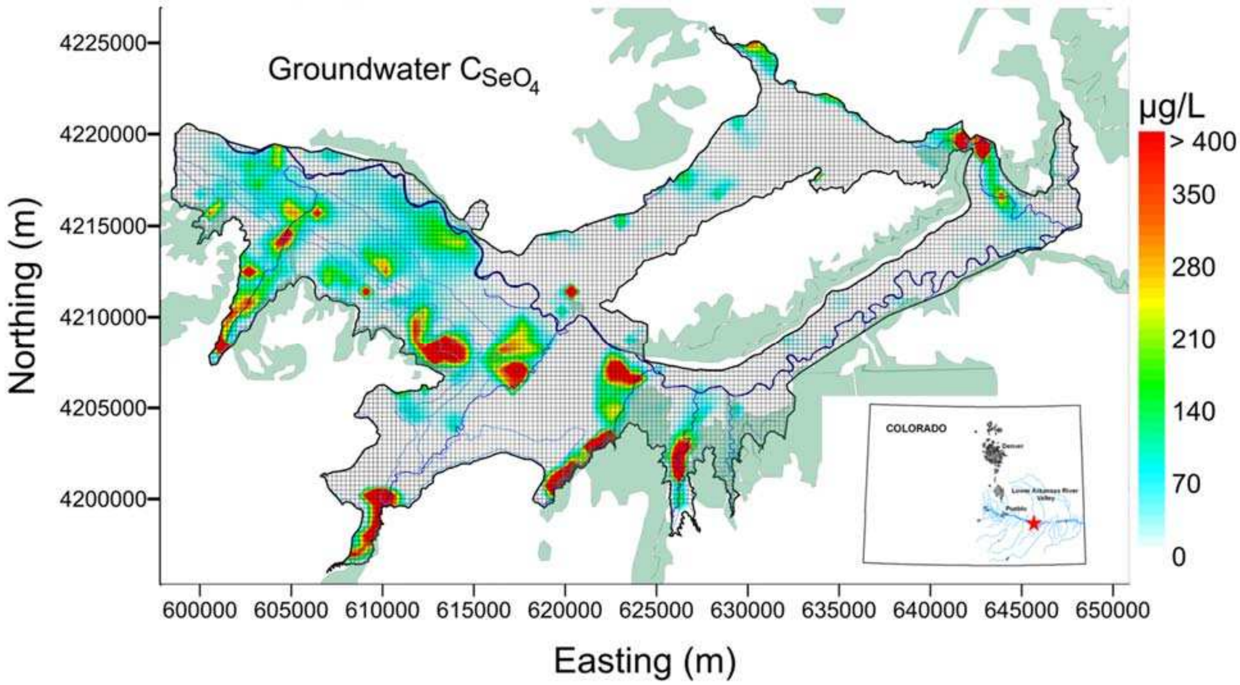

Figure 2.1: Spatial Distribution of SeO4 Concentration in Groundwater, as Simulated by the UZF-RT3D Model in the Baseline Simulation. The areas with shallow or outcropped shale are shown in green, and the finite difference grid used by the MODFLOW and USF-RT3D models are shown in the background of the figure.

In spite of the negative impacts of excessive irrigation, water has great economic and social importance in the region. A study by Naeser and Bennet (1998) looked at the value of agricultural water in the Arkansas River Valley from Pueblo, Colorado to Garden City, Kansas and found average 1995 adjusted water values are between \$45 and \$76 per irrigated acre in Colorado. Furthermore, agriculture provides 14% of all jobs in Southeast Colorado and is the second largest employment sector in the region (State Demography Office, 2012). More than that, agriculture greens the otherwise desert landscape of the valley, creating new ecosystems and sustaining the rural lifestyle of its communities. There are demands on the water from both upstream and downstream users. The Colorado Water Conservation Board projects a pending gap for municipal and industrial water users as the Colorado population continues to grow at an increasing rate and two-thirds of the states' water goes to other states under interstate water compacts (State of Colorado 2010). In 2005, Kansas successfully sued Colorado for insufficient water supplied under the Arkansas River Compact resulting in $34 million dollars in damages (Kansas Department of Agriculture 2009). Finally, scholars note a legal system of prior appropriation and the beneficial use doctrine eliminate incentives for conservation (see Gallaher et al 2013; Magnuson and Smith 2010; Schroeder and Ure 2010), and farmers in our survey agree. Western water institutions, such as those related to laws and rules created to help meet interstate compacts, must be considered in determining the feasibility of management practice implementation.

2.3 Methods

We proceed below by estimating fate and transport of Se for each practice (lease fallowing, canal sealing, reduced irrigation and reduced fertilizer application), followed by estimating the cost of each practice. We then construct Pareto frontiers with three levels of intervention: basic, intermediate, and aggressive. Finally, we identify major institutional constraints through farmer interviews and apply them to the frontiers to determine if they change how farmers might see the costs and benefits of each management option.

2.3.1 Groundwater Flow and Reactive Transport Modeling

This section provides details of using numerical groundwater modeling methods to assess the impact of specific best management practices (BMPs) on Se remediation in the LARV. The impact of the BMPs studied here, lease fallowing, canal sealing, reduced irrigation and reduced fertilizer application, were previously assessed using modeling methods to determine impacts on water logging (Morway et al., 2013) and Se contamination (Bailey et al., 2014; Bailey et al., 2015). BMPs were selected based on (i) potential to affect regional-scale groundwater flow patterns, and hence groundwater flows and associated Se loadings to the Arkansas River; (ii) the effect of nitrate (NO_3) on dissolved Se species; and (iii) the feasibility of implementation as determined through meetings with local landowners and canal companies. Bailey et al. (2015) included enhancing the function of riparian buffer zones, i.e. increasing vegetation and associated organic matter so that Se chemical reduction can be enhanced, yet this practice is not included in this assessment due to high uncertainty in the rate of riparian vegetation growth and organic matter accumulation. Full model details have been published previously (Bailey et al., 2014; Bailey et al., 2015) and, as such, this section provides a limited summary of the methods and results in order to provide a context for the economic and institutional methods presented in the following section.

Many previously published studies have laid the groundwork for this current contribution. Groundwater and surface water monitoring and water quality sampling in groundwater, the river network, and irrigation canals have been ongoing efforts (see Gates et al., 2009; Gates et al., 2016). Furthermore, laboratory studies aimed at investigating the release of Se from marine shale in the presence of dissolved oxygen (O_2) and NO_3 (Bailey et al., 2012) have occurred in the LARV during the past decade to provide principal processes and parameters for numerical groundwater models.

The groundwater flow model (Morway et al., 2013), constructed using the UZF1 package (Niswonger et al., 2006) of MODFLOW-NWT (Niswonger et al., 2011), was calibrated and tested for the 1999-2007 period, with model results compared against measured water table elevation, estimated return flows to the Arkansas River, estimated seepage along earthen irrigation canals, and estimated ET. Using the calibrated model, the effect of various management practices (sealing earthen canals, reducing irrigation volumes via increased irrigation efficiency, land fallowing) on water table elevation and groundwater return flows to the Arkansas River were assessed. Results indicate average water table depth can be increased by up to 1.1 m, thereby reducing the threat of waterlogging, and 9.9 million m^3 (8000 ac-ft) of non-beneficial groundwater consumptive use can be saved annually.

The Se and N reactive transport groundwater model was constructed using the USF-RT3D (Unsaturated Zone Flow – Reactive Transport in 3 Dimensions) (Bailey et al., 2013b) modeling code, which solves the advection-dispersion-reaction mass-balance equation for the soil-aquifer system using a finite-difference solution scheme. The model uses the groundwater flow field and sources/sinks results from the MODFLOW-UZF1 model. Full details of model theory and model application to the LARV are contained in Bailey et al. (2013a) and Bailey et al. (2014), and only basic details are presented here. Chemical species included in the model are mobile forms of Se (selenate SeO_4, selenite SeO_3, seleniomethionine SeMet) and N (ammonium NH_4, NO_3), O_2, and organic forms (organic Se and organic N in soil humus and soil litter). The model accounts for Se and N cycling in the plant-soil system (solute uptake, dead root mass and after-harvest stover deposition, organic matter decomposition, mineralization and immobilization), one-dimensional vertical leaching through the vadose zone, three-dimensional transport through the saturated zone, and mass exchange with surface water bodies (canals, Arkansas River, tributaries). Chemical reactions include sorption of SeO_4, SeO_3, and NH_4, chemical reduction of Se species, nitrification and denitrification, and autotrophic denitrification in the presence of marine shale (in bedrock and outcrop form throughout the study region), with chemical reduction simulated via first-order Monod kinetic equations. Sources and sinks of solute mass include fertilizer, irrigation water, canal seepage, river water seepage, oxidative dissolution from marine shale and its weathered residuum, and groundwater pumping.

The UZF-RT3D model was applied to the 2006-2009 period, with model results compared against groundwater Se and NO_3 concentration and Se and NO_3 daily aggregate mass loadings from the aquifer to the length of the Arkansas River within the study region (Bailey et al., 2014). Estimated spatial distribution of average SeO_4 groundwater concentration during the 2006-2009 period is shown in Figure 1, with areas of outcropped marine shale also shown. The model then was applied in a multi-decade forecast setting using the groundwater flow data from Morway et al. (2013) to quantify the effects of management practices on Se groundwater concentration and Se mass loading from the aquifer to the Arkansas River and its tributaries. BMPs (at their various levels of implementation) are applied to all fields, which impacts the infiltration rates provided to MODFLOW and hence the transport of N and Se species within the soil-aquifer system simulated by UZF-RT3D. Full details and results of model forecast and BMP assessment are contained in Bailey et al. (2015).

The following four BMPs were assessed in the current study: decrease in seasonal N fertilizer loading, decrease in applied irrigation volumes (mimicking an increase in irrigation efficiency due to a change in irrigation practice, i.e. from improved flood irrigation or conversion from flood irrigation to sprinkler or drip irrigation), fallowing of land, and sealing of earthen irrigation canals. Canal sealing, land fallowing and reduced irrigation lower the potential for deep percolation of irrigation water, thereby lowering water table elevations and gradients and decreasing the loading of Se and N to the river system. Reduced N fertilizer decreases the amount of Se in the system by (i) decreasing the potential for NO_3 in leachate water to oxidize seleno-pyrite ($FeSe_2$) in the marine shale and release mobile SeO_4 and (ii) decreasing NO_3 concentration in groundwater to the threshold where SeO_4 can be chemically reduced by microbial populations (Weres et al., 1990; White et al., 1991).

Additionally, two combination BMP scenarios are simulated under three intervention levels using these models to determine the impact of implementation on Se concentrations and aquifer mass loadings (Table 2.1). Various levels of intervention were considered for each of the BMPs as well as the combination scenarios; basic intervention was a low-level of adoption throughout the basin such as applying 10% less fertilizer or reducing canal seepage by 40%; intermediate intervention was a mid-level of adoption; whereas aggressive intervention could only be achieved if there were intensive adoption of BMPs within the basin including as much as 30% reduction in irrigation. Model results indicate >10% decreases in Se mass loading to the Arkansas River can be achieved with individual BMPs, with 20-50% load reduction achieved with three or four BMPs implemented concurrently.

Table 2.1 Simulated Levels of Four BMPs and Five Combinations of BMPs in the Lower Arkansas River Valley over 38 Years

BMPs	Basic/limited	Intermediate	Aggressive
Reduced Fertilizer	10% reduction	20% reduction	30% reduction
Canal Sealing	40% reduction	60% reduction	80% reduction
Leasing Fallowing	5% more	15% more	25% more
Reduced Irrigation	10% reduction	20% reduction	30% reduction
Combination Scenarios	10% RF, 40% CS, 5% LF	20% RF, 60% CS, 15% LF	30% RF, 80% CS, 25% LF
Combination Scenarios	10% RF, 40% CS, 10% RI	20% RF, 60% CS, 20% RI	30% RF, 80% CS, 30% RI

2.3.2 Economic Costs

In economics, a first best policy is one that maximizes net economic benefits to society. In the present case, such a policy requires full knowledge of the benefits associated with pollution reduction in addition to the costs. Because many of the benefits associated with pollution reduction are not well known or easily monetized, often a more easily reached criterion is to reduce pollution, in consideration of regulatory standards, at the least cost (known as a second best policy) (Ribaudo et al., 1999). From a decision making standpoint, producers make decisions based on private accrual of costs and benefits. In this study, the economic analysis focuses solely on the private costs and benefits (reduced costs) associated with implementing BMPs in the LARV as implementation is entirely voluntary. Costs for this study are derived from a variety of sources as described below. A more detailed description of how costs were calculated is available upon request from the authors.

Halvorson et al. (2002) suggests excessive fertilizer is being used in the LARV, thus it is assumed there are no opportunity costs associated with reduced application; however, there are cost-savings associated with reduced application. For the reduced irrigation scenario, there are reduced costs for water application and the costs of the technology change, including depreciation, maintenance costs, assuming a 15 year life-span of the equipment. Budgets from the USDA Economic Research Service were used for crop and fertilizer prices; augmentation records from the Arkansas Groundwater Users Association were used for water costs; and extension budgets from Colorado Cooperative Extension were used for irrigation technology. The data for the canal sealing scenario came from a Desert Research Institute study (Susfalk et al., 2008) that analyzes field experiments of canal sealing the LARV, including costs. Data for a lease-fallowing scenario are very scarce due to the low number of successful pilot projects. Water price data are also difficult to find. Woodka (2013) indicates $500 per acre-foot is a reasonable price expectation for leasing to a municipality in Southeast Colorado in dry years. Opportunity costs associated with not farming in the leasing scenarios are included based on crop budgets referenced above. The crop rotation was based on typical cropping patterns of the LARV. For each of the water reducing scenarios, improved crop yields were calculated due to lower water table depths and thus less adverse effects from water logging and salinity.

Equation (2.1) is used to calculate the discounted net present cost (NPC) of each of the four BMPs, discounted at a rate (r) of 3.2% (Gollier 2010). Generally, the NPC for each BMP depends on the up-front fixed costs (FC) as well as the on-going costs of maintenance (MC_t), replacement costs (RC_t), opportunity costs (OC_t), and reduced costs (S_t) accumulating due to BMP implementation over time (t) all in US dollars. Examples of opportunity costs may be crop benefits foregone upon fallowing whereas reduced costs may include an increase in crop yield associated with less waterlogging and salinization and reduced costs of fertilizer. Costs are simulated for each BMP, i, over 38 years in order to be on the same time scale as the physical model.

$$NPC_i = FC + \sum_{t=1}^{38} \frac{1}{(1+r)^t} [MC_t + OC_t + RC_t - S_t] \tag{2.1}$$

2.3.3 Pareto Frontiers

Trade-off curves, typically referred to as Pareto frontiers, are used throughout economic and engineering literature to illustrate the tradeoff between economic costs and environmental improvement (Arabi et al., 2006; Kling, 2006). The Pareto frontier results from the transformation of a common input (money) into pollution reduction (itself a function of Se processes) and costs of management (a function of prices, **p**, and technology, k). Often, these outcomes are shown on a graph with costs on the vertical axis and pollution reduction on the horizontal axis (Figure 2.2), although the axes may be flipped. The hypothetical frontier represents the reasonable expectation that as pollution is reduced, costs increase exponentially, reflecting the fact that the cheapest units of abatement are accomplished first followed by increasingly expensive units of abatement due to constraints on pollution reduction imposed by nature or technological capabilities. The Pareto frontier represents the most efficient pollution reduction options. The area to the right of the curve is infeasible due to a lack of technology, whereas the area to the left of the curve is inefficient as the same level of abatement can be achieved with less cost when on the frontier.

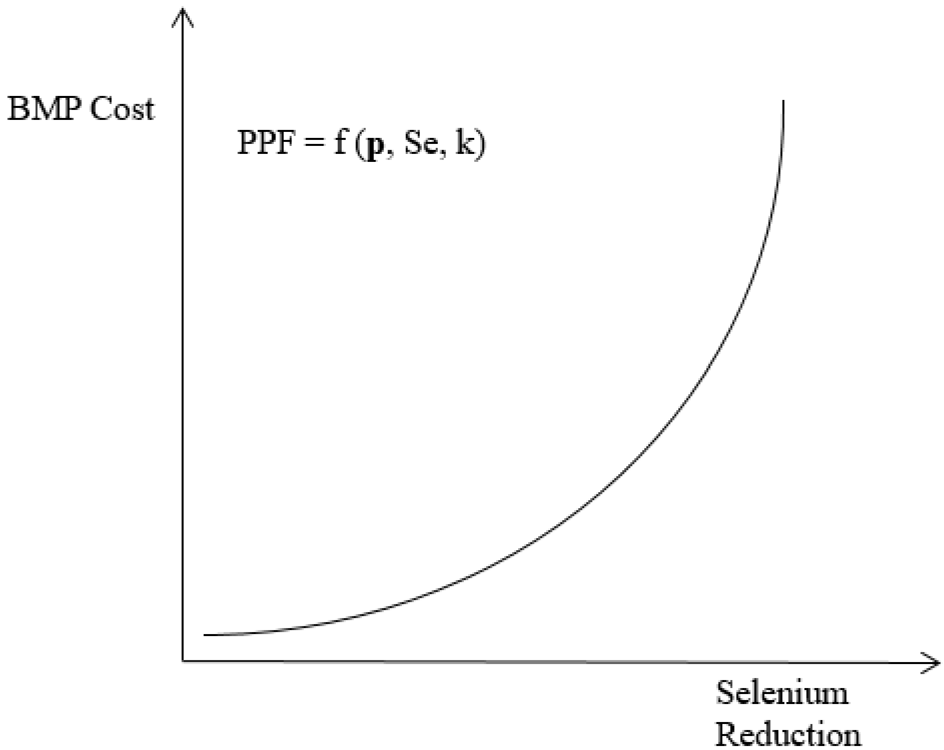

Figure 2.2 Typical Representation of an Enviro-Economic Trade-off Curve

In order to calculate the efficiency frontier, the net present cost of the alternatives were calculated for the basic, intermediate and aggressive modeling scenarios for each BMP (i) over 38 years (t) and divided by net present value of Se reduction (discounted at a rate of 1.5% as per Gollier 2010) at each level of BMP implementation (Equation 2.2). This frontier reflects the cost per unit of abatement at each level of Se reduction. Although these curves represent 3 discrete levels of implementation for each solution scenario, they are assumed to be continuous and convex between each implementation level reflecting the trade-off decision makers face in implementing BMPs.

$$Cost\ Frontier_{i,t} = \frac{\sum_{t=1}^{38} NPC_{i,t}}{\sum_{t=1}^{38} SE_{i,t}} \tag{2.2}$$

Trade-off curves as presented in Figure 2.2 can take on many forms. This typical scenario is reproduced in quadrant II of Figure 2.3. Other scenarios could involve different relationships between costs and pollution. For example, cost savings associated with BMP implementation could outweigh implementation costs, resulting in a net savings from a BMP (quadrants III and IV in Figure 2.3). Yadav and Wall (1998) find BMP implementation benefits exceed the cost to control NO_3 contamination, for example. Moreover, because the physical environment of many of the water-reducing BMPs is altered, it is also possible for pollution to increase due to a BMP, as the hydrologic environment is changed (quadrants I and III in Figure 2.3). Quadrant IV represents a case where reducing pollution makes money, and quadrant I a case where the BMP costs the producer money and makes the environment worse off.

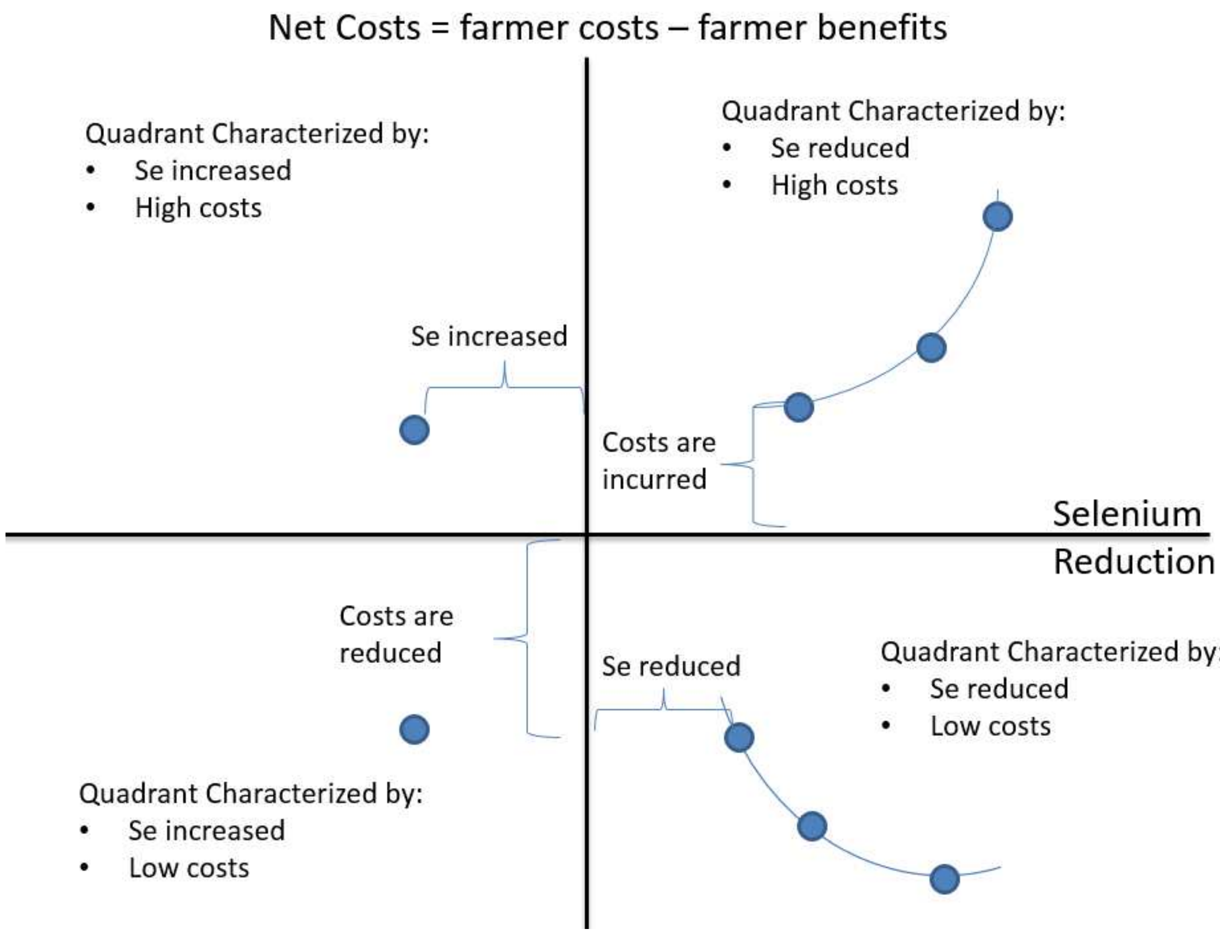

Figure 2.3 Theoretical Diagram of Farmer Net Costs and Selenium Trade-offs When Net Costs can be Negative and Pollution Could Increase in the System

2.3.4 Institutional Constraints

Tradeoff frontiers are a valuable tool, yet it is easy to misinterpret their meaning if institutional limitations are ignored. All technical options that can be measured and plotted in a curve may not be equally attainable. These limitations can make movement along a frontier "sticky", asymmetric, or practically impossible. That is, it may be feasible "on paper" to move from one point to another, but difficult or not possible in a real setting due to some institutional constraint. Therefore, we derive the "optimal" frontier without institutional considerations for our case study, then examine how institutional conditions influence the region's ability to mobilize from one scenario to another along the frontier.

In order to determine the impact of institutions, such as rules and social norms, we conducted in-person qualitative interviews of local LARV farmers. We asked these farmers about issues that might impact adoption of the identified management practices. These interviews took place in Rocky Ford, CO on May 29, 2014 and also in La Junta, CO at the Arkansas River Basin Water Forum on April 22-24, 2014. There were five questions used to begin our conversations with about 25 stakeholders (see Appendix 1 for more details on these questions). The structure of the interviews and questions were based on Luloff, et al. (2012, 14) with references to the LARV and the practices under consideration. The interviews served to identify the most important institutional challenges faced by farmers in the LARV, including but not limited to irrigation rules and other water policies that were important to practice implementation. Important policies identified include temporary supply agreements (HB-1248 and 37-92-309 C.R.S.), rules for irrigation improvement (State Engineer 2009) and the Arkansas River Compact with the state of Kansas.

2.4 Results

2.4.1 Model Results

Simulation models combined with economic data resulted in several different types of trade-off curves, like those shown in Figure 3, and some that actually saved farmers money when they implemented conservation measures. The trade-offs predicted with each of the BMPs under consideration are shown in Figure 2.4. All of the scenarios, with the exception of the lowest level canal sealing scenario, decrease Se mass loading to the river network as we would expect. The rationale for low-level canal sealing increasing Se mass loadings is not yet known for certain but is thought to be a result of the timing of the water applied. Combination scenarios offer the most effective Se and cost outcomes. Part of the rationale is that decreased fertilizer application in addition to decreased deep percolation of water will do a great deal in combination towards the reduction in Se. The cost results are driven by the cost savings associated with not having to pay for additional inputs such as water or fertilizer as well as increased yield impacts associated with a lower saline water table elevation.

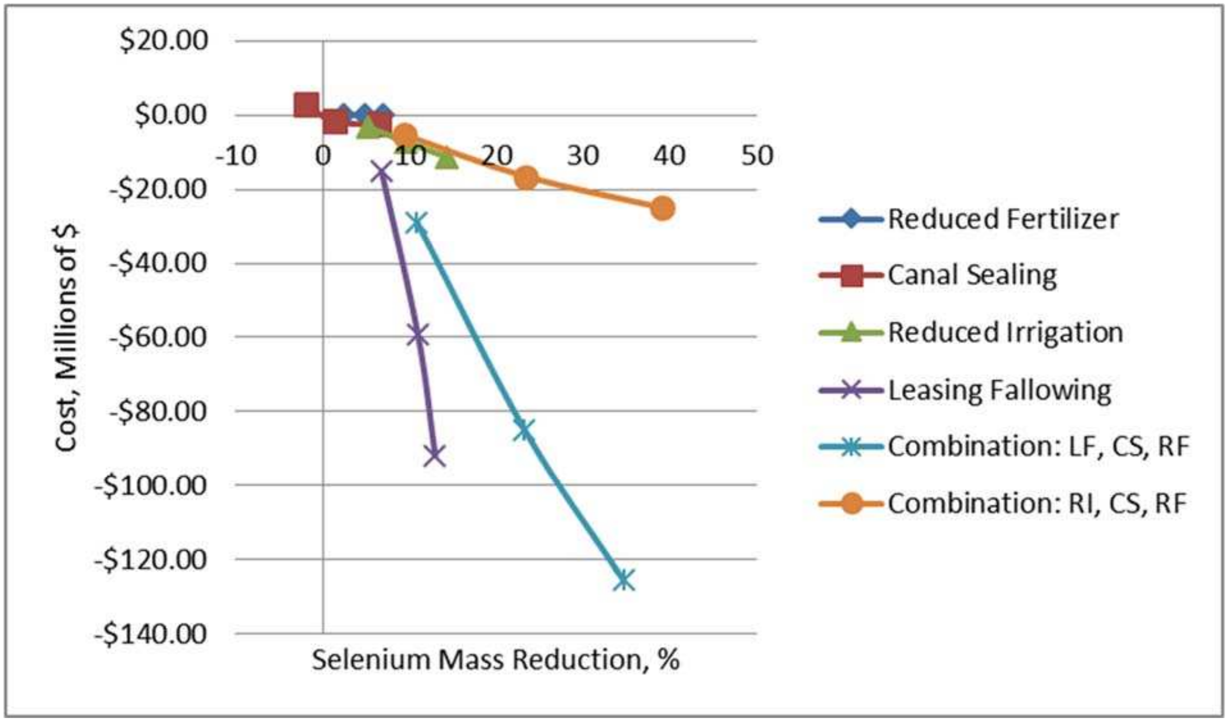

Figure 2.4: Basin-Wide Trade-off Between Cost and Percent Reduction in Se Mass Loadings for Three Levels of Intervention (Basic, Intermediate, Aggressive) for each Practice or Set of Practices

A closer look at the four individual BMP scenarios illustrates without looking at institutions, each of the BMPs, excluding canal sealing, result in greater cost savings to farmers upon implementation (quadrant IV in Figure 2.3). Figure 2.5 shows lease fallowing dominates the individual BMPs due to the high value that can be received from leasing water to a municipality. Decreasing the price of water leases serves to shift the Pareto frontier up; the Se outcomes would be the same regardless of price. The curve would lie along the zero axis if farmers were paid the same amount that they would have received from farming and Se reductions would be comparable to those achieved by reducing the irrigation application.

Reducing fertilizer is an inexpensive option but it is does not dominate in terms of pollution reduction. This frontier is enclosed within the other two curves implying that more Se could be reduced at a smaller cost with the water reducing BMPs.

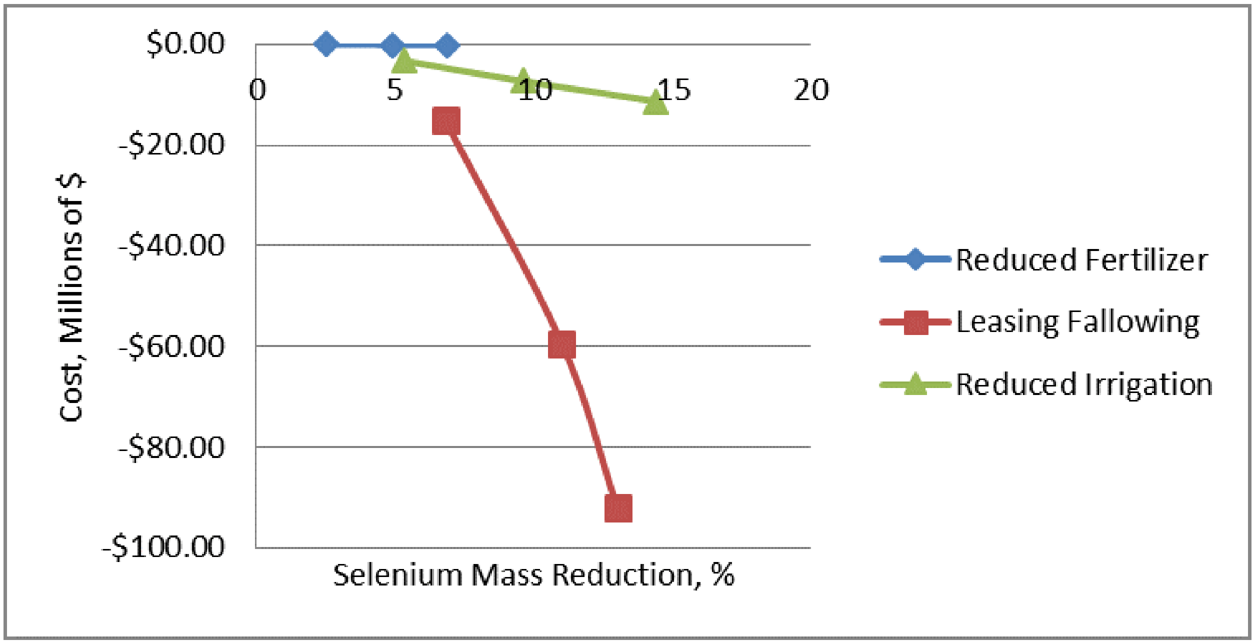

Figure 2.5: Basin-wide Trade-off Curves Between Cost and Percent Reduction in Se Mass Loadings for Three Levels of Intervention (Basic, Intermediate, and Aggressive) for Selected Individual Practices

2.4.2 Institutional Considerations

It would be good news if all of the scenarios did indeed lie in quadrant IV of figure 2.3 because that would mean it would simply be a matter of informing farmers about how they could improve their profits by adopting systems that also help reduce pollution. However, this ignores institutional constraints. Although farmers in the Arkansas Basin are quite resilient, there are a lot of institutional issues surrounding the availability and use of water. In general, farmers value the security in their water rights and their mode of operation and prefer to avoid any actions that may threaten that security (perceived or actual).

Semi-structured interviews quickly revealed farmers in the LARV feel widely constrained in terms of conservation options. Firstly, by law, if water is not put to a designated "beneficial" use, then that water could be re-allocated to another use under strict interpretation of the "Beneficial Use Doctrine" (Woskom, et al. 2016); therefore, it may not be in a farmer's best interest to reduce water use. Indeed, if farmers within an irrigation canal company use less water consistently, it technically could be considered abandonment of the canal's water right.

In interviews, farmers also cited rules about changes in irrigation methods and the Arkansas River Compact between Colorado and Kansas as reasons they would be hindered in implementing water reducing management practices such as canal sealing, reduced irrigation and (to a lesser extent) lease fallowing. In 1948, the Arkansas River Compact was implemented to settle disputes regarding return flows of the Arkansas River across the Kansas state border. The State Engineer in Colorado developed rules on irrigation improvement in 2011 in order to keep the basin in compliance after Colorado lost a lawsuit brought by Kansas in 1985. Rule 8 requires farmers to apply for a change in water right when changing their irrigation method. Rule 10 allows farmers to apply for a change in water right as a group in order to reduce transaction costs. However, some farmers in the basin see it as a way for the local conservancy district to take control of their water because farmers may only maintain consumptive use of their water. Many farmers we interviewed told us if farmers choose to change their irrigation methods and maintain the same amount of consumptive use for their water as before, they are required to pay an augmentation station for replacement water to compensate for estimated losses in return flows to the river. Therefore, the trade-off curves in quadrant IV are not reflective of reality because they do not account for the need to maintain return flows, which serves as a significant barrier to implementation.

One way to integrate these institutional constraints into the trade-off curves is to look at how the costs change under different levels of implementation due to institutions. Figure 2.6 illustrates how under low levels of irrigation reduction, within which farmers would not have to pay for augmentation, the costs are very low; this represents when a farmer changes from flood irrigation to surge irrigation for example, which is exempt from rule 8. However, when farmers reduce irrigation at greater levels to achieve even greater Se reduction, for example by adopting sprinkler irrigation, their costs increase significantly as they must pay for water augmentation. Therefore, Figure 2.6 demonstrates a portion of the Pareto frontier remains like it was in Figure 2.5, where abatement increases profits. However, a portion is also converted back to the relationship shown in quadrant II due to institutional constraints. Therefore, abatement reduces profits when institutional constraints are considered, potentially explaining slow adoption of sprinkler technology in the LARV.

The current most promising BMP from our technical analysis is lease fallowing. While the legal framework is in place for farmers to lease their water under temporary supply agreements, on the ground experiments have had mixed results. One recent attempt was shut down because some farmers within the Rocky Ford Highline canal did not believe it was a good idea. However, a pilot project in 2015 on the Catlin Canal has had some success with one farmer suggesting this new policy is a viable alternative to permanent buy-and-dry (The Lower Arkansas Valley Water Conservancy District and the Lower Arkansas Valley Super Ditch Company, 2015). Buy-and-dry, where farmers sell their water right to the cities, has left scars in the valley due to the negative environmental, economic and aesthetic impacts of dried-up farmland. Farmers who do not have water, do not have any reason to stay in the valley and as such, they have removed the water from the basin as well as all of the economic benefits of their operation and their presence in the community. Such concerns have made some farmers bitter about water leaving agriculture even on a temporary basis. Also, there may be constraints on how much water could be leased in a given year. For example, a city might not have much demand for additional water in a wet year. On the other hand, in years when there is a great deal of demand, there might not be as much water to lease. This again would make it such that the trade-off curves are not continuous, as there is a physical constraint on the amount of water that can be leased within the basin causing the level of BMPs achievable to be "kinked" at the available water level. The state of Colorado passed a new law in May 2016 that would make it easier for farmers to lease up to 50% of their water in a single year, but the consequences of that program are unknown as implementation details have yet to be decided (House Bill 16-1228).

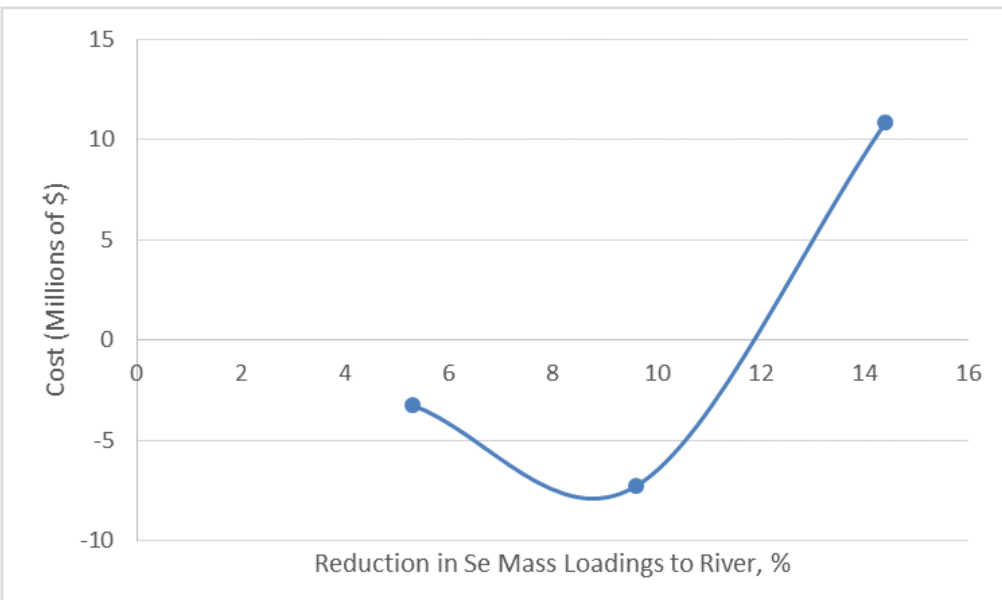

Figure 2.6: Cost of the Reduced Irrigation Practice when Augmenting at Various Levels of Implementation

Finally, farmers indicate they are already reducing fertilizer applications due to the high costs of fertilizer. Part of the rationale for over-applying fertilizer is the type of irrigation they are using; flood irrigation results in greater nutrient run-off. Until farmers change their irrigation technology, applying less fertilizer is not likely to make much of a difference. As such, the trade-off curve is not continuous or convex for the portion associated with this technology (not shown); the environmental response to greater implementation might be flat until they change their irrigation technology.

2.4.3 Behavioral Considerations

The current focus of this research is on institutional factors that can hinder a farmer's ability to move fluidly along a Pareto Frontier to adopt those practices beneficial to them and society. It would border on absurd to assume farmers are totally unaware of technologies that could be beneficial to them, as implied by our findings that available technologies lie in quadrant IV. So, while discovery through research, followed by education, is part of the solution, there is extensive literature on behavior considerations in adoption that also could explain why producers are not adopting technologies that are implied possible by the frontiers. Hoag et al. (2012), for example, found in a study of thirteen water quality programs that farmers were influenced by more than just profit with notable influences coming from support relationships, trust concerns and lack of control, and ownership of the projects by the farmers themselves. A recent article by Ribaudo (2015) on voluntary implementation of conservation finds there are two types of farmers who make a voluntary decision to implement practices: conservationists and productivists. These two types of producers are differently motivated by the social characteristics suggested by Hoag et al. (2012) and others. Ribaudo (2015) suggests policy design take into account the social and biophysical factors that contribute to water quality as well as program performance.

2.5 Conclusions and Discussion

Selenium reduction is achievable in the LARV through management practices that reduce deep percolation of nutrient-rich water. Without accounting for institutions, each of the practices considered in this study are cost-effective, with combination scenarios dominating outcomes. In defiance of common sense, it appears farmers are not adopting practices that would improve their incomes, and produce environmental benefits at no cost to them. Nevertheless, consideration of institutional factors reveals the practices studied might not be implementable at all levels in the LARV under current constraints. While our cost estimates show each of the practices to be achievable, many of the farmers cite western water institutions as large hurdles to reducing water application through reduced irrigation and canal sealing scenarios. Many farmers admit lower levels of these BMPs might be achieved (such as using poly-acrylamide on fields or updating irrigation technology to surge valves); yet, higher levels of implementation involve much greater "unseen" costs such as having to have changes approved in water court. Institutions serve to "kink" the trade-off curve associated with practices making cost-effective practices much more costly and sometimes impossible at higher levels of implementation.

The economic and environmental tradeoffs represented in trade-off curves also are influenced by interactions between different best management alternatives. For example, application of fertilizer is highly related to the type of irrigation technology utilized. Without changing from current flood irrigation practices to a more efficient irrigation scenario, reduction of fertilizer is not as feasible an option because much of the applied fertilizer runs-off the field with the flood waters. The most pollution reduction would be achieved if less water and less fertilizer were applied; yet, farmers in the LARV are not implementing these practices.

Reduction of fertilizer does not conflict with existing water institutions, but it does conflict with existing farming practices.

Lease-fallowing seems like a good solution to the problem of Se and water shortage issues within the state. It is a compromise scenario where the water-gap can be filled without permanently removing water from agriculture; however, there remain barriers to implementation in spite of some success in the recent pilot program. Moreover, with limited access to water markets, settling on the market price for water has resulted in rumors about prices well-beyond the value of farming. One farmer we interviewed put this issue into perspective: “I don’t want to sell my water, but I don’t want to lose the right to do so if I choose.” There is resistance to water leaving the river basin, likely never to return again. Moreover, there might be a physical constraint associated with higher levels of leasing; under reasonable assumptions and the existing lease-fallowing frameworks, there is not enough water available to lease in years when it would be most demanded by municipalities. Nevertheless, a recent law passed in Colorado that makes leasing easier to undertake could change how farmers and others view leasing in the near future.

Due to this research, a stakeholder advisory committee has been created in the LARV to advise this research group regarding the direction of future research on management solutions for water quality and water quantity issues (Arkansas River Management Action Committee, http://www.coloradoarmac.org/). Future modeling efforts will focus on the uncertainties introduced by existing water institutions as well as uncertainties in the economic and physical outcomes, including changes in stream Se concentration brought about by reduced Se mass loading. Policy regimes that can reduce the uncertainties associated with western water institutions and nonpoint source pollution will continue to be explored to solve the problems of Se and other pollutants into western water systems. New technologies are constantly emerging.

A promising way to relax institutional constraints on the augmentation of flows, brought about by water-reducing BMPs in the Arkansas River, was initially proposed by Triana et al (2010b). Storage and release of water from on-stream reservoirs would allow collective augmentation of altered return flows. This and many other approaches are currently being explored in more detail and may result in an advancement in the ranking of some of the considered BMPs.

Finally, this research shows institutional constraints are important but we have barely scratched the surface about the depth and breadth of constraints that LARV farmers and other stakeholders face on a daily basis. A more thorough accounting and understanding about these constraints would likely produce even more understanding about why farmers behave as they do and what it would take to change those dynamics.

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3. CHAPTER 3: UNCERTAINTY AND TECHNOLOGY ADOPTION WITH IMPERFECT PROPERTY RIGHTS: LESSONS FROM THE ARKANSAS RIVER VALLEY

3.1 Introduction and Context

Water resources in the arid west and other parts of the world are becomingly increasingly scarce as population growth and water quality impairment put new demands on this limited resource. With those increasing demands comes an urgency to conserve water and to consume the resource more efficiently throughout the myriad of uses. Much of the conservation pressure comes down to agriculture, as this sector is allocated as much as 80% of the water available in states like Colorado where water is often over-appropriated (Schaible and Aillery 2003). There are pushes for the agricultural sector to use water more efficiently, yet farmers point to the property right structure in place as an adherent to more efficient irrigation adoption (Sharp et al. 2016) while scholars contend that more efficient use of the water does not necessarily meet conservation goals and can complicate water allocation for downstream users (Anderson 2013). This setting is further complicated by the stochasticity of water flows in a given year and by the nature of conservation irrigation adoption which is inherently an irreversible decision due, in part, to the property rights structure and water allocation paradigms present in an agricultural production system.

This paper applies a net present value/option value framework to explore optimal investment thresholds for conservation technology under uncertain water flows and irreversible conservation investment. It extends previous option value irrigation investment studies (Carey and Zilberman 2002; Bhaduri and Manna 2014) by incorporating beliefs about the application of western water right structures into the private investment decision making for an irrigator. An empirical application summarizes adoption behavior under the actual application of property rights institutions in the Arkansas River Basin in southeast Colorado. This research fills a gap in literature by defining the importance of secure property rights on conservation behavior and highlights how application of property rights can impact water security for current and downstream users.

3.2 Background and Literature Review

3.2.1 Property Rights Overview

Water scholars debate whether water should be treated as any other economic good. Efficient allocations of private goods can be achieved in a marketplace. However, water is unique in numerous ways such that property rights for water can be tricky to establish. Water is neither a purely private good nor a purely public good, which makes it subject to market failure; moreover, it is highly mobile and reused multiple times, making property right assignments difficult (Hanemann 2005). Prior appropriation, sometimes known as “The Colorado Doctrine”, was the property rights system adopted in 1876 as an institution that could take into account prior use of a finite, mobile water supply and protect those who had first diverted the water to a productive economic use (Gallaher et al. 2013). While this system may have been appropriate during settlement of the arid west, Gallaher (2013) warns that “strict adherence to a water rights doctrine that was established in the 19th century can limit the types of policy tools that are within the feasible set of options available to policy makers in the 21st century” (Gallaher et al. 2013).

Colorado’s rapidly growing population has pushed leaders in the state to begin to discuss methods of meeting a pending water “gap,” or supply deficit, caused by a projected doubling of the population by 2050. While new supply initiatives are included in these discussions, policy makers are looking to water conservation efforts to meet much of the state’s projected water needs (CWCB 2011). Often, conservation in agriculture focuses on using water more efficiently both through the adoption of more efficient irrigation systems and through better water management practices. Both of these approaches allow for more of the water applied to be consumptively used rather than returned through surface water runoff or groundwater return flows. Increased consumptive use in irrigation implies that less water could be diverted for agricultural uses while maintaining the same value of the crop. The saved water could be diverted to other water demands which may have a higher value in use comparatively. In the western states[2], 51.5 percent of water applied in irrigated agriculture was by conservation irrigation technology (defined as sprinkler or drip) by the start of this millennia (Schaible and Aillery 2003). Yet, the Arkansas River Basin lags behind this average significantly, with furrow irrigation constituting almost 80% of total irrigated acreage, even after recent gains in the use of sprinkler irrigation (Figure 3.1).

The decision making for conservation irrigation technology is motivated primarily by private benefits of each of the farmers. Increased consumptive use of the water implies that the farmer should be able to use less water in order to garner the same economic benefit from irrigating. Colorado policy defines a water right as the "actual historical, beneficial consumptive use" which implies the amount of water evapotranspired by the crops over a period of time (Waskom et al. 2016). By strict definition of the water right, changes in irrigation technology that increase consumptive use should necessarily decrease the total amount of water diverted by the farmer as less water is required to meet historical consumptive use. There are a few economic implications of this policy: 1) a

[2] This refers to the western states as defined by the United States Department of Agriculture which includes: Texas, Oklahoma, Kansas, Nebraska, South Dakota, North Dakota, Montana, Wyoming, Colorado, New Mexico, Arizona, Utah, Idaho, Nevada, California, Oregon and Washington.

farmer should not be able to use their "saved" water to increase production by increasing acreage 2) the economic benefits of adoption must be realized in terms of decreased costs of inputs into the production process (this could be through lower labor, management or energy costs associated with irrigating) and 3) downstream users should not be impacted by an upstream irrigators investment decision.

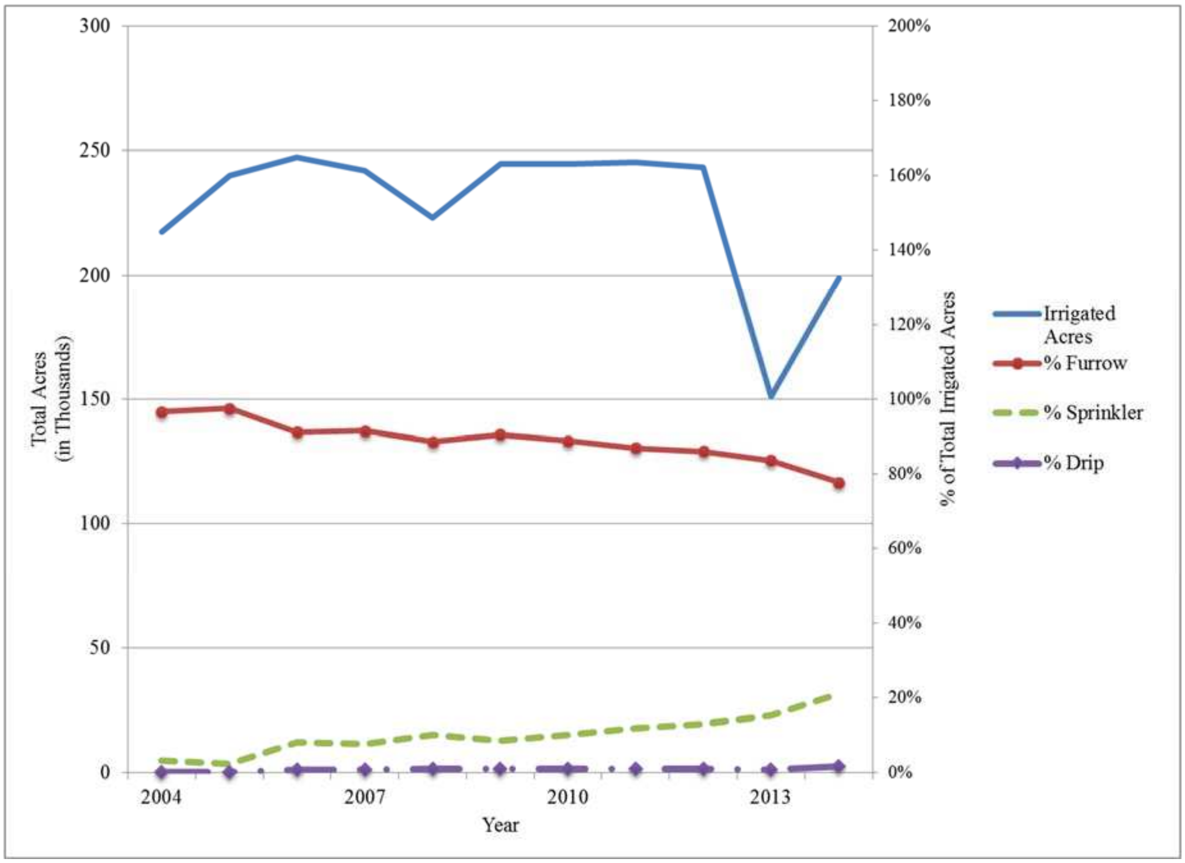

Figure 3.1: Lower Arkansas River Valley Irrigated Acres by Technology (2004-2014). Source: Colorado Division of Water Resources, based on the Hydrologic Institution Model (the H-I Model is used to maintain the Kansas-Colorado Arkansas River Compact).

Applications of this property rights system though have not necessarily been consistent compounding confusion, uncertainty, and conflict over water rights (this is explored in more depth through the empirical section. Justice Gregory Hobbs of the Colorado Supreme Court from 1996 to 2015 wrote in an article on western water adjudications "due to natural western water scarcity, we are no longer developing a resource. Instead, we are learning how to share a developed resource" (Hobbs 2006, 5). Decisions on water court cases set precedent for future decisions on water appropriation. According to Justice Hobbs, , there are twelve fundamental principles of western state water law; for irrigation investment decisions, the most important among these twelve include:

1. Water right transfers are of consumptive utilization.
2. Return flows belong to down-stream prior appropriators.
3. Senior rights are allocated first unless one can prove that their water supply is mainly made up of water not subject to the appropriation rules of a basin.

The first two principles should not change, *ceteris paribus*, the expected benefits of production accrued to the farmer as farmers should still be able to maintain historical consumptive use and thus the economic benefits associated with that production. However, they cannot gain *privately* the benefits associated with this increased efficiency as they are not able, under strict interpretation of the policy, to increase production in any way. Instead, the water savings can presumably be appropriated to a new and different beneficial use. Similarly, downstream users should also not be influenced by the conservation adoption decisions of the upstream irrigator. That being said, if the farmer were able to maintain their initial water allocation without penalty upon conservation adoption, then they could gain greater economic benefit but at the direct expense of a downstream user who may not receive the expected return flows (as more water is used consumptively by the upstream user).

In order to ensure that the economic incentives are as intended by the policy, the Arkansas River Basin in Southeastern Colorado has created some rules to protect users (both upstream irrigators and downstream irrigators in Kansas). The office of the state engineer utilizes water models to simulate expected surface and groundwater flows under a changed irrigation scenario in order to determine if return flows are changed by the change and technology (Wolfe 2009). The state engineer is then charged with maintaining the same flow as indicated in the compact by reducing water allocation to the farmer or requiring the farmer to augment their supplies with water not subject to the system of prior appropriation. Rule 8 requires an application for a change in water right that details any improvements in irrigation systems and impacts on flows (2 CCR 402-8). The rule also allows for the optional submission of information pertinent to leaching and consumptive use. Recognizing the high cost of acquiring such information, Rule 10 adds a provision for multiple growers to act as a single party in filing an application to improve an irrigation system (2 CCR 402-10). Rule 10 provides relief in the costs of determining the impact of irrigation changes on return flows and administrative burden. These rules requires a legal change of water right including a detailed plan for alternative supplies (augmentation) for water if acreage is expanded or water application does not increase. The state engineer advises, via irrigation improvement rules, that all applications that would result in a violation of water right policies will be denied (Wolfe 2009). If this process is technically accurate, then again the economic incentives to adopt are only realized through savings in inputs; however, if there is even a small amount of generosity in the models regarding maintenance of water supplies, this provides an arbitrage opportunity for producers to actually gain privately from more efficient use as they capture the newly available water over other users (both urban and downstream). This complicated rules structure—the new water right and the new process—is inherently an irreversible process. Once one has gone through the process of converting and realizing their new water right, it is very difficult to undo the process and be sure that their original water supply is maintained.

Additionally, water is an inherently complicated resource due to the stochasticity of water flows from year to year. If snow pack in the Rocky Mountains is low in a given year, then junior water right holders are especially vulnerable to supply uncertainty as their allocations are distributed after more senior uses according to the third principle above. These issues in property rights for water precipitate a framework of investment decision that takes into account a producers belief about how water allocation would change upon conservation investment adoption, the stochastic nature of water and the idea that investment under this property rights structure is inherently irreversible.

3.2.2 Option Value Literature Review

Often when looking at investment, it is important to determine if a decision has a positive net present value (NPV), indicating that the net benefits over the life of the project exceed the net benefits of the next best alternative. If the NPV is negative, then we should not observe investment as investors are worse off and therefore would not undertake the project. However, there are occurrences where the NPV appears to be positive and yet we do not observe investment. Indeed, adoption of conservation technology is often profit-neutral or profitable for the farmer according to traditional NPV analysis (Knowler and Bradshaw 2007). Yet, adoption of conservation technology still lags behind expectations (Ribaudo 2015). One explanation emerging from this puzzle is a concept known as option value that suggests that when investment decisions are irreversible and can be delayed, traditional NPV analysis inaccurately predicts adoption as decision makers hold on the option to wait and see how economic variables change in the future (Dixit and Pindyck 1994).

The option value method has been applied to various problems of environmental conservation, particularly for forecasting purposes to predict *ex ante* how agents might respond to a new policy. Purvis et al (1995) look at how uncertainty regarding the design of environmental policies can impact investment decisions for dairy producers. They use simulation for their empirical analysis and find that uncertainty about policies that change overtime will decrease experimentation and postpone investments (Purvis et al. 1995). Similarly, Carey and Zilberman (2002) explore how creation of water markets might impact investments in modern irrigation technology. Their key finding is that creation of water markets will result in farmers avoiding investment until the expected present value exceeds the investment cost by a large hurdle rate due to the new opportunity cost of their water resources created by the water market (Carey and Zilberman 2002). Seo, et al. (2008) find the problem of irrigation technology adoption (and entry and exit of irrigated agriculture) to be influenced by stochastic crop output price. They empirically determine the switching points that trigger entry into irrigated agriculture (sprinkler system adoption) and exit (dryland agriculture). Additionally, they find that policies that encourage new irrigation systems do not actually result in water savings because of the low exit threshold—farmers continue to farm extensively after sprinkler adoption even if it is not profitable (Seo et al. 2008). Another article looks at supply uncertainty and storage to find that when farmers have an option to store water on site, they are more likely to invest in more efficient irrigation technology (Bhaduri and Manna 2014).

3.3 Contribution to Literature

In the case of irrigation investment under western water institutions, undergoing a change in irrigation system is virtually irreversible. This is primarily because the total water right available to the farmer is reduced in order to account for greater consumptive use of the water.

Farmers are faced with either a reduced water right in future time periods or an additional cost for augmentation water, which is not permanent and directly restricts profits. While literature has discussed the inefficiencies associated with these western water regimes, there has been a lack of research quantifying these inefficiencies. This research extends the property right literature by quantifying a delay in investment caused by property rights enforcement. More specifically, this study quantifies the option value associated with waiting to adopt water-saving irrigation technology under a use-based property rights regime. No other study looks at the impacts of property rights on adoption under an option value framework. The two closest study that this study emulates is a study of irreversible irrigation investment in California with the presence of water market by Carey and Zilberman (2002). This study differs from Carey and Zilberman (2002) in that water is the stochastic component instead of prices and property rights are integrated into the economic framework. Additionally, this study identifies, using a small conservation irrigation adoption dataset, how these property rights rules are actually being implied and the consequences of implementation on investors and other water users.

3.4 Methods

This section develops a model of decision making for farmers choosing to invest in a conservation irrigation system under use-based property rights for their primary input, water, which has a stochastic supply over time, influencing profit flows via uncertain crop yields and costs associated with irrigating. To begin, the threshold level of water at which a farmer would invest under a NPV rule is derived. The property rights regime can be applied to this framework to show, in a simpler framework, the intuitive relationship between application of western water institutions and the investment decision. Because the simpler NPV framework may predict investment where investment does not occur, the value of the option to invest is derived in order to obtain the critical level of water availability at which a farmer would adopt conservation irrigation over conventional irrigation given uncertainty and irreversibility. The belief about property rights is also incorporated into this framework to explore the interaction between the option value and the technical application of property rights. After the intuition and functional relationships of the irrigation investment decision are derived, a simulation for a representative farm in the Arkansas River Basin will serve to illustrate how parameterization of the stochastic component and integration of property rights can impact investment decision making for one water constrained river basin. Finally, an actual conservation investment data set is explored to illustrate how the water rights policies are actually being applied and the implications for water conservation efforts.

3.4.1 Model Development

While adoption of water conservation technology is on the forefront of policy makers' minds, farmers are more motivated by private returns to investment, both in the short and long term. The agricultural producer decision to adopt technology depends greatly on how it impacts profits within a given growing season, considering also the impacts of this investment on longer-term profitability. The decision making environment is often complicated by uncertainty, both in terms of the weather as well as the allocation/availability of scarce, yet necessary, water resources. It is under this framework that we develop a decision making model for farmers that captures the motivations of farmers as well as the institutional environment under which they operate.

To begin, the model assumes that a farmer may irrigate a given crop with either a conventional irrigation technology ($i = 0$) or a conservation technology ($i = 1$). Both technologies are represented with a Von Leibig production function such that water applied in any given time period (w_t) increases output ($y_{i,t}$) linearly until a maximum level of production ($\bar{y}$) (following Carey and Zilberman, 2002). The slope of the production function (b_i) under conservation irrigation is steeper than under conventional irrigation, achieving maximum production with less water application ($b_1 > b_0$). w_t is all water applied, including consumptive and non-consumptive use whereas b_i is the portion of water consumptively used by the plant for crop yield. The general production function is shown in equation 3.1, with figure 3.2 as a graphical display of the two production functions. w^* is the amount of water that, when multiplied by the slope coefficients, b_i, yields maximal production, $\bar{y}$. Figure 3.2 shows that less water applied is required to meet maximal yield in a given time period (t) under conservation technology compared to conventional technology. The difference in the two slopes can be interpreted as efficiency gains. In other words, conservation technology uses water more efficiently compared to conventional technology leading to greater yield per unit of water applied.

$$y_{i,t} = \min(\bar{y}, b_i * w_t) \tag{3.1}$$

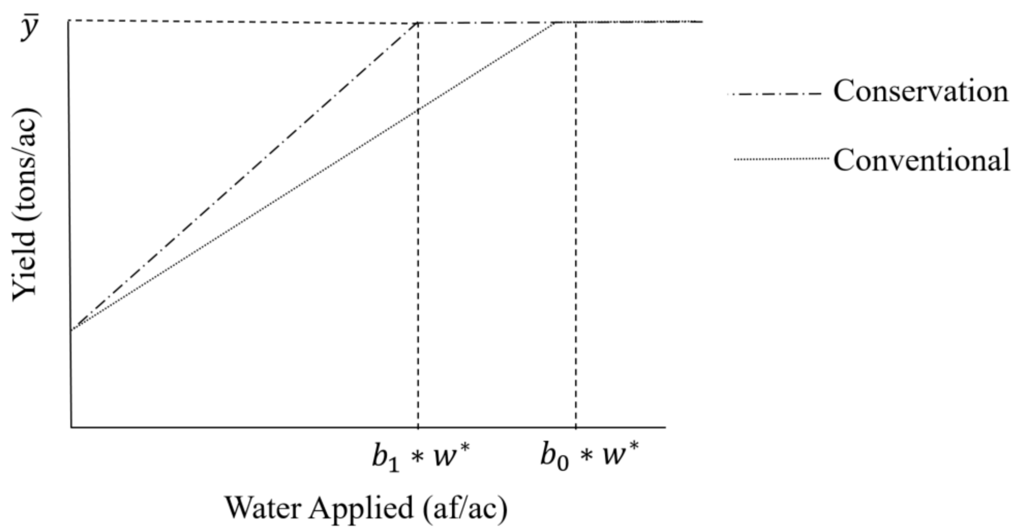

Figure 3.2: Von-Leibig Production Function under Conventional and Conservation Irrigation

It is assumed that water is limiting production, (water available does not exceed w^*) meaning the production function (equation 3.1) may be simplified to $b_i * w_t$. Moreover, it is assumed that all water available, W_t, is applied to the crop such that water applied equals water available in any given year, or $w_t = W_t$. Irrigation costs depend on the technology used. These costs include the variable cost of water application (c_i) such as the cost of labor and energy, as well as fixed costs (f_i) such as the cost of infrastructure and management. It is generally assumed that these costs are quite different for each technology and thus would be important to consider within the investment decision. Other costs related to production, such as seed, fertilizer and other inputs not related to irrigating, are assumed to not differ between the production processes and thus would not matter in the investment decision. Current value profits associated with each irrigation system $(\pi_{i,t})$ within a given time period t under a constrained water supply equal revenue less the cost of irrigating (equation 3.2) where p is the constant, exogenous price received for the irrigated crop.

$$\pi_{i,t} = (p * b_i - c_i) * W_t - f_i \tag{3.2}$$

To incorporate the property rights institutions, conservation technology profits are scaled such that if the conservation technology is adopted, the water available to the firm is a fixed proportion ($\gamma \in [0,1]$) of their previous water availability. This parameter, γ, is assumed to be a function of the change in efficiency between the conventional irrigation and the conservation technology such that $\gamma = b_0/b_1$ and is assumed to be between zero and one. Were this value greater than one, this implies that adoption of a conservation technology actually results in less efficient use of one's water. In reality, there is a great deal of slippage in this parameter which we revisit in the empirical section. We will model the empirical estimate of γ as $\hat{\gamma}$. Let π_t represent the net difference in current value variable profit in year t, incorporating this property rights regime (equation 3.3).

$$\pi_t = (\gamma\pi_1 - \pi_0)W_t \tag{3.3}$$

Water available for irrigating (W_t) is the source of uncertainty in this model. Water availability is assumed to be stochastic and follows a Geometric Brownian Motion (GBM) stochastic process, as seen in equation (equation 3.4).

$$dW_t = \alpha_w W_t dt + \sigma_w W_t dz \ (dz \sim n(0,1)) \tag{3.4}$$

The GBM is appropriate here as water is projected to follow a non-zero trend over time due to climate change and results can be easily compared to those in Carey and Zilberman (2002) and Seo et, al (2008). Additionally, it is a convenient functional form as it yields a solution whereas other stochastic processes can only approximate the water level at which one would switch. This functional form assumes that a change in water within a small time period (dW_t) is determined by a drift parameter (α_w) and a volatility parameter (σ_w), with dt as the time increment and dz as the increment of the Weiner stochastic process (Dixit and Pindyck 1994). The drift rate, α_w, is the proportional change in the expected quantity of water available each year and it's absolute value is expected to be between zero and one. A value over one would imply that water is expected to change more than 100% from year to year. A negative value for α_w implies a decreasing trend in the stochastic variable whereas a positive value for α_w implies an increasing trend in the stochastic variable. A decreasing water supply may make investment in conservation technology more lucrative whereas an increasing water supply would not precipitate the need for a production system that uses the increasing resource more efficiently. Under climate change projections and increasing urban pressures for water, water levels in agriculture in Southern Colorado are expected to decrease over time implying a negative percent change is appropriate for the α_w parameter (Colorado Water Conservation Board 2010). The last term of the GBM ($\sigma_w W_t dz$) represents the variability of water supply and has an expected value of zero; dz is distributed normal with mean 0 and a variance of 1.

Given that W_t is stochastic, so too is the flow of variable profits in a given time period. Ito's Lemma can be applied in order to show that π_t also follows a GBM stochastic process. Ito's Lemma states that if $F(x,t)$ is a function of the stochastic state variable, x and time, t, then $dF = \frac{\partial F}{\partial t}dt + \frac{\partial F}{\partial x}dx + \frac{1}{2}\frac{\partial^2 F}{\partial x^2}(dx)^2$. Substituting the stochastic process (equation 3.4) into (equation 3.3) and taking the differential gives the equation of motion (equation 3.5) for the current value flow of net profits.

$$d\pi_t = 0 + (\gamma\pi_1 - \pi_0)dW_t + 0$$

$$d\pi_t = (\gamma\pi_1 - \pi_0)(\alpha_w W_t dt + \sigma_w W_t dz)$$

$$d\pi_t = \alpha_w(\gamma\pi_1 - \pi_0)W_t dt + \sigma_w(\gamma\pi_1 - \pi_0)W_t dz$$

$$d\pi_t = \alpha_w \pi_t dt + \sigma_w \pi_t dz \qquad (3.5)$$

3.4.2 The Net Present Value of Investment

Over an infinite time horizon, the net present value of investment follows equation 3.5 where $f = f_1 - f_0$.

$$V_T \equiv E\left[\int_{\mathrm{t}}^{\infty} \pi_t e^{-\rho(s-t)} ds - \int_{t}^{\infty} f e^{-r(s-t)} ds\right] \tag{3.6}$$

Given the stochastic nature of water, the farmer discounts the current value economic flows related to water, π_t, with a risk adjusted rate of return (ρ), while economic flows not dependent on stochastic water, f, are discounted with the risk-free rate of return (r). It is assumed that the rate of return required for a risky venture (ρ) exceeds the risk-free rate of return (r) as an investor would expect greater returns in a risky venture compared to a safe venture. Nevertheless, it is not required that the two discount rates differ in order for a solution to arise. Since the stochastic current value of investing π_t follows a GBM process with a mean value of $\alpha_w \pi_t$ and a variance of $\sigma_w^2 \pi_t$, absolute changes in the stochastic variable (π_t) are lognormally distributed for this stochastic process (for more details on the characteristics of the GBM, see Dixit and Pindyck 1993, 70-74). As such, the expectation can be expressed as equation 3.6 (as per Dixit and Pindyck, p. 72). Given an upfront investment cost at the time of the investment, I_T, under a traditional net present value approach, one should undertake an investment if the expected net present value of the project is at least as large as the costs of investment (equation 3.6). Because π_T is stochastic, it is not possible to solve for the time period in which an investment would be made but it is possible to re-arrange (equation 3.6) as the water level (W^{NPV}) at which investment would be made in time T (equation 3.7).

$$E(V_T) = \frac{\pi_T}{\rho - \alpha} - \frac{f}{r} \geq I_T \tag{3.6}$$

Setting (6) equal to zero and moving the terms not multiplied to W^{NPV} to the right hand side, results in: $\frac{(\gamma\pi_1-\pi_0)W^{NPV}}{\rho-\alpha} = \frac{f}{r} + I_T$. Isolating W^{NPV}on the left hand side and substituting $\delta = \rho - \alpha$ results in $W^{NPV} = \left(\frac{\delta}{\gamma\pi_1-\pi_0}\right) * \left(\frac{f}{r} + I_T\right)$ which is then simplified to (7).

$$W^{NPV} = \left[\frac{f/r+I_T}{(\gamma\pi_1-\pi_0)/\delta}\right] \text{ where } \delta = \rho - \alpha \quad (3.7)$$

Given this investment rule, a few comparative statistics are of note. Firstly, the derivative of the project with respect to costs reveal that as long as the net marginal profit is positive, then increasing costs (both fixed and lump sum investment) increase the threshold. These two comparative statics are given by equation 3.8 and equation 3.9 respectively. This implies that as costs of investment increase, both in terms of fixed costs and in terms of upfront investment cost, it will serve to delay investment. Implicit in this result is that if these costs were subsidized through cost-share or other programs, it should serve to increase the likelihood of investment, even at low water allocations. If the net marginal profits were not greater for conservation technology compared to conventional ($\gamma\pi_1 \leq \pi_0$) then there would be no water level at which it an investment would be made. Additionally, the comparative static for the property rights institution parameter, γ, is given by equation 3.10.

$$\frac{\partial W^{NPV}}{\partial f} = \frac{\delta}{r(\gamma\pi_1-\pi_0)} > 0 \; if \; \gamma\pi_1 > \pi_0 \quad (3.8)$$

$$\frac{\partial W^{NPV}}{\partial \, I_T} = \frac{\delta}{\gamma\pi_1-\pi_0} > 0 \; if \; \gamma\pi_1 > \pi_0 \quad (3.9)$$

$$\frac{\partial W^{NPV}}{\partial \gamma} = -\frac{\delta r \pi_1(f+rI_T)}{[r(\gamma\pi_1-\pi_0)]^2} < 0 \; if \; \pi_1 > 0 \quad (3.10)$$

The partial derivative of the NPV rule (equation 3.7) with respect γ is negative as the numerator is always negative so long as sprinkler profits are positive and the denominator is always positive. This implies that as a farmer's water is restricted, the investment threshold of pre-adoption water supply must increase in order to compensate for this loss of property right. Recall that within the net marginal profit terms, $\pi_{i,t}$, yields are higher for conservation technology as the slope is steeper due to efficiency gains; however, marginal costs, c_i, also enter this term and are expected to be lower for conventional irrigation compared to conservation (as no pumping is required). It is reasonable to assume since prices for output are higher than marginal costs however, that without the presence of gamma, profits for conservation technology exceed those of conventional irrigation. Gamma serves to diminish the profits from adoption as it makes conservation technology less lucrative; lower levels of gamma necessarily imply a stiffer penalty and thus farmers would need even more water in order to overcome this detriment.

3.4.3 The Option Value

The NPV rule has been found to be an insufficient indicator of investment under uncertainty and irreversibility of the investment. More specifically, the farmer has an ability to wait to invest until more information arrives and therefore the profitability can be even greater than break-even; this "holding premium" is known as the option value and constitutes the point at which a farmer would undertake an irreversible investment considering the value of the investment opportunity as well as the value of the option to wait. This option value approach is based on the idea that when firms make an irreversible investment decision they give up the "option" to wait to invest until a future time period when more information arrives—in other words, investment comes at an opportunity cost which can significantly impact the expected net benefits and the timing of investment.

Dixit and Pindyck (1993) have created a framework that utilizes dynamic programming in order to determine when a firm might invest when that investment is both irreversible and faces a situation of uncertainty over profit flows. Under the option value framework, the optimal investment, a discrete yes (1) or no (0) decision, is one that maximizes the discounted net present value of the difference between the value of the conservation technology investment, V_T, and the irreversible investment cost, I_T (equation 3.11). The option is discounted by the risky rate of return, ρ, implying that this investment requires a greater rate of return than for a non-risky venture. To do this optimization problem, it is important to note that V_t is a function of π_t and thus is itself stochastic. In fact, V_t moves according to equation 3.12. Substituting V_T into the optimization problem (equation 3.11) results in equation 3.13. Let $K = \frac{f}{r} + I_T$. Now, substituting v_T (recall this is interpreted as the net flow of profits at the point T when the investment is made) and K into equation 3.13, results in the final optimization problem representing the value of option the option to invest, $F(V)$ (equation 3.14). The objective of the decision maker is to maximize the expected present value of the conservation investment at the time of the investment less the cost of investment (and any fixed increase in current value costs) given a stochastic variable project value (dv_t).

$$\max_{I=\{0,1\}} E[(V_T - I_T)e^{-\rho T}] \tag{3.11}$$

$dV_T = \frac{1}{\rho-\alpha_w} d\pi_t$ expand this by substituting (5) in for $d\pi_t$,

$$dV_T = \frac{1}{\rho-\alpha_w}(\alpha_w \pi_t dt + \sigma_w \pi_t dz) = \alpha_w \frac{\pi_t}{\rho-\alpha} dt + \sigma_w \frac{\pi_t}{\rho-\alpha} dz$$

Notice that V_T also includes a non-stochastic component $\left(\frac{f}{r}\right)$ and so we define $v_T = \frac{\pi_T}{\rho-\alpha}$ to represent the stochastic present value of the risky portion of the investment.

This new variable, v_t can be described by GBM:

$$dv_t = \alpha_w v_t dt + \sigma_w v_t dz \tag{3.12}$$

$$max\, E\left[\left(\frac{\pi_T}{\rho - \alpha} - \frac{f}{r} - I_T\right) e^{-\rho T}\right] \quad (3.13)$$

$$F(v_T) = max\, E[(v_T - K)e^{-\rho T}] \text{ subject to } dv_t = \alpha_w v_t dt + \sigma_w v_t dz \quad (3.14)$$

The investment itself yields no cash flows until the time at which the investment is taken, and thus, the problem because one of optimal stopping in continuous time. Generically, the value the firm gets in waiting is the total expected return on the project over a short time interval, dt, ($\rho F dt$), equal to the expected rate of capital appreciation of the option, $E(dF)$ (3.15) (Dixit and Pindyck, 1994, p. 140), given that the investment has not occurred. Simply put, the option will be exercised at the point where the option is at its greatest level and equal to the value of the incremental value of the project. Were it to occur at a different point, the firm would either have value in waiting for the difference in value to be at its greatest level or the value of the project itself is less than the potential value.

$$\rho F dt = E(dF) \quad (3.15)$$

In order to take the expectation of the stochastic term, $E[dF]$, Ito's Lemma is applied again, using a version of Ito's lemma that says the total derivative of a stochastic function of x and t is given by equation 3.16 (Dixit and Pindyck 1994, p. 80). Applying this rule to our value function, dF, results in equation 3.17. I have dropped the t subscript for convenience. Next, 3.17 is substituted into 3.15 and since $E[0dt]$ and $E[dz]$, they both equal zero and can be eliminated from equation 3.17. Additionally, the term dt appears in every term meaning it can also be eliminated from the system. Finally, let $\delta = \rho - \alpha_w$ and substitute $\alpha_w = \rho - \delta$ into equation 3.17. Compile terms on one side of the equals sign to obtain the ordinary differential equation in F (equation 3.18).

$$dF = \left[\frac{\partial F}{\partial t} + a(x,t) * \frac{\partial F}{\partial x} + \frac{1}{2}b^2(x,t)\frac{\partial^2 F}{\partial x^2}\right]dt + b(x,t)\frac{\partial F}{\partial x}dz \tag{3.16}$$

$$dF = 0dt + \left[(\alpha_w)vF'(v) + \frac{1}{2}\sigma^2 v^2 F''(v)\right]dt + \sigma v F'(v)dz \tag{3.17}$$

$$\frac{1}{2}\sigma^2 v^2 F''(v) + (\rho - \delta)vF'(v) - \rho F = 0 \tag{3.18}$$

To solve for the threshold value of the investment (and corresponding level of water), some boundary conditions must be considered. First of all, if the project value goes to zero it will stay there because $dv = 0$ when $v = 0$ (equation 3.19). Additionally, the project will only be exercised where the option value $F(V^*)$ equals the optimal value of the investment less costs of investment $v^* - K$ (equation 3.20). Finally, the investment will only take place at a point where the option value is a smooth and continuous functions at the point where the project is undertaken, v^* (equation 3.21) (Dixit and Pindyck 1994, chapter 5).

Boundary Conditions:

Stochastic process condition: $F(0) = 0$ (3.19)

Value matching condition: $F(v^*) = v^* - K$ (3.20)

Smooth pasting condition: $F'(v^*) = 1$ (3.21)

Equation 3.18 represents an ODE in F. As such, a general solution must be developed which has parameters that, when varied, can obtain every solution to the system. Since (3.18) is linear in $F(v)$ and its derivatives, the general solution can be expressed as a power solution (3.22). Previous work has confirmed that this functional form, with parameters (A, β), enables a solution to arise that is consistent and economically reasonable so long as boundary conditions (3.19-3.21) are met (Carey and Zilberman 2002; Dixit and Pindyck 1994).

$$F(v) = Av^{\beta} \tag{3.22}$$

To prove that the guess for the general solution to the value of the option to invest is in fact the appropriate solution, we can substitute Av^{β} and it's derivatives into (3.18) in place of $F(v)$, $F'(v)$ and $F''(v)$. The solution will be where this new substituted function (equation 3.23) is equal to zero.

Beginning with $F(v) = Av^{\beta}$, take the first and second derivatives:

$$F'(v) = \beta A v^{\beta-1}$$

$$F''(v) = (\beta^2 - \beta) A v^{\beta-2}$$

Substitute these terms into (3.18) and simplify to obtain the following:

$$\frac{1}{2}\sigma^2 v^2[(\beta^2 - \beta)Av^{\beta-2}] + (\rho - \delta)v[\beta A v^{\beta-1}] - \rho[Av^{\beta}] = 0$$

Dividing through by Av^{β} results in an equation that is quadratic in β:

$$\frac{1}{2}\sigma^2(\beta^2 - \beta) + (\rho - \delta)\beta - \rho = 0$$

$$\frac{1}{2}\sigma^2\beta^2 + \left[-\frac{1}{2}\sigma^2 + (\rho - \delta)\right](\beta) - \rho = 0 \tag{3.23}$$

Solving this quadratic equation for β for the two roots;

$$\beta = \frac{-\left(-\frac{1}{2}\sigma^2 + (\rho - \delta)\right) \pm \sqrt{\left[-\frac{1}{2}\sigma^2 + (\rho - \delta)\right]^2 - 4\left[\frac{1}{2}\sigma^2\right][-\rho]}}{2\left[\frac{1}{2}\sigma^2\right]}$$

Which simplifies to a positive root (3.24) and a negative root (3.25).

$$\beta_1^* = \frac{1}{2} - \frac{(\rho - \delta)}{\sigma^2} + \sqrt{\left(\frac{(\rho - \delta)}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{\sigma^2}} > 1 \tag{3.24}$$

$$\beta_2^* = \frac{1}{2} - \frac{(\rho - \delta)}{\sigma^2} - \sqrt{\left(\frac{(\rho - \delta)}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2\rho}{\sigma^2}} < 0 \tag{3.25}$$

It is common practice to focus only on the positive root (equation 3.24) as it is not likely that an investment will take place if the value function is negative. To find the water level at which an investment would be made, W^{OV}, we now utilize the boundary conditions, using the functional form of the solution to equation 3.18. Firstly, we know from our value matching condition, that the option will be exercised only when the value of the project equals the general solution (equation 3.22) at the optimal exercise point (equation 3.26). Secondly, we know that the derivative of the option value must equal 1 at the optimal exercise point (equation 3.27) as per the smooth pasting boundary condition. We now have two equations (equations 3.26 and 3.27) in two unknowns (v^* and A). Solving equation 3.27 for $= \frac{1}{\beta^* v^{*\beta^*-1}}$, and substituting that value into equation 3.26 results in $\frac{1}{\beta^* v^{*\beta^*-1}} * v^{*\beta^*} = v^* - K$. Simplifying, the cut-off level at which a firm would invest becomes equation 3.28.

$$Av^{*\beta^*} = v^* - K \tag{3.26}$$

$$\beta^* A v^{*\beta^*-1} = 1 \tag{3.27}$$

$$v^* = \left(\frac{\beta^*}{\beta^* - 1}\right) K \tag{3.28}$$

The first term of the option value rule (equation 3.28) is known as the hurdle rate. It is easy to see that since $\beta > 1$, then the hurdle rate will exceed 1. This represents the delay in investment when incorporating the option value. To solve for the water level at which a firm would undertake the investment, we work backward from the cutoff level of v^* to the cutoff level of water, W^{OV}, at which a producer would adopt conservation technology. Substituting $v^* = \frac{\pi_T}{\rho - \alpha_w}$ into equation 3.28 results in: $\frac{\pi_T^*}{\rho - \alpha_w} = \left(\frac{\beta^*}{\beta^* - 1}\right) K$. Next, expand the K term $K = \frac{f}{r} + I_T$:

$\frac{\pi_T^*}{\rho-\alpha_w} = \left(\frac{\beta^*}{\beta^*-1}\right)\left(\frac{f}{r} + I_T\right)$. Substitute $\pi_T^* = (\gamma\pi_1 - \pi_0)W^{OV}$ and solve: $\left(\frac{(\gamma\pi_1-\pi_0)W^{OV}}{\rho-\alpha_w}\right) =$ $\left(\frac{\beta^*}{\beta^*-1}\right)\left(\frac{f}{r} + I_T\right)$ simplifying and noting that $\delta = \rho - \alpha_w$, the threshold level of water at which an irreversible investment would be made under uncertainty is given by equation 3.29.

$$W^{OV} = \left(\frac{\beta^*}{\beta^* - 1}\right)\left(\frac{\delta(f + rK)}{r(\gamma\pi_1 - \pi_0)}\right) \tag{3.29}$$

As before, the first term in equation 3.29 is commonly referred to as the hurdle rate, which incorporates the irreversible and uncertain nature of the investment. It is easy to see that since $\beta > 1$, then the hurdle rate will exceed 1. The second term is identical to the water level at which investment would occur using the NPV rule. Moreover, this result conforms with previous studies which all find that the uncertainty associated with water resource uncertainty delays investment in conservation technology (Carey and Zilberman 2002; Geltner, Riddiough, and Stojanovic 1996; Khanna, Isik, and Winter-Nelson 2000). The implication of this result is that investment requires a higher water level compared to net present value rule.

As this hurdle rate is clearly important to the solution, there are a few interesting characteristics to consider. First of all, δ, the opportunity cost of waiting, is increasing in β^* because the second part of equation 3.30 is always smaller than the first part, $\frac{1}{\sigma^2}$. In turn, this has a compressing effect on the hurdle rate because as β^* increase, the hurdle rate decreases. This implies that an investment would be made earlier if the opportunity cost of waiting were higher. Additionally, if $\sigma^2 \to \infty$, then $\beta^* \to 1$ $(\frac{1}{2} - 0 + \frac{1}{2} = 1)$ (check using equation 3.24 and take the limit). In turn, value would go to infinity because, using equation 3.28, $v^* = \left(\frac{1}{1-1}\right)K = \infty$. This implies that the project would never be undertaken if variability were infinite.

$$\frac{\partial \beta^*}{\partial \delta} = \frac{1}{\sigma^2} - \frac{1}{\sigma^2}\left[\left(\frac{\rho-\delta}{\sigma^2} - \frac{1}{2}\right)\right]\left[\frac{1}{\sqrt{\left(\frac{\rho-\delta}{\sigma^2}-\frac{1}{2}\right)^2+\frac{2\rho}{\sigma^2}}}\right] > 0 \tag{3.30}$$

The option value threshold (equation 3.29) is decreasing in the property rights parameter, γ as shown in equation 3.31. This means that as gamma decreases, e.g. as water allocation is restricted to protect return flows, the value threshold increases. This restriction is further exacerbated by the hurdle rate which compounds the negative impact of property rights on investment.

$$\frac{\partial W^{OV}}{\partial \gamma} = -\left(\frac{\beta}{\beta-1}\right)\frac{\delta r \pi_1(f+rI_T)}{[r(\gamma\pi_1-\pi_0)]^2} < 0 \; if \; \pi_1 > 0 \tag{3.31}$$

3.5 Data and Model Parameterization

For simplicity, this study simulates profits for a 1-acre sized representative field grown in alfalfa—a crop that takes up roughly 36% of irrigated agriculture in the Arkansas River Basin. For this exposition, it is assumed that the farmer cannot increase his intensive margin (farming more on less land) or his extensive margin (spread the water out on greater acreage). In reality, we would expect this to happen but because the policy is based on “historical consumptive use” this implies that the farmer should not, under the existing institutional framework increase the intensity or extensity of their production.

Table 3.1 shows the values for the parameters entering into the profit function (equation 3.2) for the two types of irrigation technology. Conventional irrigation is modeled as flood (gravity) irrigation and the conservation technology is assumed to be mid-elevation sprinkler application (MESA) center pivot. Both of these technologies are assumed to use surface water flows which are subject to the property rights institutions described previously[3]. It is assumed that conventional irrigation has an efficiency rate around 60% while conservation technology has an efficiency rate of 90%. This implies that 60% of water applied using flood irrigation actually gets to the plant to be consumptively used in the production of the crop whereas 90% of the water applied using sprinkler irrigation is used consumptively. One study of alfalfa in the western U.S. estimates the water production function for alfalfa to be 0.177*acre-inch implying that one acre-inch of water consumed would result in 0.17 more yield (Bauder et al. 1991). In order to estimate the slope of the production functions, the efficiency for each technology is multiplied by this value (so the slope for conventional is calculated as $b_0 = 0.177 * 0.6 = 0.1062$) (Table 3.1).

Table 3.1: Parameters for the Profit Function

Description	Name	Value
Price for output[1]	p	$200.00
Maximum production[2]	$\bar{y}$	8
Fixed cost of conventional[3]	f_0	$31.50
Fixed cost of sprinkler[3]	f_1	$2.34
Variable cost of conventional[3]	c_0	$0.00
Variable cost of sprinkler[3]	c_1	$0.99
Slopes of production functions[4]		
Slope for conventional	b_0	0.1062
Slope for sprinkler	b_1	0.1682
Investment Costs[3]	K	$154.91
1 Data from USDA 2016 2 Data from Davidson, Bartolo, and Tanabe 2013		
3 Calculated for local environment with data from Schaible and Aillery 2012 and Amosson, et al. 2011		
4 Slopes calculated based on irrigation efficiency information in Amosson, et al., 2001 and alfalfa production data in Bauder, et al., n.d.		

[3] Ground water flows have their own sets of property rights institutions as well. It would be interesting to explore in more depth a groundwater scenario as an extension of this model.

Price per output is assumed constant and roughly equal to the price per ton of alfalfa reported in USDA (2016) Alfalfa Reports ($200/ton). Additionally, the maximum production is assumed to be around eight tons per acre according to local extension reports (Davidson, Bartolo, and Tanabe 2013). Cost data came from USDA data, Texas A&M irrigation cost data (Amosson et al. 2001), and from a USDA report on irrigation (Schaible and Aillery 2003). It is assumed that costs for both systems are spread out over 120 acres although the parameters listed above have been converted to the cost per acre. The lower fixed costs for conservation technology is driven by lower labor costs. Fixed costs for conventional irrigation is labor cost per acre. Variable costs for sprinkler are simply the per unit diesel cost to pump the water out of the surface pond while it is assumed that conventional irrigation does not incur costs per unit of water applied (as the labor needed to open the gate is the same regardless of amount of water applied and is considered a fixed cost). The total upfront investment cost, K, assumes expenditures on the pumping apparatus, a stabilization pond, the equipment itself, the pipeline, and installation costs.

Table 3.2 defines parameter values used in this study. The flow rates $\{r, \rho, \delta, \alpha, \sigma, \sigma^2\}$ are assumed to be constant although the problem is sensitive to changes in these variables. More specifically, in order to have a solution, it must be the case that $r > \beta_1(r - \delta)$, which is confirmed by the parameter values below. Any change in $\{r, \rho, \delta, \alpha, \sigma, \sigma^2\}$ would change the value of β_1. Increased volatility in water from year to year, represented by σ^2, serves to suppress investment as returns to production (and thus the value of investment) become more volatile. The same logic would apply to a positive value for the drift rate (α). If water levels are expected to increase, the value of the investment opportunity (the increased benefits associated with more efficient use of water) would decline over time leading to fewer conditions where an investment would be necessary to maximize value of one's operation. A more rapidly declining water level would lower the threshold as you would need to benefit from increased productivity more quickly while a less rapidly declining water level would increase the threshold as the difference in net profits would not be as pronounced.

Table 3.2: Table of Interest Rates and Model Parameter

$r = 0.04$	$\rho = 0.10$	$\alpha = -0.03$	$\gamma = \{0:1\}$
$\sigma = 0.15$	$\sigma^2 = 0.0225$	$\delta = \rho - \alpha_w = 0.13$	$\beta_1 = 1.379$

While the true value for the parameter, let's call this φ, is technically equivalent to b_0/b_1, the application of the property rights institution has been such that this parameter is not as constant as what would be implied by the policy. As such, γ is varied between 0 and 1 for each water threshold rule in both the NPV and OV frameworks in order to illustrate how the thresholds change based on the value for this property rights enforcement parameter.

3.6 Results and Discussion

This study utilizes Matlab (2015, student edition) to solve for the net present value water level at which one would switch to sprinkler irrigation (W^{NPV}) and the option value water threshold considering the irreversible nature of the investment (W^{OV}) (code is included in Appendix 2). These thresholds are valuable as they allow for us to predict if and when a farmer would make an investment. It may be the case that the NPV rule over-predicts investment as it does not take into account the irreversible nature of the investment. The OV rule is assumed to be a more accurate predictor of investment as it takes into account the irreversible nature of the investment. If both rules predict investment then it must be concluded that there is some other process that influences the decision making environment.

Results suggest that the net present value of sprinkler adoption is positive under a traditional NPV approach as well as under the option value framework, such that for any water level, farmers should be adopting conservation (sprinkler) irrigation. This shows that it is not just option value that delays investment for farmers as under these conditions, investment is still predicted. However, the loss in water right due to irrigation improvement rules increases the switch threshold under the NPV rule and this threshold gap upon a loss in water rights is more pronounced for the option value threshold. These results suggest that strict adherence to use-based property rights suppresses investment. Additionally, when the property rights structure is imposed on an option value framework, investment is only predicted under a very limited set of conditions compared to under the traditional NPV approach.

3.6.1 Results of the NPV Analysis

Assuming that a farmer were to maintain consumptive use of their water only (e.g. $\varphi = 0.7$, if the conservation system is 30% more efficient), then for any water level, a farmer should be willing to adopt sprinkler irrigation over flood irrigation as the expected net present value of the investment is positive (figure 3.3). The net present benefit of adoption of the sprinkler system starts at around $575/acre with a near zero water allocation and increases to about $750 with a 60 inch allocation. This result is largely driven by lower costs not directly attributable to water application (f).

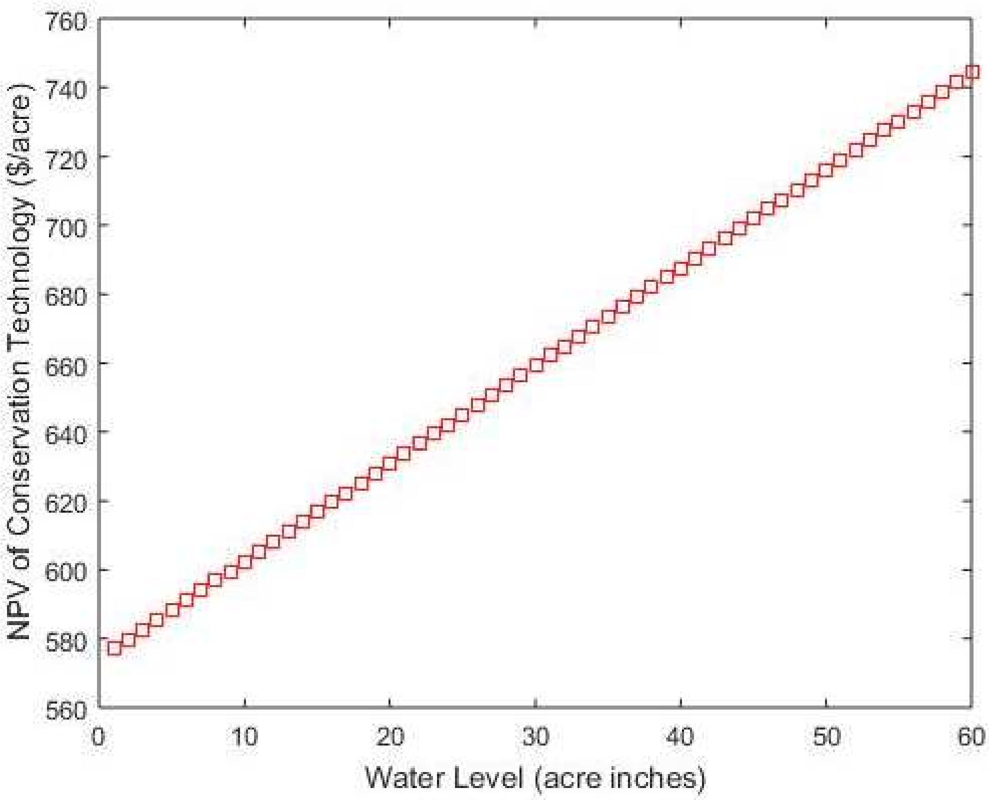

Figure 3.3: A Graphical Representation of the NPV Rule for Various Water Levels

However, the positive NPV result is sensitive to the property rights system. If a farmer adopts sprinkler irrigation and is able to keep the entirety of his water right ($\gamma = 1$), then he would be better off switching to sprinkler irrigation for any level of water due to the difference in fixed costs and the increasing productivity per unit of water. However, under the irrigation improvement rules, it is assumed that a farmer will lose a portion their water right as they can only maintain consumptive use. If, through adopting a sprinkler, a farmer increases consumptive use from 65% to 95%, the appropriate γ level would be 0.7 (1-0.3). This implies that for any γ level above 0.7, the farmer will at least maintain yield if not increase it (assuming for simplicity that there are no benefits from a sprinkler such as more uniformity in application). The function of the cut off water level at which a farmer would switch irrigation technologies is shown graphically in Figure

3.4. As γ drops below 0.69, the farmer requires a much greater water level in order to switch irrigation technologies as the portion of water the farmer has available decreases in gamma. The value falls to zero at around 0.688 implying that as long as the farmer remains very close pre-adoption productivity or above it, the investment is worthwhile and the farmer would adopt under any water level (represented by the line being on the horizontal axis).

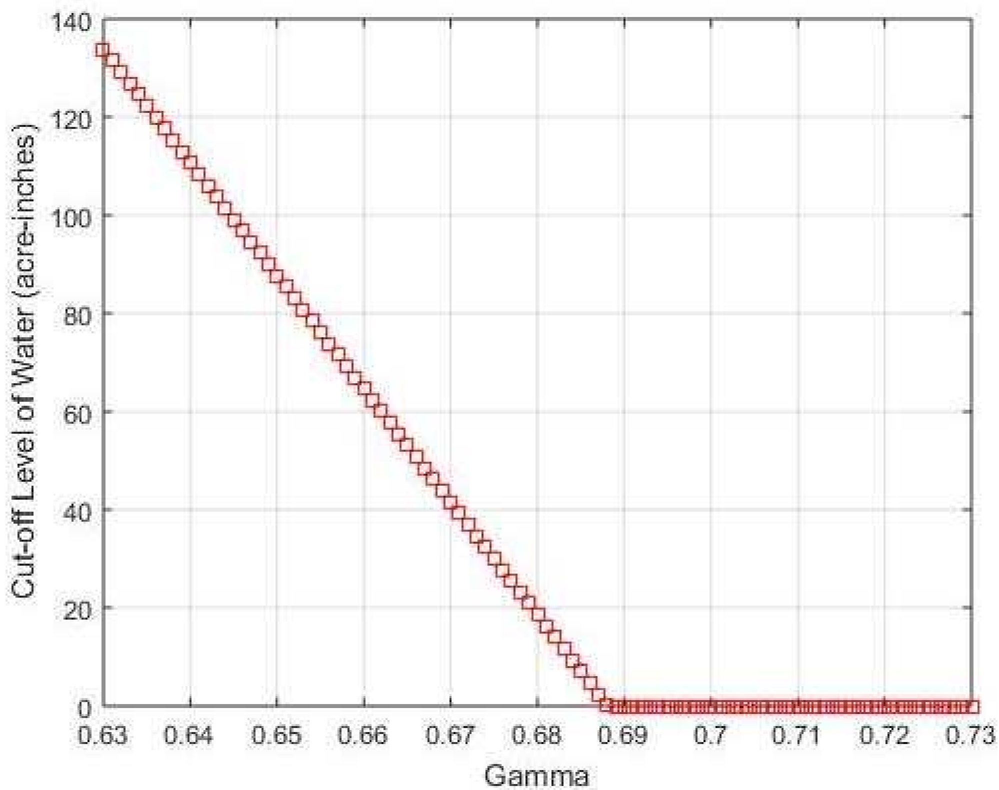

Figure 3.4: NPV Threshold Water Level Required for Farmers to Adopt Conservation Irrigation

3.6.2 Results of the Option Value Analysis

Given that the project has a positive NPV under reasonable assumptions regarding the property rights regime, it is puzzling that so little adoption is seen. The source of uncertainty associated with the property rights regime shown graphically above tells part of the story—more specifically if there is uncertainty regarding the level of gamma, one might observe less adoption. However, it is also useful to discuss the option value associated with the irreversible and uncertain investment in sprinkler irrigation and how the property rights regime impacts that result. Figure 3.5 is the counterpart of the NPV rule for the option value assuming a farmer maintains consumptive use of their water ($\gamma = 0.7$). This rule still indicates that farmers should be switching to conservation irrigation so long as water levels are non-zero although the net present value of the benefit of adopting sprinkler irrigation is two orders of magnitude less than under the traditional NPV rule with expected net benefits only starting at around $5 for the first acre inch compared to $580 for the first acre inch in the NPV rule. This is because the opportunity cost of the option value has been netted out of the value of the investment. Essentially, the value of waiting under this investment would be the difference in the OV function compared to the NPV function.

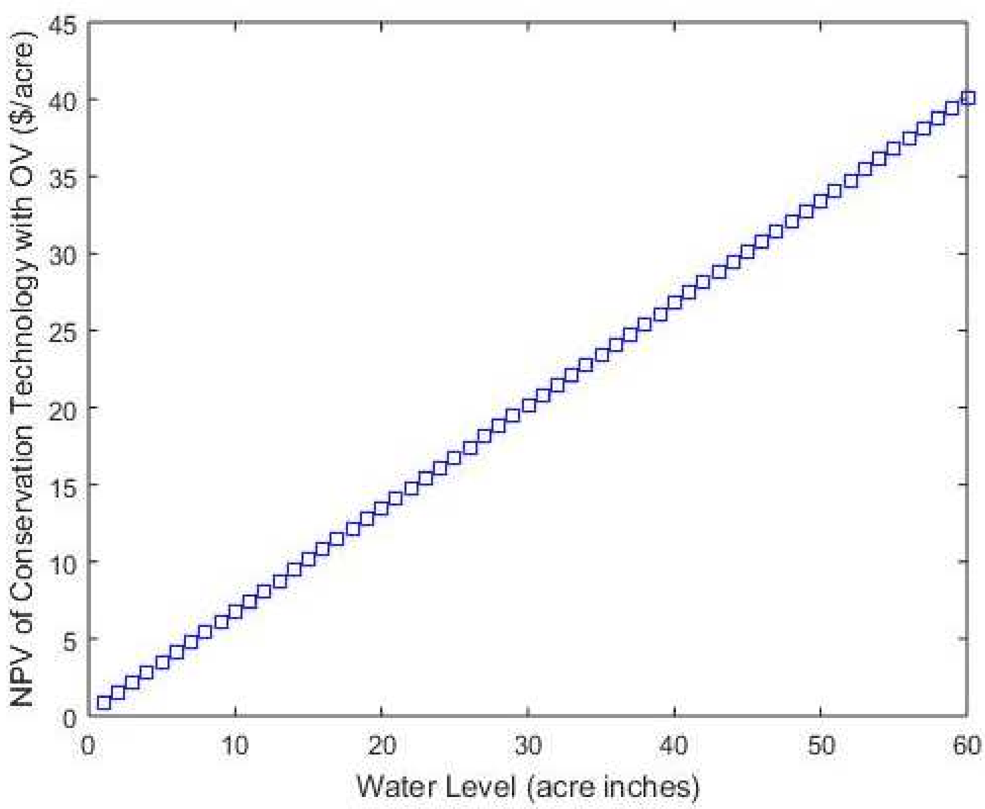

Figure 3.5: A Graphical Representation of the Option Value at Various Water Levels

As before, these results are sensitive to the property rights regime. Figure 3.6 looks at how the threshold level of water required for a switch changes as gamma varies from 0 (no maintenance of one's water right) to 1 (full maintenance of one's water right) -- recall this is where the present value is equal to zero. Like under the NPV rule, the option value rule still indicates that adoption should occur so long as the farmer maintains a water level very close to the consumptive use of the water ($\gamma \geq 0.688$). In other words, if a farmer believes that adoption of conservation irrigation technology results in a losing the full change in consumptive use of their water supply, they would be unwilling to adopt conservation technology. Additionally, figure 3.6 illustrates that the cut-off level of water under the OV rule is much more sensitive to changes in gamma. A small decrease in gamma leads to a much higher value for the threshold under the OV framework compared to that under the NPV rule implying a tougher penalty from property rights enforcement under the option value. This is because this framework takes into account the option of waiting which, once exercised, represents a cost to the investor as the option is no longer available after it has been exercised. Additionally, the OV threshold increases as the constraint on water increases because the benefits of waiting under a small water supply are increasingly large.

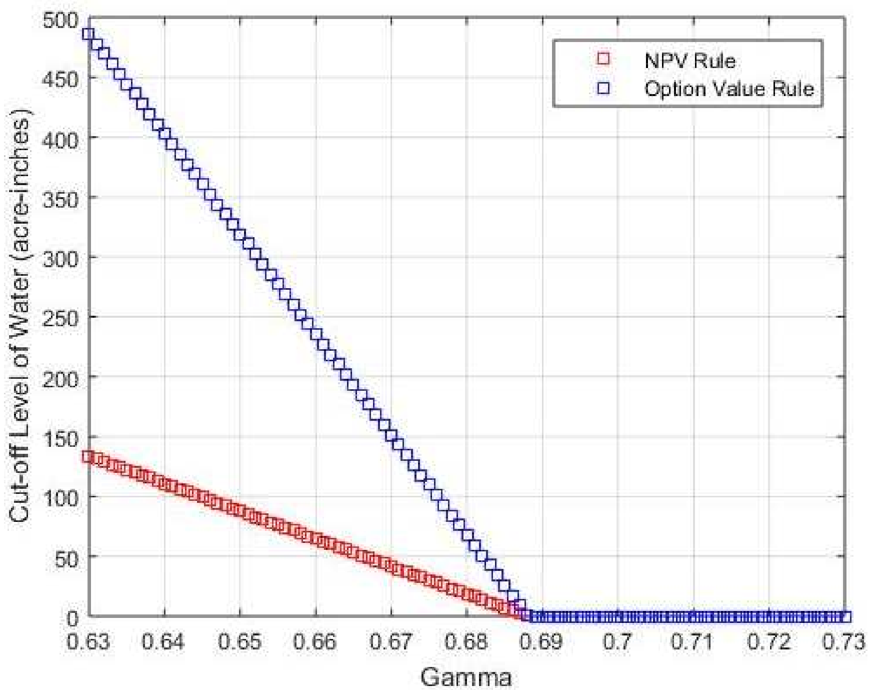

Figure 3.6: Threshold Water Level Required for Farmers to Adopt Conservation Technology under the NPV and Option Value Rules

3.6.3 A Discussion of Real World Application of the Policy

In the previous section, a numerical exercise showed that farmers should be adopting conservation irrigation so long as they are able to maintain consumptive use of their water. These results are largely driven by the costs associated with irrigation as farms are assumed to not be able to intensify or expand their production under the existing water rights framework. The following section uses a limited adoption dataset for the Arkansas River Basin in Southeastern Colorado to explore how the rules are currently being applied to farmers who adopt and the degree to which the assumptions of the model hold in an empirical setting. Using the idea of the property rights variable, γ, as opposed to the technically correct parameter, φ, this data is used to explore water security for adopters in the basin and implications for future adoption as well as for other users.

The dataset contains all Rule 10 plans filed in the basin—recall that this is the change in water right plan that allows users to apply together reducing transaction costs of adopting conservation irrigation. The canals on the Arkansas River Basin that have filed these joint rule 10 plans are Amity, Catlin, High Line, Holbrook, Fort Lyon and a few smaller canals that are lumped together. The average date of first use is earliest for the High Line Canal and latest for the Fort Lyon canal. That said, the Fort Lyon has the largest flow compared to the other canals and it is thus not surprising that most conservation adoption is occurring along the Fort Lyon Canal. In total, 232 fields in the valley have filed these plans historically. In 2016, 18 new fields converted 2,304 acres to sprinklers. In 2017, 13 new fields converted 918 acres to sprinklers. Adoption in 2016 and 2017 represent 17% of total sprinkler adoption in the valley since the inception of the Irrigation Improvement Rules (2011).

Under these Rule 10 plans, there is data for acreage converted as well as water deficit for each adoptee in the Lower Arkansas River Basin. Figure 3.7 illustrates that the average level of gamma (the proportion of water maintained post-sprinkler adoption) remains very high throughout the Arkansas River Basin. On average, almost 95% of total water right for all fields in the collective irrigation improvement plan was maintained upon adoption for the entire basin. The only canals that did not maintain their original water level in 2017 were the High Line Canal and other small canals that were grouped together. The difference in the applied level of gamma between canals is based on the model used to allocate water to all the users in the system. The Arkansas Conservancy District uses the Irrigation System Model Analysis (ISAM) model to determine how much water is allocated to each user based on assumptions about the depth to groundwater, soil moisture, conveyance and leakage from ponds and canals (Goble 2014). Any difference in the average gamma between canals is based on the results of ISAM and inherently related to the assumptions applied.

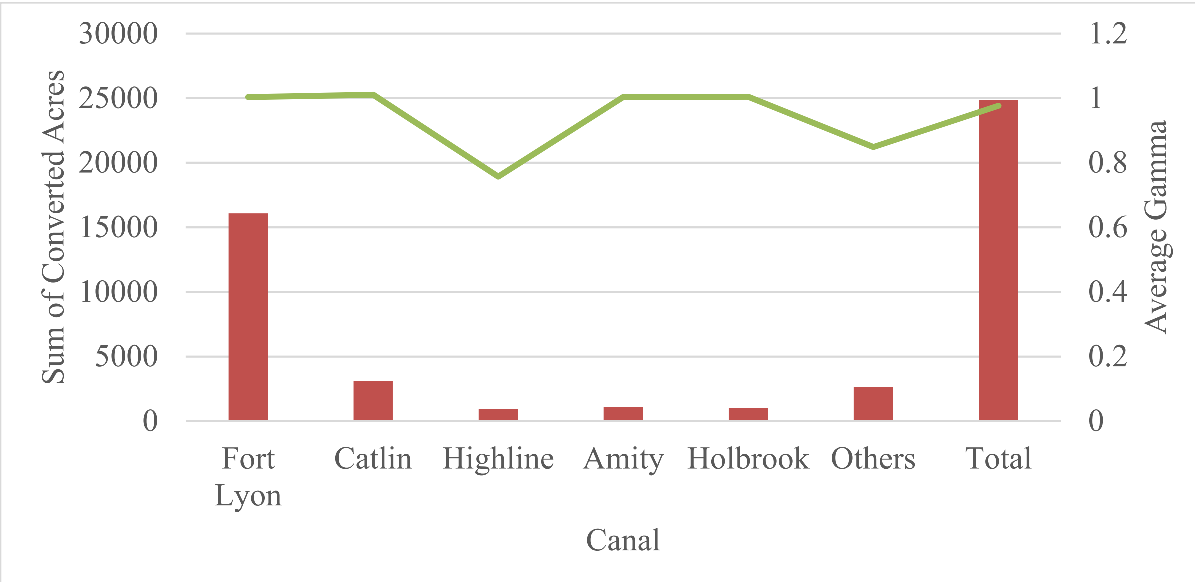

Figure 3.7: Acres Converted to Sprinkler in the Arkansas River Basin Compared to the Average Value of Gamma in 2015

It appears that cases of conservation irrigation technology adoption since the Irrigation Improvement Rules have been in place has not resulted in much loss of water for irrigators, counter to a strict interpretation of the rules on technology adoption – sprinklers are usually at least 2/3's more efficient than conventional systems (0.9 compared to 0.6). Moreover, in this data set there are certainly situations wherein a particular field "owes" the system some water due to an increase in the extensive margin (greater acreage irrigated under the new irrigation system). At the moment this deficit can be made up by the purchase of augmentation water which is not subject to the property rights system or can be offset by someone else choosing to irrigate less.

Based on the calculated value for gamma, it is not surprising that there has been a recent increase in sprinklers in the Arkansas River Basin since the implementation of these Irrigation Improvement Rules. This supports the notion from the NPV and OV simulations that farmers should be adopting conservation technology so long as gamma is sufficiently high as farmers are able to gain in other ways in addition to increased yield. This data set seems to imply that while farmers contend that converting to conservation technology is inhibited by the use-based property rights system, actual implementation of the policy falls short of creating the insecurity in water that would dissuade investment.

3.7 Conclusions and Future Research

This paper extended previously published research on investment for irrigation technology under uncertainty with an innovation to look at the impact of property rights on this and a more traditional investment approach, the NPV rule. As policy makers target water conservation as a way to meet pending demands on water quantity in the west, there must be consideration of existing property rights systems that impact conservation decision making. The private benefits of adopting conservation technology are eroded by rules on irrigation that serve to maintain return flows at the expense of current agricultural water users in the Arkansas River Basin. Additionally, the option of a farmer to wait to investment may impact a farmers decision making on irrigation technology adoption.

Results of simulations show that farmers should be investing in conservation technology under a net present value approach and under an option value approach. Nevertheless, the farmer would not adopt conservation technology if, in application, they were to lose a portion of their water right upon investment in excess of their consumptive use. Because farmers under use-based property rights for water in the arid west have previously cited the potential to lose some of their water allocation upon as a disincentive to adopt, the last section of this paper looks at how these property rights are actually being applied. It appears that, for the most part, farmers are able to maintain the entirety of their pre-adoption water right allocation. The implications from this are that farmers, under the existing application, are actually benefiting even more from adoption as they are able to extend their acreage or farm more intensely.

In future research, it is worth looking at how the existing patterns of adoption impact downstream users. Specifically, if farmers are maintaining their full water allocation in spite of increasing consumptive use, then downstream users are likely going to be negatively impacted by the current implementation strategy under these Rule 10 plans. A comparison could potentially be made in a stochastic, dynamic framework between the economic value of maintaining one's water flows versus those waters remaining in the hands of a downstream user. In other words, one can compare a legally binding water distribution scenario to one dictated by economic value.

Additionally, this model could be extended to incorporate a terminal value for water upon an exit from agriculture. Issues of buy and dry and a value gap between the urban sector and the agricultural sector imply an arbitrage opportunity for farmers. Other studies have found that the terminal value for agricultural land serves to delay conversion of land to conservation purposes (Turvey 2003; Geltner, Riddiough, and Stojanovic 1996); a similar result would be expected for conservation irrigation technology adoption. It would be interesting to see how the property rights parameter further influences this threshold level under a terminal value for water.

Overall, I expect more farmers to be investing in conservation technology in the coming years as there is certainly an economic benefit from the conversion! It also seems as though the restriction in property rights is more words than deeds as farms are maintaining a good deal of water in irrigation for their land under existing applications of the Rules on Investment. The lessons learned from this framework can be extended beyond the reaches of the Arkansas River Basin and their complicated rights structure. More generally, insecure property rights exacerbates a delay in investment due to uncertainty and irreversibility in the investment. Allowing for a flexible implementation of property rights rules can loosen this constraint on decision makers and potentially lead to even greater conservation gains.

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4. CHAPTER 4: AN EXPERIMENTAL APPROACH TO TESTING VOLUNTARY CONSERVATION BEHAVIOR IN WATER QUALITY TRADING MARKETS

4.1 Introduction and Context

Nutrient pollution in U.S. waterways remains a problem of great concern in spite of reductions in nutrient loading from point sources (PS) since the enactment of the Clean Water Act in 1972 (Ribaudo, Savage, and Talberth 2014). Historically, pollution from non-point sources (NPS) such as agriculture or urban stormwater runoff has been difficult to trace, leading to difficulty in creating effective regulations; yet NPS generate the majority of nutrient pollution, largely from agricultural sources (Selman et al. 2009). Watershed managers increasingly turn to the use of multiple voluntary mechanisms to motivate NPS involvement in pollution control. For example, farmers are asked to voluntarily implement water or land conservation practices and municipalities are encouraged to upgrade existing storm water technology in order to alleviate NPS pollution runoff. One promising way to address pollution is to encourage the use of water quality trading (WQT) markets. Water quality trading markets are a pollution credit market with PS as buyers of pollution credits and NPS as sellers of pollution credits. Thus far, these markets have seen limited success with very few trades taking place (Selman et al. 2009). However, these markets can potentially address pollution at least cost while engaging the NPS pollution sectors in pollution control (Ribaudo, Savage, and Talberth 2014).

An ability to overcome issues in WQT markets could lead to a potential break-through in engaging NPS in pollution control. Hoag et al. (2017) showed that these programs only work when a host of economic, environmental and institutional hurdles are low, which they called a policy utopia because it is so rare in the United States. It is therefore important to have precise information about these hurdles in order to find places where trading programs can bridge the gap between efficient abatement from farmers and actual abatement (Hoag et al., 2017). Among other issues, the uncertainty regarding the equivalence of NPS pollution control to PS pollution control, often signified by the "trading ratio," creates structural and behavioral issues in these markets as a ratio that is too high limits the cost-effectiveness of pollution control and a ratio that is too low can lead to worse environmental outcomes (Hoag and Motallebi 2017). Additionally, farmers are often required to contribute to pollution control in their own sector in the form of meeting a "baseline." The motivation to meet this threshold often comes in the form of regulation threats such that if a sector does not contribute significantly to pollution control, they will face future regulation. For example, in Colorado, the Colorado Department of Public Health and Environment implemented Regulation #85 to mitigate nutrient pollution in the state's waterways. This regulation places nutrient effluent limits on wastewater treatment plants (WWTPs) with voluntary management of agricultural run-off that will lead to regulation by May 31, 2022 if "sufficient progress has not been demonstrated in agricultural nonpoint source nutrient management" (5 CCR 1002-85, Regulation #85, adopted June 11, 2012). Regulatory threats introduce another area of uncertainty for NPS: uncertainty about whether or not the sector will continue to avoid regulation.

While several studies have looked at the impact of trading ratios and achieving a threshold on costs or trading prices (Motallebi et al. 2016), few have looked at how these transaction hurdles might change the behavior of buyers and sellers making trades in WQT markets. This study uses experimental techniques to evaluate how the institutional design of water quality trading markets with respect to the trading ratio and threat of regulations influences behavior of participants in those markets. Experiments were conducted in the summer of 2016 to simulate a fixed duration water quality trading market that would allow us to examine behaviors associated with trading ratios and regulations related to baseline. Participants were assigned the role of “farmer” (NPS seller) or “wastewater treatment plant manager” (PS buyer). In the base treatment, the trading ratio is set to 2:1, where two units of abatement by farmers generates one pollution credit that can be sold. Additional voluntary abatement by farmers is allowed after the trading round. A second treatment, referred to throughout as Ratio, mimics the base treatment but farmers also have an opportunity to undertake costly verification of their true trading ratio instead of relying on the regulatory standard of 2:1. Participants that choose to verify will find their true ratio to be higher (3:1), lower (1:1) or equal to the regulatory standard (2:1), meaning that they may gain or lose by verifying their ratio. A third treatment, called Regulation, mimics the base treatment but also asks farmers to implement voluntary abatement to contribute to a known and fixed threshold. If farmer’s are able to abate enough units by the required time period to meet the threshold, they avoid regulation; otherwise, there is a 80% chance they will become regulated as a sector, stopping trading and requiring fixed abatement for all firms the remainder of the game.

There are three primary research questions that these treatments seek to address. First, would WQT market participants verify their trading ratio at a given cost? Historically, economists and others have argued that regulating NPS pollution is difficult because the source is too difficult to trace (Segerson 1988). Recent advances in modelling have made it possible to link NPS pollution to their source. We ask, would they want to? Second, is avoiding regulation is a good motivator for voluntary abatement when participants have access to a pollution market? Colorado’s regulation 85 is banking on this threat. However, if regulators are turning to threats of regulation in order to motivate pollution control from NPS, it is important to know if this is actually an effective strategy, particularly when farmers experience negative consequences in the market if they are unable to avoid regulation. Third, what are the comparative impacts on welfare outcomes under the institutional variations included in the three treatments? This question addresses how WQT market design influences costs, profits and environmental outcomes.

4.2 Literature Review

4.2.1 Water Quality Trading Literature

A policy statement in 2003 titled "Effluent Trading in Watersheds" discusses the EPAs position to promote the use of effluent trading to meet water quality objectives. This framework was updated in 2003, now known as the Framework for Watershed-based Trading, to provide greater guidance on how to implement a successful trading program (IEc 2008). The political impetus for this policy is that WQT is much more popular among the regulated sectors because it allows for flexibility in lieu of imposing fixed standards or taxes that inevitably have distributional impacts (King and Kuch 2003). Moreover, as a cap-and-trade framework, it is touted as a policy instrument that minimizes costs (Goulder 2013).

Under a cap-and-trade framework, a regulatory structure defines a maximum level of impairment or a minimum level of reduction to meet social goals. Various pollution sources will be required to meet this cap either through new or updated technology or by purchasing credits from a different source who reduces pollution to the level required to meet the cap. Typically, only PS are regulated but can trade credits among themselves or sometimes more cheaply from NPS that are not required to implement practices but that can do so for the purpose of generating credits. Figure 4.1 provides a schematic of this process. The regulator creates rules and sets the cap. NPSs can implement conservation and sell whatever is in excess of any requirements that they already face. Point sources either upgrade their own systems to meet regulated standards or buy credits from someone else. In this way, PS are the demanders of credits and the demand curve corresponds to their willingness to pay for credits while NPS are suppliers of credits and the supply curve corresponds to NPS willingness to accept for credits. Under this framework, cost-minimization is achieved in theory because the PS would not pay for credits to reduce pollution unless the price of the credit is less than it would cost the point source to reduce pollution. The market functions as any other market if there is sufficient demand from PS for credits and sufficient supply from both PS and NPS (King and Kuch 2003).

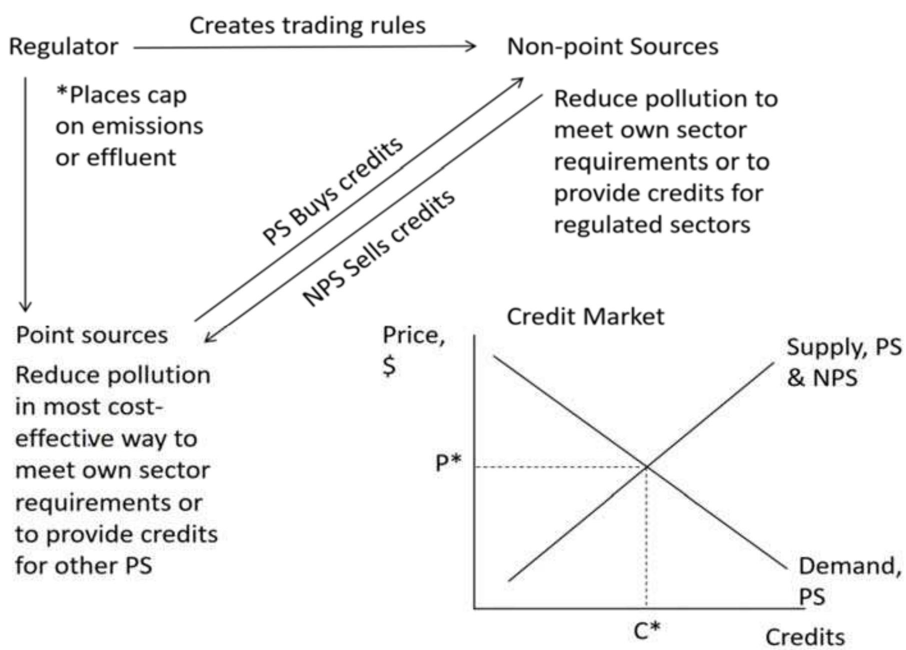

Figure 4.1: Visual Representation of the Process of Water Quality Trading
This diagram was made by the author but implements information provided by (Ribaudo, Savage, and Talberth 2014; King and Kuch 2003; Goulder 2013).

Four common market structures are commonly identified in the literature for WQT markets: exchanges, bilateral negotiations, clearinghouses and sole-source offsets (Woodward and Kaiser 2002). The choice of the structure must be related to the nature of the pollutant, the goals of the program, the level of uncertainty, the monitoring and enforcement requirements, and the regulatory environment (Woodward, Kaiser, and Wicks 2017). Exchanges are most like the true cap-and-trade system illustrated in figure 4.1, as all prices and transactions are public knowledge and the units traded are homogenous. Bilateral negotiations on the other hand, involve negotiations between a buyer and a seller and the responsibility of each party is identified; such a system can be more costly than an exchange due to the high transaction costs inherent in such a market. Sole-source offsets are actually not markets at all but rather an economic transaction between a polluter for a unit of sanctioned abatement that occurs elsewhere. Finally, a clearinghouse has a market with an intermediary (the clearinghouse) that defines the units of exchange and breaks the link between buyer and seller; such a market reduces transaction costs tremendously and eliminates the regulatory links between buyers and sellers (Woodward, Kaiser, and Wicks 2017).

According to a 2008 EPA report, "the primary potential benefit of WQT that attracts consideration by policy makers is the potential ability to control pollutants at an overall lower cost to society" (IEc 2008, 1). Goulder (2013) contends that largely within the umbrella of the cap and trade framework, there have been gains in economic efficiency under this policy compared to a standard (command and control) in air quality markets. However, water quality trading markets have not seen as much success as other pollution markets due to the attributes of water quality as a physical process but also due to institutional considerations (Goulder 2013). Others find that the economic efficiency gains in WQT markets seem to be dampened by uncertainty and transaction costs (Nguyen et al. 2013). Using an agent-based simulation model, Nguyen, et al. (2013) find the most efficiency gains when there is a clearinghouse rather than bilateral negotiations. Similarly, Woodword, Kaiser and Wicks (2002) argue that the appropriate market structure matters greatly in terms of the meeting water quality goals and having successful trading programs.

Various case studies have identified where there has been success in WQT and factors that inhibit successful program development. Hoag and Hughes-Popp (1997) observe no markets with trades and summarize six factors influencing the success of WQT: low transaction costs, robust market size, heterogeneous abatement costs, low enforcement costs, certainty in trading ratios, and binding regulations (a cap). By 2003, King and Kuch still found little evidence for WQT trading due to significant market structure issues such as thin markets and unbinding regulations and institutional barriers which are relatively easier to overcome. By 2009, the picture is somewhat less grim with identification of 26 trading programs that had experienced trades (Selman et al. 2009). They identify the same rationale for failure as previous studies with the additional insight that point sources (WWTPs primarily) are typically risk averse such that they would prefer to install costly upgrades that they can control rather than expose themselves to risk by making trades with other parties (either other PS or NPS). Hoag et al. (2017) summarize the literature to conclude that economic, physical and institutional conditions necessary for a high chance of successful trading of nitrogen credits between PS and NPS are found in only about 5 percent of impaired watersheds in the US. However, they also conclude that understanding how factors like trading ratios and baselines effect trades can improve the chance of success and expand that domain.

The trading ratio, or the rate at which NPS control is converted into PS pollution control, interacts with market performance in various ways (Malik, Letson, and Crutchfield 1993). Higher ratios lead to higher costs of pollution control and less demand for credits from the NPS (Motallebi et al. 2016; Shortle 2013) whereas lower ratios lead to potentially poorer environmental outcomes (Motallebi et al. 2016; Horan and Shortle 2005). Moreover, ratios are often arbitrary and not based on scientific models leading to uncertainty over future trading ratios

(Malik, Letson, and Crutchfield 1993). Resolution of uncertainty, say through a multi-attribute credit market that allows exact environmental outcomes to be known to both PS and NPS leads to more environmentally and economically efficient outcomes (Ghosh and Shortle 2009).

Additionally, issues of trust and uncertainty impact participation from farmers in particular (Breetz et al. 2004). Regulatory uncertainty is rampant wherein farmers often have to meet a “baseline” amount of pollution before they can participate in trading. It is often uncertain what is required *individually* in order to meet this baseline threshold and serves to greatly increase the costs associated with abatement as NPS implement the cheapest options to meet the baseline (Ghosh, Ribaudo, and Shortle 2009). This serves as a disincentive for farmers to engage in pollution control until they are actually regulated. This disincentive is exacerbated by a general sense of distrust of regulators and other polluters in a watershed wherein farmers hesitate to give more information to regulators in terms of pollution control potential or to other polluters lest this information be used against them (Motallebi et al. 2016; Breetz et al. 2004).

Perhaps the rationale for the dismal view of water quality trading is due to a lack of indicators for success. Breetz et al. (2004) defines success as “the program’s ability to bring farmers to the table and implement BMPs for the purposes of trading.” Under these criteria, 10 out of 14 projects analyzed in their study were considered successful. Predictors of success followed closely what has been outlined above as inhibitors! When uncertainty is reduced and trust is formed, farmers are able to participate in a program in at least some capacity. Selman et al. (2009, P. 2) define success as stakeholder satisfaction, trading activity, and meeting environmental goals although the authors fail to identify how many of the active trading programs they would consider as successful. Regardless, WQT continues to lag compared to what theory would suggest in terms of the quantity of actual trades.

In spite of the factors listed above that negatively impact the success and participation in WQT markets, Motallebi et al. (2017) find that this progression in research can be used to pre-identify where trading can work. However, their work shows that how farmers interpret or feel about the parameters in these programs can be very important. For example, they found that many farmers require an adoption premium (or hurdle rate) above the actual cost of implementing new conservation practices (Motallebi et al. 2016)); a WQT program provides just that opportunity as the willingness to pay of PS is likely higher than other cost sharing opportunities. Additionally, various lines of research suggest that if it were possible to reduce the uncertainty regarding the trading ratio and future regulation, more efficient outcomes could emerge for these water quality trading markets (Horan and Shortle 2017; Motallebi et al. 2016; Hoag and Motallebi 2017). Economic experiments offer an avenue to understand how farmers interpret and react to some of the key parameters of WQT programs, like voluntary baselines and trading ratios.

4.2.2 Experimental Literature

While markets for pollution have been prevalent both for air quality and water quality, much of the *ex post* analyses identify numerous factors that impact the success of a particular program. In order to better identify how specific factors impact the behavior of participants and thus the market and environmental outcomes of these policy regimes, a laboratory setting can be helpful as much of the exogenous factors that have subtle influences in real-world settings can be controlled. Participants have the opportunity to participate in a market setting earning money based on their relative performance while researchers can isolate characteristics that are theorized to influence human behavior as well as to test different market structures before implementing them. Generally, economic experiments have proven helpful in exploring the gains from trade in emissions markets as well as the impact of market design on performance (Muller and Mestelman 1998).

Experimental studies that simulate a WQT market typically resemble a combination of the clearinghouse and exchange market structures described above in what is known as a "baseline and credit" institution (Jones and Vossler 2014). This market is like an exchange as credits generated from NPS are assumed to be equivalent to abatement by the PS so that the trade is simply a transfer of a good—the equivalent unit of abatement. However, it is like a clearinghouse in that there are often no transaction costs to trading, negotiations are not required, and trades are anonymous.

There have been several economic experiments conducted that relate to the design of water quality trading programs. Jones and Vossler (2014) explore how variation in upfront investment costs impacts the generation of credits. They find that when firms are required to make a binding abatement choice prior to trading, there is a large decrease in efficiency as firms tend to over-invest in abatement technology (Jones and Vossler 2014). Similarly, Suter et al. (2013) find that over-abatement by point sources occurs when participants have limited abatement potential with existing technology and are risk averse. The "lumpiness" associated with water quality improvement technology for point sources makes trading problematic as an upgrade moves the pollution to a new tier in terms of pollution levels which may exceed regulatory limits (Suter, Spraggon, and Poe 2013).

Policy design related to meeting environmental goals has also been studied with experiments. Banking of permits has opposing impacts serving to smooth out price variability but increasing problems of non-compliance and worsening environmental outcomes (Cason and Gangadharan 2006). Another experiment found no evidence that enforcement may be more effective based on firm-specific characteristics (Murphy and Stranlund 2007). Furthermore, compliance has countervailing impacts. On the one hand, increased enforcement results in fewer violations and motivates firms to increase the number of permits purchased which increases the price; higher permit prices then motivate firms towards greater violations (Murphy and Stranlund 2006).

Another related literature uses experiments to look at behaviors where public goods are involved. Public goods experiments have been a focus of economic experiments since their inception. Most of the public good games focus on the provision of public goods—including that of environmental quality. Indeed, there are strong parallels between asking farmers to implement practices voluntarily for pollution control and typical public good games. This body of literature has generally found that public goods are difficult to provide as individuals put private gain ahead of public gain (Laury and Holt 1999). More recent experimental literature finds that in a one-shot public good game repeated several times often leads to free-riding as predicted by theory wherein the interior Nash equilibrium involves participants failing to provide the public good collectively (Laury and Holt 1999); nevertheless, there is evidence of a "conditional cooperator" who contributes to the public good because others' contributions encourage them to cooperate and provide the public good (Fischbacher, Gachter, and Fehr 2001). Additionally, when participants have an opportunity to punish non-cooperators, provision of the good increases (Kroll, Cherry, and Shogren 2007). Similarly, when a group is able to turn a public good into a club good through membership fees, it drastically increases provision (Bchir and Willinger 2013).

Several experiments have been conducted on threshold, or step-level, public goods wherein coordination takes place over several time periods and culminates in either provision of the public good or a situation of free-riding as in the one-shot public good game. It is often the case that there is uncertainty regarding what the threshold actually is; much of this literature comes to the conclusion that, like in one-shot public goods games, provision depends on conditional cooperation. However, some authors find that thresholds with lower expected mean levels experience greater provision than those with a higher mean (Suleiman, Budescu, and Rapoport 2001). Uncertainty regarding the consequences of meeting the threshold has also been studied, with researchers finding the less uncertainty there is related to the consequences of not meeting the threshold, the more likely it is that a public good will be provided (Barrett and Dannenberg 2013).

4.3 Contribution to the Literature

This study considers three WQT rule scenarios: Base, Ratio, and Regulation. Base sets up a water quality trading market between "farmers" and WWTP "managers". Participants are not required to trade; however, parameters are set such that there are gains from trade should participants decide to interact in the WQT market. While pollution markets have been used in previous experiments, this experiment chiefly looks to voluntary measures that farmers take that influence their participation and competitiveness in WQT markets. Ratio and Regulation extend the Base to look more specifically at trading ratios and voluntary threat regulations, respectively.

Other economic experiments that have focused on the trading ratio, have largely focused on the stochastic nature of pollution control and devising a permit that reflects this stochastic pollution scenario from NPS. No one has addressed the question, if models are able to estimate delivery ratios at a given cost, would farmers be receptive to knowing this information with certainty given that it could influence their competitiveness in a pollution market? Ratio addresses this question and provides a starting point for analyzing whether or not NPS are willing to invest in resolving this source of uncertainty in order to improve their place in the market, even given a known down-side risk.

The Regulation scenario examines whether the threat of regulation is a sufficient motivator to enhance trades. While the Regulation treatment has components mirroring what has been done previously, there are a few points of novelty in this treatment. In most public good games, participants are working towards a common goal in order to provide the public good generating benefit for the collective. In some cases, this can be progress towards avoiding a public bad wherein if a threshold is not met, the collective experiences negative profits due to not contributing enough. This treatment mirrors this threshold public bad set-up except that this experiment includes a market. The market provides a direct opportunity cost to voluntary abatement towards the threshold and, at the same time, it allows for firms to lower some of the costs of abatement through market activities. This experiment searches for evidence of both of these effects and addresses the question in this context: is avoiding regulation a strong motivator for voluntary abatement when participants have access to a pollution market?

Finally, these experiments allow farmers to voluntarily determine their own environmental impact (Ratio) and to voluntarily contribute to a threshold in order to avoid regulation (Regulation), both of which influence competitiveness within the pollution market. The key question then becomes: what are the comparative impacts on welfare outcomes under the institutional designs inherent in these experimental markets? Interest in participation in a water quality trading market is driven by economic concerns—is it profitable for PS and NPS? Yet regulation is driven by maximizing the benefit of pollution control. Does allowing for verification of the trading ratio or voluntary threat regulation actually benefit the environmental outcomes? Each of these welfare outcomes are explored given the institutional characteristics of each WQT market design.

4.4 Experimental Design and Procedures

The experiments were designed using the experimental software, z-Tree, developed by Fischbacher (1999). In all treatments, participants, in a six-person group, are first privately informed of their role: four are identified as farmers and two are identified as WWTP managers. Each treatment consists of 33 rounds, called years in the experiment, where the first three rounds are practice rounds (non-binding) and three games of ten rounds each are played subsequently to establish behaviors under review in this study. One of the games is chosen at random at the end of the experimental session to be the game that determines the take home earnings for participation, which are a sum of the yearly earnings over the ten round game. As participants do not know which game is going to be binding, it is in their best interest to maximize profits (game earnings) in all three games. Expected earnings average $20 but actual earnings are determined based on game performance (at a 100:1 exchange rate). In addition, each subject is given a $5 show-up fee. In the two-hour session, 30-45 minutes are dedicated to instructions and practice and the remainder of the time is spent in the experiment. Talking or sharing of roles or information is strictly prohibited among participants.

To add context to the experiment, participants are informed that they are all neighbors within a watershed with a goal of achieving a certain amount of pollution control (figure 4.2). Examples of the instructions for the WWTP participants are included as appendix 3. WWTPs are informed that they each contribute eight units of pollution to the watershed each year, while farmers are informed that they each contribute four units of pollution to the watershed each year. As such, pollution from PS is 16 units and from NPS is 16 units. Both have an opportunity to implement abatement for every unit of pollution in order to meet regulations (WWTPs), improve water quality (farmers), or generate credits (farmers). WWTPs have the same requirement in all treatments: to abate four units of pollution either through buying credits in the market or by automatically implementing the deficient abatement at the WWTP after the trading round. WWTPs are allowed to buy as many as eight credits from farmers but they are not allowed to choose to abate more of their own pollution as the program automatically implements their deficit abatement. Farmers have the opportunity to abate as many as four units of pollution each at increasing cost per unit of abatement (Farmer cost information sheets for each treatment is included in Appendix 4). The default trading ratio for all farmers is 2:1 such that two units of abatement is required to generate one credit to the WWTP. Farmers are the sellers of credits and WWTPs are the buyers of credits and no trading is allowed between participants in the same sector. This bilateral experimental design was chosen because under homogenous cost schedules within each sector, no intra-sectoral trading is predicted and allowing trading within one's own sector might serve to unnecessarily complicate the decision-making environment.

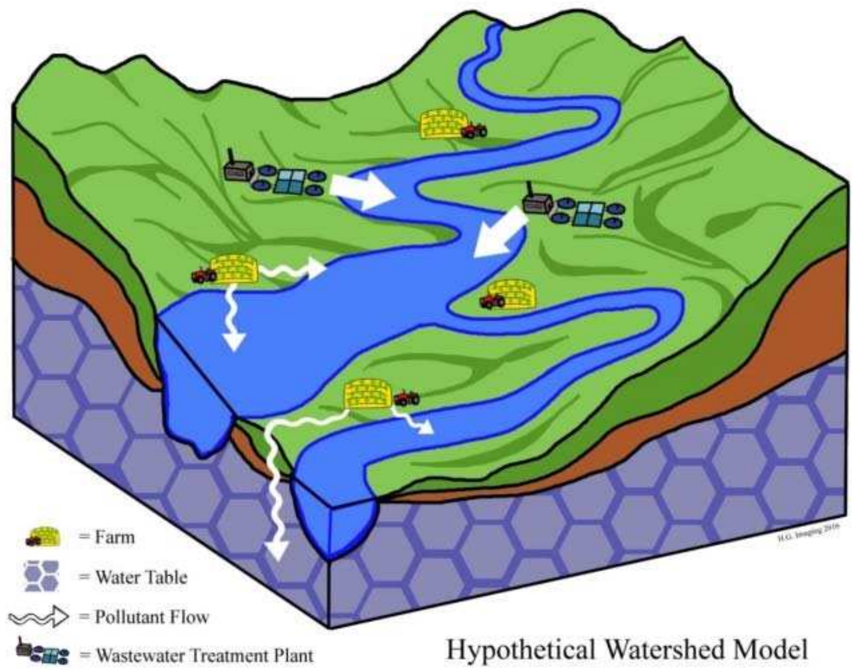

Figure 4.2: Fictitious Watershed Illustrating the Relationship between Sources and Pollution Contribution

This experiment features a baseline and credit market design, which means that the WWTP roles are given a regulation and can meet that regulation by paying for abatement at the firm or by buying credits to cover that pollution from those with the role of farmer (figure 4.3). The regulator defines how trades can take place between the two sources of pollution, including the rate at which NPS abatement can be exchanged for credits (the trading ratio). There are three treatments: the base treatment (Base), a trading ratio treatment (Ratio) and a NPS voluntary regulation treatment (Regulation). NPS face no mandatory regulation except if a threshold is not met in the Regulation treatment; however, there are rules in place in each treatment that define how NPS abatement translates to a credit. In Base and Regulation, there is a set ratio of two units of abatement at the farm for every one credit to sell in the market (2:1). As such, each farm may only sell up to two credits in these treatments as only four units of abatement are available for each farm.

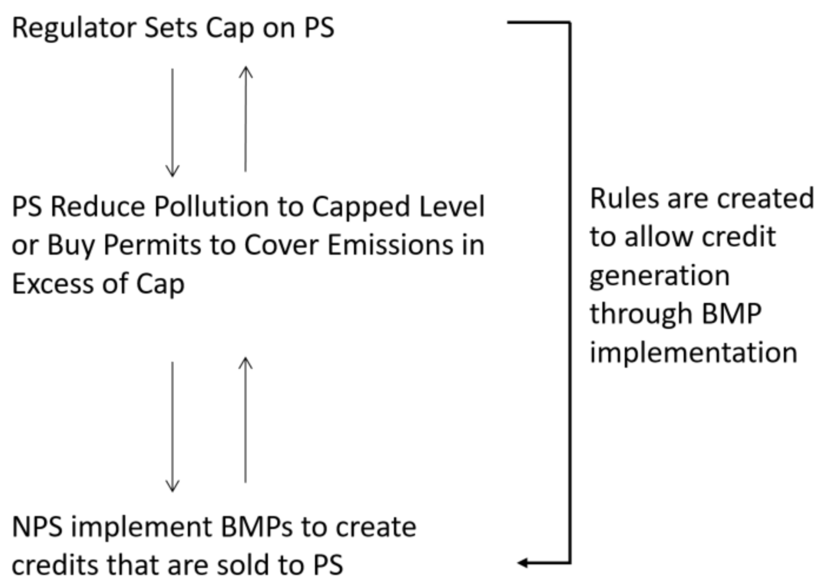

Figure 4.3: Diagram of Baseline and Credit Institutional Design

In Ratio, NPS may pay a one-time fee to “verify” their true trading ratio in each game. By default, NPS have a 2:1 trading ratio and there are three possible options for this ratio once verified (3:1, 2:1 and 1:1). Whichever ratio the WWTP is verified to have remains their trading ratio for the remainder of the game, resetting at the beginning of the next game (rounds 4, 14, and 24). If a farmer has a 1:1 ratio, they can sell as many as four credits. If a farmer has a 3:1 ratio, they can only sell one credit at most because partial credits are not allowed and they only have four units of pollution available. In each group, there are two farmers with a trading ratio of 1:1, one farmer with a 2:1 trading ratio, and the last farmer has a trading ratio of 3:1. As such, there is a 50% chance of getting an improved trading ratio (1:1), a 25% chance of keeping the default ratio (2:1), and a 25% chance of having a worse trading ratio (3:1) and participants are informed of this distribution.

In Regulation, NPS are informed of a voluntary regulation wherein as a group, they must contribute at least 28 units of voluntary abatement over seven years. If they fail to meet this threshold by the end of the seventh year (rounds 10, 20 and 30), there is an 80% chance they become regulated (this chance is independent each game and is based on a random number generator in z-Tree). As a newly regulated sector, trading halts and each NPS automatically is charged for two units of abatement for the remaining three rounds of the game. The pool of credits is reset each game so that voluntary contributions are not carried over between games. PS also have their required abatement implemented automatically as they have no other source of credits to meet their regulation during this regulatory stage. If NPS do not become regulated, either because they met the threshold or they did not become regulated by chance, then trading continues as per the first seven rounds and NPS are still asked to abate voluntarily.

4.4.1 Game Play Progression

Each round is played out in various stages according to figure 4.4. The first stage is information about the regulation each participant faces. In all treatments, WWTPs are informed that they must abate four units of pollution either by buying credits or implementing their own abatement according to their cost schedule (included as Appendix 5). In Base, farmers are informed that they are not regulated. In Ratio, farmers are allowed to verify their trading ratio by paying a cost of 50 (figure 4.5). If they choose to verify their ratio, instead of being asked if they would like to verify their ratio, they are reminded in this screen of what their verified ratio is for the remainder of the game. In Regulation, farmers observe information about their progress towards their voluntary regulation (figure 4.6). Once the Regulation treatment reaches year eight, farmers are informed in this stage about whether they as a sector have become regulated.

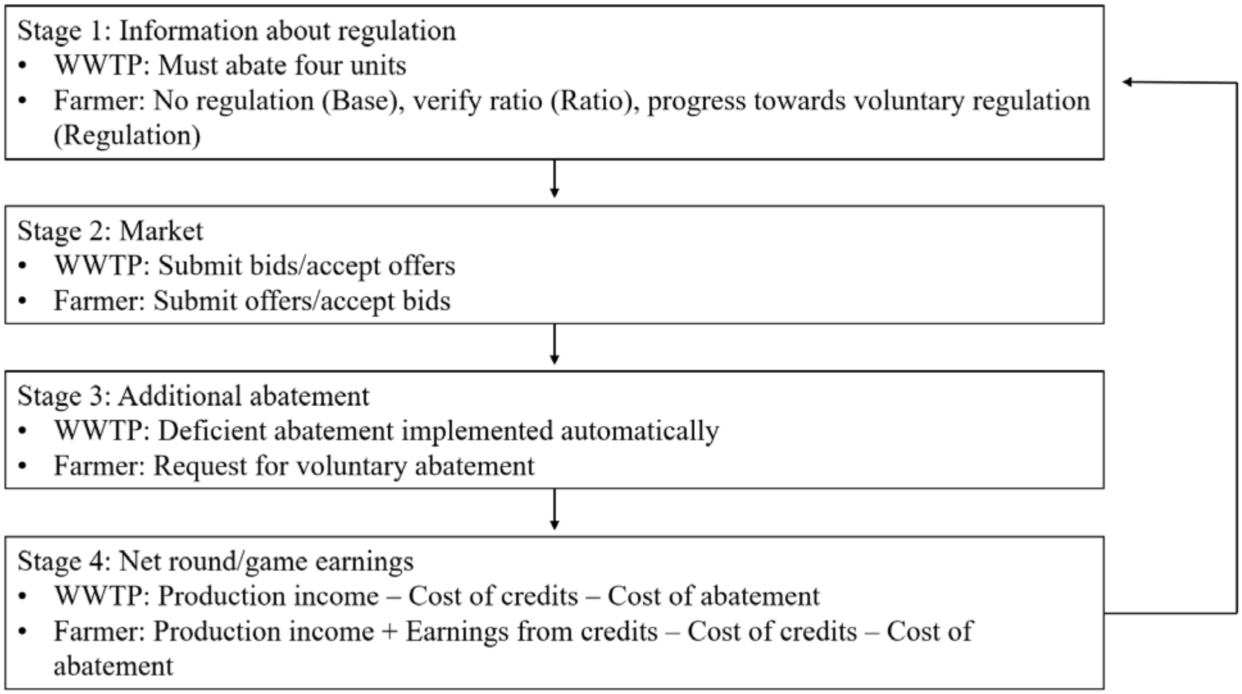

Figure 4.4: Game Progression within the Experiment

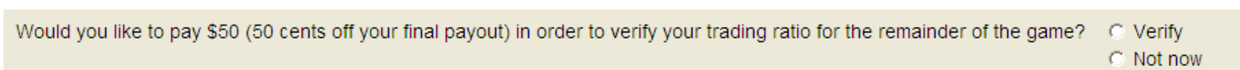

Figure 4.5: Screenshot of Trading Ratio Verification

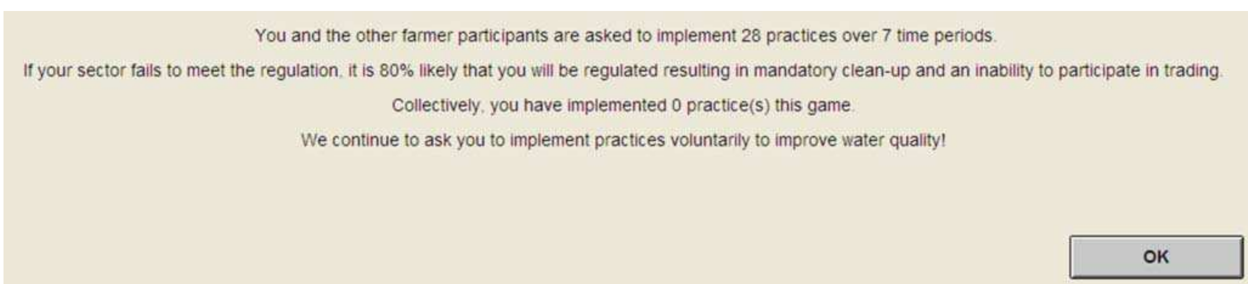

Figure 4.6: Screenshot of Progress towards Regulation

The market (stage 2) depends on the participant's role. As farmers are only sellers of credits, they are only allowed to make sell offers or accept bids. If the farmers collectively become regulated in Regulation, then all participants are informed that the agricultural sector did not meet its regulatory requirements and thus trading is no longer permitted (stage 2 is skipped for all participants). As buyers of credits in all treatments, WWTPs can make bids to buy credits or accept seller offers (a screen shot of the WWTPs market is in figure 4.7). These bids and offers are constantly updated as they are accepted (meaning they leave the list) and as more are made so that a participant is not allowed to sell (or buy) more than one credit at a time. If a farmer (WWTP) makes a better offer (bid) then the previous offer (bid) is removed so that a participant is not stuck with selling or buying more credits than they intended. Additionally, once a participant accepts a bid (or offer), all previous offers (or bids) from that participant are removed, again to remove the potential to buy or sell more credits than intended. The market was programmed in this way so that firms were unable to buy or sell credits unintentionally or at prices that they would not prefer. Bids (offers) are also ordered in the market so that the most appealing bid (offer) is the first available which allows for competition among participants and conversion to a stable equilibrium price. Trading rounds are confined to 90 second time periods. In the practice rounds, more time is given as the game is paused to allow for participants to try the software without time constraints. Within the market stage, participants are also informed of their ongoing profits including their production income, number of credits purchased (sold), the cost of credits (credit earnings) and the cost of pollution control (for farmer's only as WWTPs are not informed of their cost of additional practices until the next screen).

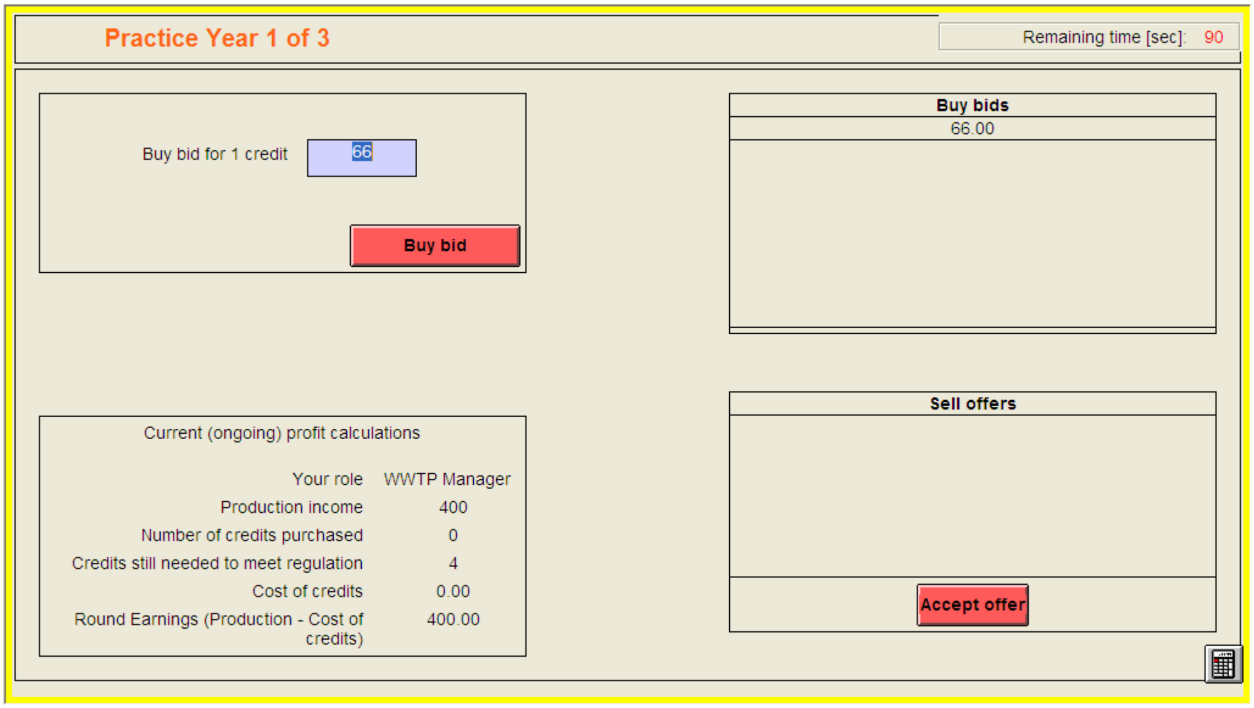

Figure 4.7: Market Screen Example for a WWTP

After trading, participants enter stage 3 wherein WWTPs are informed about how many units of abatement are being implemented, which shows the deficit of their regulation and their number of credits purchased. Farmers are asked during this stage to abate voluntarily to improve water quality as shown in figure 4.8. In Regulation, farmers are additionally reminded that voluntary abatement contributes to their sectoral threshold (figure 4.9). Farmers are informed, through additional information on their cost sheet (appendix 4), that this threshold would be met if each farmer implemented one practice voluntarily in each round towards the threshold. Farmers are also informed that they will be equally as well off if all farmers contribute and meet the threshold as they would be if they did not contribute to the threshold at all. Abatement implemented to generate credits in the market does not count towards this threshold.

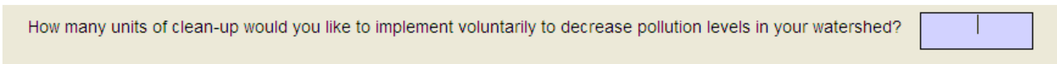

Figure 4.8: Farmer Voluntary Abatement Screen

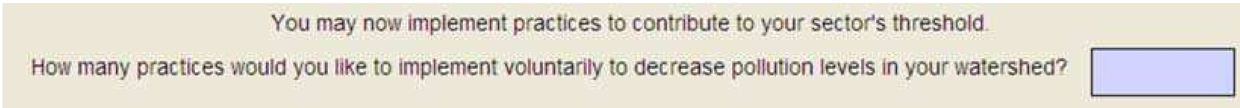

Figure 4.9: Voluntary Abatement for Regulation

In the last stage all participants are informed of their round earnings and their cumulative game earnings. Round earnings for a WWTP and farmers follow equations 4.1 and 4.2 (respectively). Firms earn production income (the same in every game and based on the type of participant with WWTPs earning double the income as farmers), which is spent on credit purchases (WWTPs) and credit generation (farmers) and on additional abatement, which is mandatory for WWTPs and voluntary for farmers. Farmers additionally earn money from the sale of credits. Cumulative game earnings are the sum of earnings in each of the ten rounds of each game as follows:

$$\text{WWTP Profit}_{i,t} = \text{production income}_t - \text{cost of credits}_{i,t} - \text{automatic abatement}_{i,t} \qquad 4.1$$

$$\text{Farmer Profit}_{i,t} = \text{production income}_t + \text{credit earnings}_{i,t} - \text{cost of abatement}_{i,t} \qquad 4.2$$

4.4.2 Experimental Parameters and Expectations

Each participant earns money each round from "production" that they can use to buy credits (WWTPs) or to implement abatement on site. WWTPs earn \$400/year in production income and farmers earn \$200/year in production income. The marginal abatement cost (MAC) function for farmers follows equation 4.3 and the MAC function for WWTPs follows equation 4.4, with a as abatement. If a WWTP were to implement one unit of abatement for example, the costs would be $1^2 + 50 = 51$. However, no costs are incurred if no abatement takes place. The cost schedule for farmers is included in table 4.1 and for WWTPs in table 4.2. In the trading ratio treatment, farmers have the same cost schedule but their costs reflected the amount incurred for credit generation under each possible trading ratio (table 4.3). The costs do not reflect abatement costs based on empirical information, but are convenient functional forms that enable trading to take place and generally reflect higher MAC for WWTP at low abatement levels.

$$MAC_{Farm} = a^3 + 10 \text{ with } TC = 0 \text{ if } a = 0 \quad (4.3)$$

$$MAC_{WWTP} = a^2 + 50 \text{ with } TC = 0 \text{ if } a = 0 \quad (4.4)$$

Table 4.1: Farmer Cost Schedule

Practices	Per-Unit Cost of Clean-up	# of Credits	Total Cost of Practices
1	11	--	11
2	18	1	11 + 18 = 29
3	37	--	11 + 18 + 37 = 66
4	74	2	11 + 18 + 37 + 74 = 140

Table 4.2: WWTP Cost Schedule

Number of Practices	Per-Unit Cost of Practices	Total Cost of Practices
1	51	51
2	54	51 + 54 = 105
3	59	51 + 54 + 59 = 164
4	66	51 + 54 + 59 + 66 = 230

Table 4.3: Farmer Cost Schedule in Ratio Treatment

Practices	Per-Unit Cost of Practices	Total cost of practices	Credit (1:1)	Cost per credit (1:1)	Credit (2:1)	Cost per credit (2:1)	Credit (3:1)	Cost per credit (3:1)
1	11	11	1	11	--	--	--	--
2	18	11+18 = 29	2	18	1	29	--	--
3	37	11+18+37 = 66	3	37	--	--	1	66
4	74	11+18+37+ 74 = 140	4	74	2	111	--	--

At a 2:1 default trading ratio and with only four units of pollution, each farmer is constrained to only two credits being physically possible to trade each year. From an individual profit maximization standpoint, farmers in Base and Regulation treatments are expected to sell one credit each during every market period. WWTPs are expected to purchase two credits each—two farmers supply one credit each to each WWTP. Figure 4.10 is a graphical illustration of this theoretical market, cost to supply and willingness to pay, based on the parameters chosen for this experiment. The fifth market credit comes at a cumulative cost of $227 (a marginal cost of $111) but with a willingness to pay of only $213 (a marginal benefit of 59). As such, if the fifth credit is sold, it is at a loss in welfare from the buyer. Beyond four credits, it is cost minimizing for the WWTP to implement practices at their own cost.

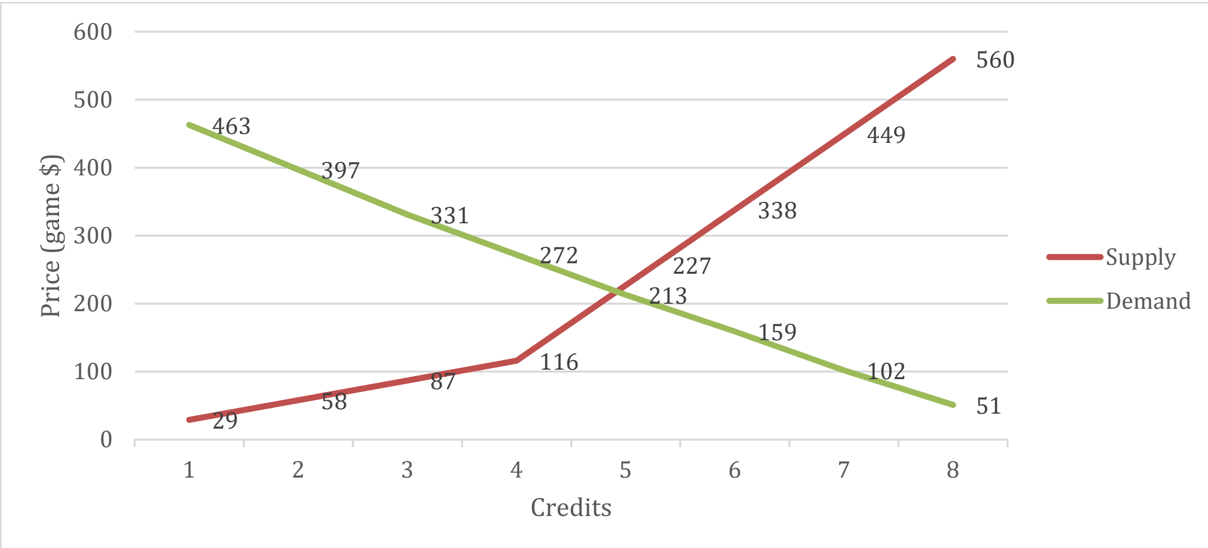

Figure 4.10: Water Quality Trading Market Supply and Demand Curves

In Ratio, it is expected that prices will be lower as the range of acceptable prices falls between $11, the lowest farmer marginal cost with a 1:1 trading ratio, and $66. Under reasonable prices, an equilibrium quantity of six credits is expected to be transacted (figure 4.11). Farms with a 1:1 trading ratio would sell between two and three credits each (as many as two farmers could have a 1:1 ratio), the farmer with a 2:1 trading ratio should still be able to sell one, although at lower expected prices than in the base treatment as this farmer is competing with lower price competitors with a 1:1 trading ratio, and the 3:1 ratio would be priced out of the market with a willingness to accept equal to the maximum marginal willingness to pay of the WWTP ($66). It is not expected that more than eight credits would be purchased as there is only a demand for eight (four per WWTP) although it is still allowed in the programming of the game with eight credits as the maximum allowable credit purchases.

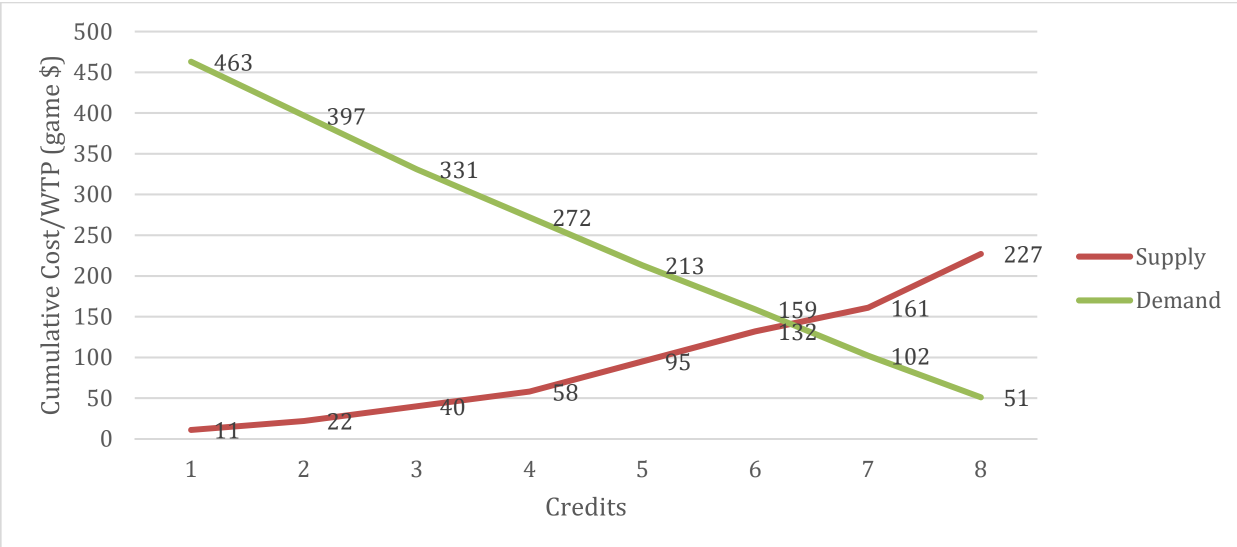

Figure 4.11: Water Quality Trading Market Supply and Demand Curves for Ratio Treatment

In the Base and Regulation treatments, prices are expected to be between the lowest marginal cost, $29, and the maximum marginal benefit, $66. In Ratio, the prices are expected to be between the lowest marginal cost $11 and the maximum marginal benefit, $66. Although it is possible for Ratio prices to be roughly equivalent to those in Regulation and Base, since farmers are only aware of their own cost schedule and not of that of the WWTPs, it is likely that initial offers would be lower in this Ratio treatment leading to overall lower trading prices so long as participants verify a 1:1 trading ratio early on in the game. If verification is delayed by participants, a 1:1 ratio is not revealed early on in the game, or if the market is driven by bids rather than offers, prices are expected to be higher.

Given the expected trading prices and volume, expected earnings in each year are approximately 200 game dollars ($2), which summed over ten rounds results in expected earnings of $20 per participant. If no trading took place, farmers would earn exactly 200 game dollars per year and WWTPs would earn 170 per year. However, if trading did take place with a mean trading price of 41/credit, farmers could earn 212/year and WWTPs would earn 213/year. Credit prices below 41 result in proportionally higher profits for WWTPs whereas credit prices above 41 favor farmers.

4.5 Data Collection

In July 2016, experiments were conducted in Fort Collins, Colorado on campus at Colorado State University. Table 4.4 has some summary information about the participants of the study. Recruitment was largely within the CSU campus and there were five groups of six participants who were given the Base and Regulation treatments whereas only four groups of six were given the ratio treatment. The sample of 84 participants were well-educated individuals with 80% of respondents having an undergraduate degree or higher. The fields of study for participants varied with social science (economists and sociologists primarily) being the largest single group followed by engineering students (~30% each) (figure 4.12). The average age of the participants was 30 years. Additionally, 82% of the sample was white and 83% were students at the time of the study. 87% said that they were knowledgeable about pollution and 64% indicated that they use water recreational resources at least once a month (figure 4.13). While this sample is likely representative of Fort Collins, it is not necessarily representative of all of Colorado and certainly not of the U.S. overall.

Table 4.4: Demographic Characteristics of Experiment Participants

Participants	84; Base: 30, Regulation: 30, Ratio: 24
Gender	Male: 48, Female: 35, Unspecified: 1
Ethnicity	Caucasian: 69, Non-Caucasian or unspecified: 15
Age	Mean: 29.65, standard error: 1.28
Education	Post Doctorate: 5, Master's degree: 47, Bachelor's degree: 20, Some undergraduate study: 17
Student	Student: 70; Non-student: 14
Knowledgeable about pollution (self-identified)	Yes: 73; No: 11
Risk Preference (self-identified)	Risk averse: 21; Risk neutral: 42; Risk loving: 21

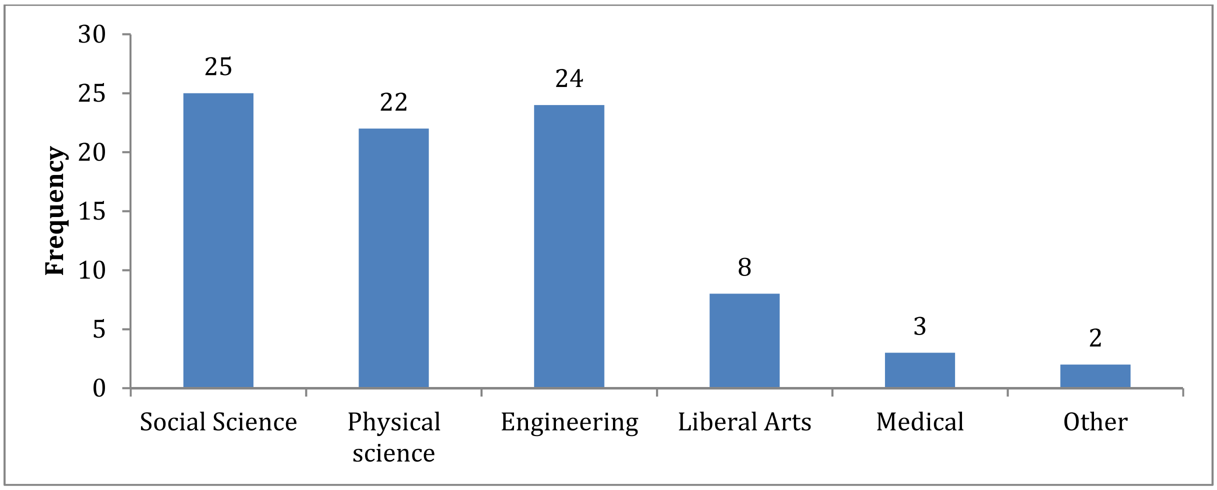

Figure 4.12: Field of Study of Experiment Participants

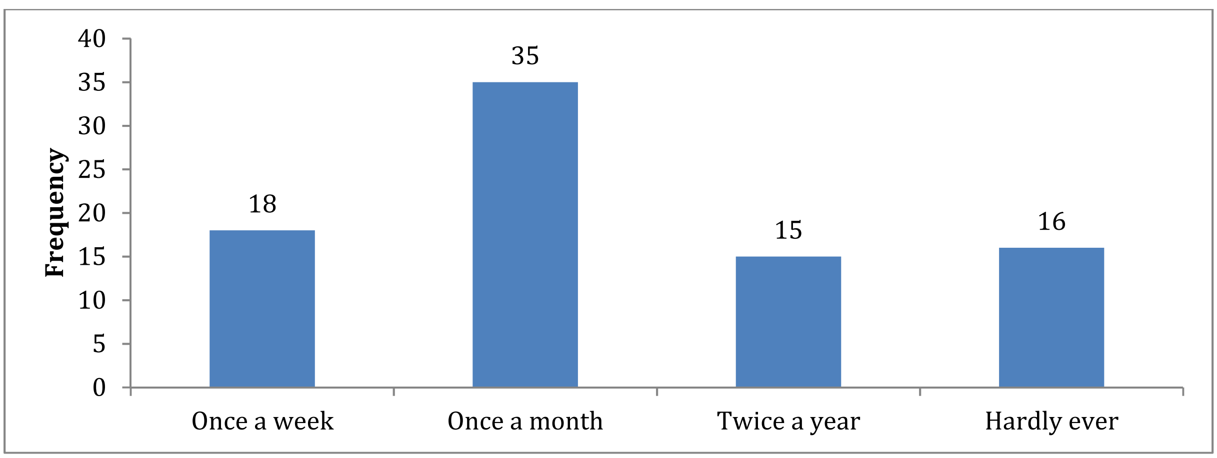

Figure 4.13: Frequency of Use of Water Resources Recreationally

4.6 Results

The results section is broken down by each of the three main research questions. The primary result for the first question is that people are willing to verify their trading ratio even if it comes with a fixed cost and financial risks in the environmental market. Participants verified their ratio 94% of the time. With regard to the second question, threat of regulation with uncertainty does not motivate sufficient abatement to avoid regulation as only one group out of five was able to meet the threshold (and only two out of the three times). However, participants did implement more practices voluntarily in Regulation compared to Base and Ratio (although a non-zero amount of voluntary abatement took place in all treatments). This implies that a voluntary threat induces greater abatement even if it is not sufficient to meet a given threshold. Econometric models also show that there are synergistic qualities between the WQT market and voluntary abatement meaning that the two policies could be used in tandem to achieve greater amounts of abatement. Finally, with regard to the third question, more precise trading ratios and voluntary regulations do impact welfare outcomes. When firms were allowed to trade more credits via more favorable trading ratios, all participants (PS and NPS) earned greater profits. However, increased abatement resulted in significantly lower profits for the Regulation treatment. Environmental outcomes were better in the Regulation treatment compared to the other two treatments, followed by Ratio. This result is driven by mandatory abatement in Regulation and more efficient trading in Ratio.

4.6.1 Are Participants Willing to Verify their Trading Ratio at a Given Cost?

In Ratio, farmers have an opportunity to verify their "true" trading ratio at any point throughout the game. If a farmer decides against verifying their ratio, their ratio remains at the default 2:1 ratio for the entirety of the game. Once verified, the revealed trading ratio is the new rate at which farmers can exchange abatement for credits for the remainder of the game. A farmer has no way of knowing whether the verified ratio will improve his financial situation or make it worse although the expected value is a slight improvement over the status quo (the expected value for the ratio is 1.75:1 compared to the default ratio of 2:1). Roughly half (58%) of the farmer participants in this treatment verified their ratio immediately (in the first round of each game). The rationale for this behavior could be that they can immediately start benefiting from an improved trading ratio and thus earn back the 50 cent investment over 10 full rounds.

Of those who did not verify their ratio immediately (only 42% of participants), there were three other options available to them: they could verify in period 2 (15% of remaining participants), wait to verify even later than period 2 (70% of remaining participants), or not verify their ratio ever in the game (15% of remaining participants). There were only three games wherein a participant never verified their ratio (out of 48 possible). Two of the three instances were the same person. Given that 70% of those who did not verify immediately eventually did verify, the question then is what would cause this behavior? One explanation is that they were waiting to observe market activity (prices and credits sold) before verifying. For example, if one observes high prices, it might be discerned that someone else has verified high trading ratios and therefore verification is a relatively "safe" investment. Figure 4.14 is a break-down of the verification behavior observed in the game for those who did not verify their ratio immediately—recall this was the remaining 42% of participants. Market prices in all of these games were higher than expected with most prices being in the favor of farmers (over $42). A similar percent of participants verified eventually regardless of the market signals. More experiments will need to be done in order to really tease out whether market activities influenced verification behavior.

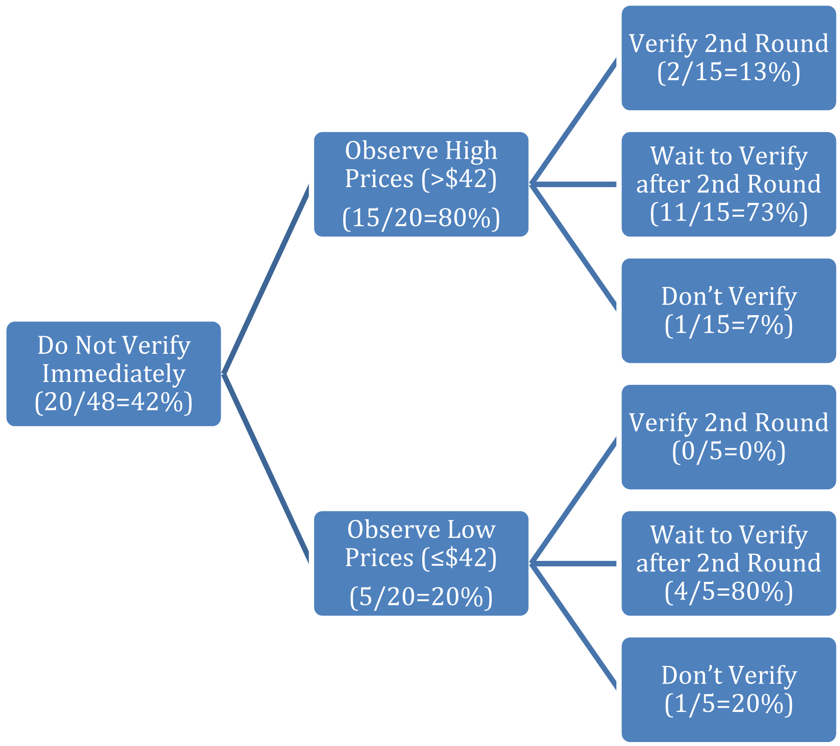

Figure 4.14: Strategic Behavior Regarding Following in Verification

Overall, most participants did eventually verify their trading ratio at some point in the game. There is (limited) empirical evidence that participants did take the option to verify the trading ratio even if it was not a good economic decision (at low market prices for example). These observations suggest that there is promise for integrating verification of environmental impact into a WQT market as firms, at least under the parameters of this experiment, were willing to undertake a cost to find out their environmental impact under the knowledge that it could hurt (or help) them in the pollution market.

4.6.2 Is Avoiding Regulation a Good Motivator for Voluntary Pollution Control?

The Regulation treatment asks farmers to implement 28 voluntary practices by the end of the seventh round to avoid regulation, otherwise they would have an 80% chance of becoming regulated. The threshold was only met in two out of fifteen games in this treatment. The threshold was met by the same group in both instances. Figure 4.15 is a graph of the cumulative abatement by all groups in Regulation in the first, second and third game[4]. The dashed line represents the cumulative threshold requirement. "Group 5" was the only group to meet the regulation in that first game although "Group 1" came within one unit of abatement of reaching the threshold. In the second game, no groups were able to meet the threshold, then by the third game, "Group 5" was able to meet the threshold again. Interestingly, "Group 1" also continued to contribute to the threshold although not in high enough levels to avoid regulation in the second and third game (reaching 10-11 units respectively). One participant in this group continued to abate voluntarily while the other farmer participants contributed very little after game 1. No participants in Groups 2-4 contribute much to the threshold after game 1.

[4] The last game only has 9 rounds due to an error in data download from z-tree. It does not matter in this situation though as they must meet the threshold by the 7th round in order to avoid regulation with certainty.

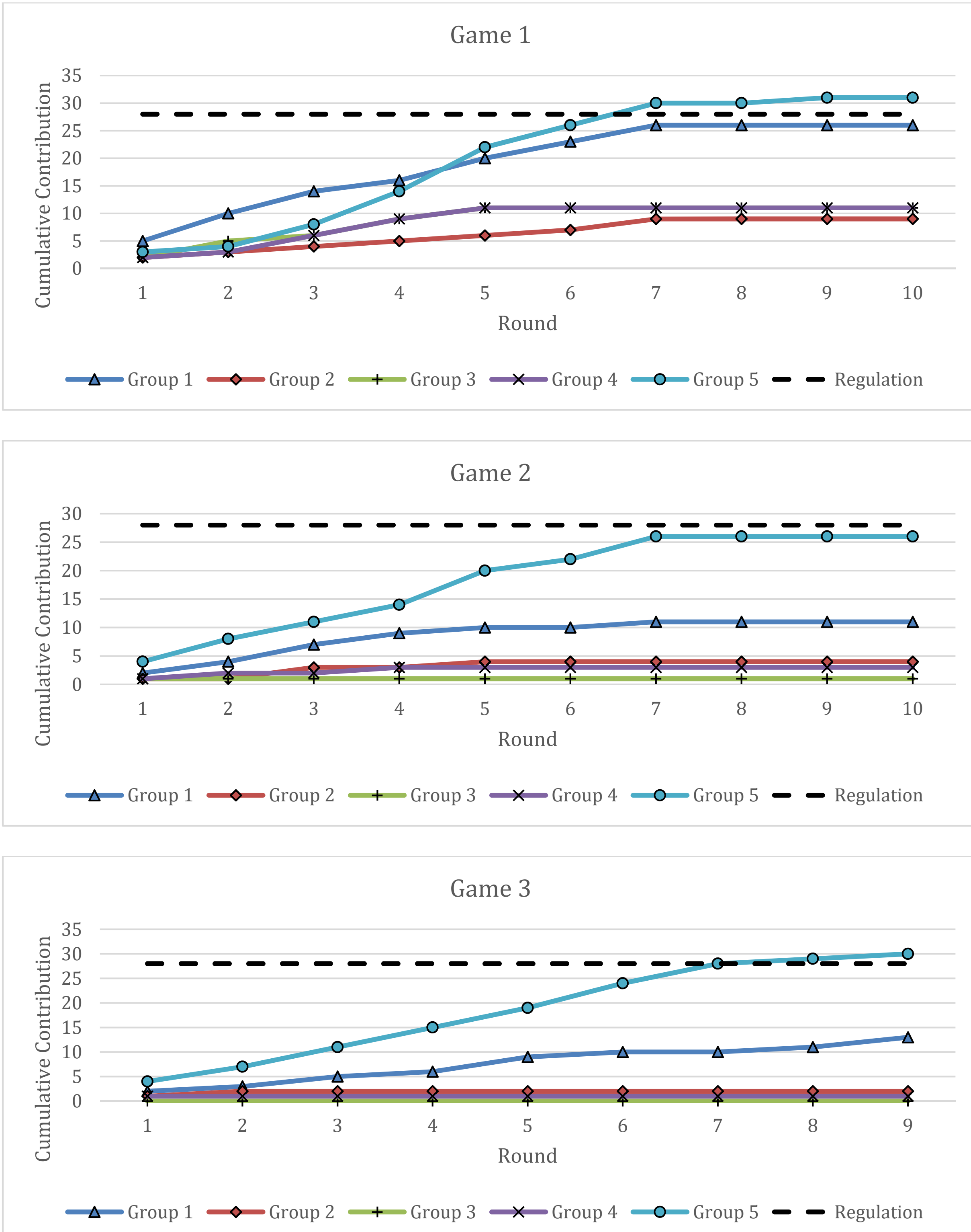

Figure 4.15: Cumulative Voluntary Abatement in Regulation Treatment

Figure 4.16 shows summed costs of voluntary abatement by treatment in each round excluding practice rounds (rounds 4-13 are game 1, rounds 14-23 are game 2, and rounds 24-32 are game 3). In Base and Ratio, farmers primarily implemented practices if they did not sell any credits in the market, meaning they could implement voluntary practices for only $11 (or $18 with a 1:1 trading ratio having sold only one credit at the market). In Regulation, most abatement was additional to market participation and thus more expensive at $37 (the cost of the 3rd practice).

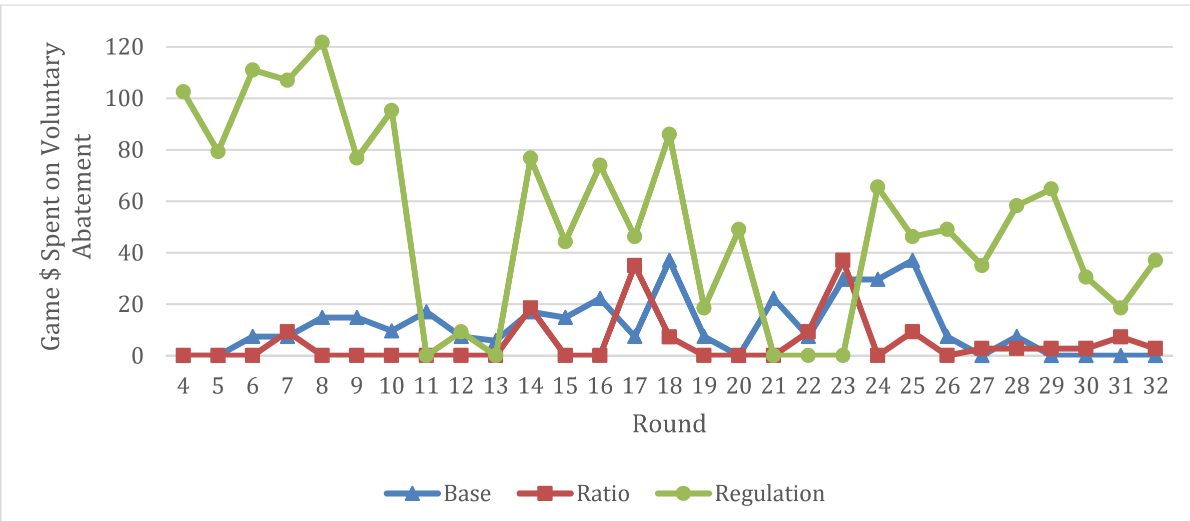

Figure 4.16: Comparison of Per-Period Cost of Voluntary Abatement Across Treatments

The data suggest that avoiding regulation is a good motivator for pollution control. More abatement was taken, and at a greater cost in Regulation compared to Ratio and Threshold. That being said, the threshold itself was only met in a minimal number of cases and abatement tended to drop off after the first game as participants in Regulation became discouraged. There is not as steep a decline in abatement in Ratio and Base in later games.

In order to explore further what motivates voluntary abatement with the presence of a pollution market, figure 4.17 shows that voluntary abatement (abatement in addition to credit generation) occurs in all treatments but there appears to be more abatement in the Regulation treatment (in non-regulated periods) (figure 4.17). There is a marked decrease over time in voluntary abatement in the Regulation treatment after the first game; nevertheless, voluntary abatement still does occur at higher levels for this treatment compared to others except during regulated rounds (where abatement is not voluntary).

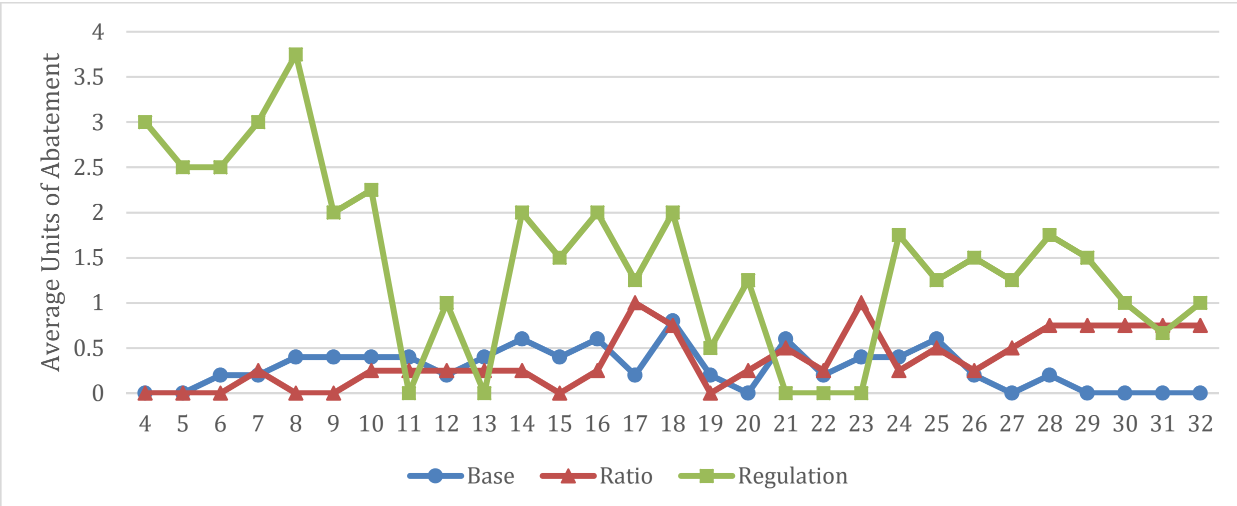

Figure 4.17: Additional Practices Implemented Over Time by Treatment

In order to determine if voluntary abatement was statistically significant for these treatments, table 4.5 contains the results of an aggregate pooled ordinary least squares model with cluster robust standard errors. It regresses the total number of voluntary practices implemented in each time period for each unique group of participants on treatment (Base is constant, Ratio, and Regulation). One can interpret the coefficient as the additional (or deficit if the coefficient is negative) number of practices expected to be implemented within a particular group. This model shows that participants implement practices voluntarily in all treatments (as the constant is significant at the 10% level) and they implement more practices in the Regulation treatment (1.2 practices more per group compared to Base). Voluntary abatement in the Ratio treatments is not significantly different compared to Base. Overall, the model lacks significance with an F-stat less than the critical value at a 90% level of confidence.

Table 4.5: Model 1: Pooled Aggregate Ordinary Least Squares Model for Voluntary Abatement

Variable: Voluntary Abatement	Pooled OLS (with cluster robust standard errors)
Base (constant)	0.275** (0.11)
Ratio	0.095 (0.23)
Regulation	1.294** (0.55)
Observations	375
Model Significance	F(4,13): 2.73 (p-value: 0.1020)
R squared	0.2285
**Indicates significant at a p-value of 0.05	

The models in table 4.6 explore how an individual's characteristics and market activity affect voluntary abatement. Each of these models uses a subset of the full panel with 84 individuals and 29-30 time periods (missing the last round of the last game of a few groups due to a data storage error). As WWTPs are not given an opportunity to implement additional abatement voluntarily, they are removed from this analysis (28 individuals). Additionally, one participant in the Ratio treatment was able to abate without being charged for this abatement due to an error in the z-Tree code. As this participant was not getting accurate information about the impact of their voluntary abatement on their own profit, this individual is removed from the data set leaving 55 individuals (and total observations of 1540).

Model estimation techniques must take into account that although the panel data may differ across time, they are likely not independent draws of the events and a relationship may exist based on previous experiences as well as personal characteristics of the individual. Three of the most common econometric models for panel data are the Pooled OLS Model, a Fixed Effects model and a Random Effects Model.[5] The key difference between these lies in the assumptions about how the individual specific error term is distributed. In order for the coefficients of any

[5] A non-linear equicorrelated probit model is also available upon request. This model has a similar significance to other models and the same regressors are significant; however, interpretation of the marginal effects of the coefficients is much different and might confuse the exposition presented in this paper.

econometric model to provide consistent estimates of their true population parameters, they must remain constant and have an expected value of zero and a variance of σ^2. This may be a lofty assumption because other literature on conservation behavior suggests that characteristics of the individual does have an impact on conservation behavior in a real world setting. If the individual has characteristics that make them more likely to be a conservationist, then the error term would be correlated over the rounds based on the individual effects

The Pooled OLS model averages the variables of interest across the population and uses cluster-robust standard errors that cluster on the individual, overcoming any problems with the error term being correlated with the regressors. A Random Effects (RE) model is the individual effects model which is able to capture how an individual's characteristics, which do not change throughout time, influence the economic phenomena at hand, capturing the remaining error that is correlated with the individual. The assumption for the RE model to be consistent and efficient is that it must be the appropriate model in that we do think the individual characteristics matter and that the error term (which is a composite of the error associated with the individual and the other unexplained heterogeneity in the model) is uncorrelated with the regressors. A Hausman test concluded that individual effects were correlated with the error term making a RE model inappropriate (the chi-square statistic was -552.68 and thus the null hypothesis that individual effects were random was rejected) (Cameron and Trivedi 2010). If the error is correlated with the regressors, as was concluded in this case, a Fixed Effects (FE) model is appropriate. This model is robust and uses the method of least squares to estimate the regressors that are time variant leaving out the problematic time-invariant individual characteristics as parameters and instead including the individual effects into a unique intercept for each individual. The downfall of this model is that we cannot discern the impacts of different individual characteristics (such as gender versus identification as being an environmentalist) on voluntary abatement as we could in the RE model.

Table 4.6: Econometric Models for Voluntary Abatement

Variable: Voluntary Abatement	Model 2: Pooled OLS	Model 3: Random Effects	Model 4: Fixed Effects
	0.447***	0.447***	0.230***
Lagged Quantity	(0.05)	(0.02)	(0.03)
	-0.105**	-0.105**	-0.289***
Credits	(0.04)	(0.05)	(0.06)
	0.001	0.001	0.003***
Money	(0.00)	(0.00)	(0.00)
	-0.003**	-0.002**	-0.004***
Period	(0.00)	(0.00)	(0.00)
	-0.068	0.068	
Ratio	(0.07)	(0.05)	--
	0.083	0.083*	
Regulation	(0.07)	(0.04)	--
	-0.068	-0.067**	
Environmental Issues	(0.06)	(0.03)	--
	0.009	0.009	
Gender	(0.03)	(0.02)	--
	0.07**	0.070**	0.142***
Ratio*Credits	(0.03)	(0.03)	(0.04)
	0.024	0.024	0.073*
Regulation*Credits	(0.05)	(0.04)	(0.042)
	0.221***	0.221***	0.240***
Constant	(0.07)	(0.05)	(0.03)
Individual effects			0.194
Observations	1540	1540	1540
Model Significance	F(10): 15.10***	Wald chi2(10): 572.31***	F(6): 20.95***
R squared	0.272	0.272	0.198

***Indicates significant at a p-value of 0.01
**Indicates significant at a p-value of 0.05
*Indicates significant at a p-value of 0.10

In all models described above, the dependent variable is voluntary abatement. These were the additional pollution control farmers were asked to voluntarily implement at the end of each trading round. This comes at a direct cost to a farmer with no benefit with the exception of the regulation treatment wherein voluntary abatement accumulated towards a pool with a known probability of regulation if this pool did not reach the specified size. These models regress the number of voluntary practices implemented by each individual in each round on lagged voluntary practice implementation, market variables (time and individual variant) and demographic attributes of the individuals (time invariant). As all of these models are linear, coefficients for the Pooled OLS, RE and FE models can be interpreted as expected additional abatement undertaken by an individual given the presence of one more unit of the regressor. For example, if someone implemented discrete voluntary abatement in the previous time period (Lagged Quantity), that person would be expected to continue implementing more abatement (0.45 more units to be exact in models 2 and 3 and 0.23 more units in model 4). In all cases, this variable is significant at the 1% level implying that those who implement practices tend to continue doing so over time.

The market activity regressors do have some impact as well on voluntary abatement. In all models, the number of credits you sell is detrimental to the number of additional practices you implement voluntarily. This is intuitive because if you sold two credits in the market, you do not have any additional pollution that you can voluntarily abate. Money earned from the sale of credits was not significant in the Pooled OLS and Random effects model but it was significant at the 1% level in the fixed effect model. It stands to reason that a participant would make similar offers over time and thus make a similar amount of money each round. Generally, the wealthier participants can afford to spend a little bit more on voluntary abatement. We observe a similar phenomena in the Ratio*Credits variable, which is an interaction variable multiplying the binary value for being in the ratio treatment by the number of credits traded. As Ratio participants were able to sell more credits, they had more money to spend on credits in addition to more units of abatement left to implement voluntarily. The same market interaction term for Regulation

(Regulation*Credits) was only significant in the FE model at the 10% level. At a constant 2:1 trading ratio, they had less opportunity for the market to have synergistic qualities with voluntary abatement.

Individual characteristics were largely insignificant in the econometric models. It would seem that knowledge about environmental issues may decrease abatement at a very marginal rate. Other studies have found that those knowledgeable about environmental issues tend to be better environmental stewards (Knowler and Bradshaw 2007). Similarly, gender does not play a large impact on abatement decisions and it not statistically different from zero in the Pooled OLS or RE models while previous research suggests that gender may influence conservation behavior. It may be that the sample is too homogeneous to pick up this behavior.

Finally, these econometric models support earlier evidence that voluntary abatement occurs even in the presence of a pollution market. In fact, there seem to be some synergistic impacts of the market with voluntary abatement when firms are implementing their trading ratios. These econometric models also support the argument that those who are contributing to pollution control (in Regulation and otherwise) tend to continue doing so. The estimated impacts of the Regulation on abatement is mixed in the models. Generally speaking, it increases abatement although that impact is only significant at the 10% level in the RE model and in the FE model (as the interaction term Regulation*Credits). This lends evidence that improving market efficiency could improve voluntary control more consistently than a voluntary threat regulation.

4.6.3 The Impacts of Resolving Uncertainty on Pollution Markets and Welfare Outcomes

In order to explore the welfare impacts of institutional design on the pollution credit markets, prices, credits transacted and profits were averaged for each round and then averaged by treatment. Figures 4.18 – 4.20 display these market outcomes for each treatment. Credits transacted (Figure 4.18) vary between 3 and 5.5 credits on average for the Base and Regulation treatments, which is pretty close to our expectation. Over time the credits transacted becomes very close to the expected quantity of 4. Ratio stays fairly close the expected 6-7 credits although there is an unexplained jump in transactions for the end of the second game for those groups (rounds 21-23). There seems to be some evidence for anchoring prices (as we would expect with a double auction format). Prices are much less volatile for all treatments (Figure 4.19)with prices remaining consistently within expectation and constant over time. Prices tend to favor farmers more than WWTPs as prices are generally above $42/credit implying farmers have greater surplus than WWTPs. Ratio experienced higher prices due to a higher volume of trades and thus more welfare for all participants (Figure 4.20). However, profits had greater variation in Ratio and Regulation than profits in the Base. As such, it should be noted that these institutional design changes may increase volatility in WQT markets.

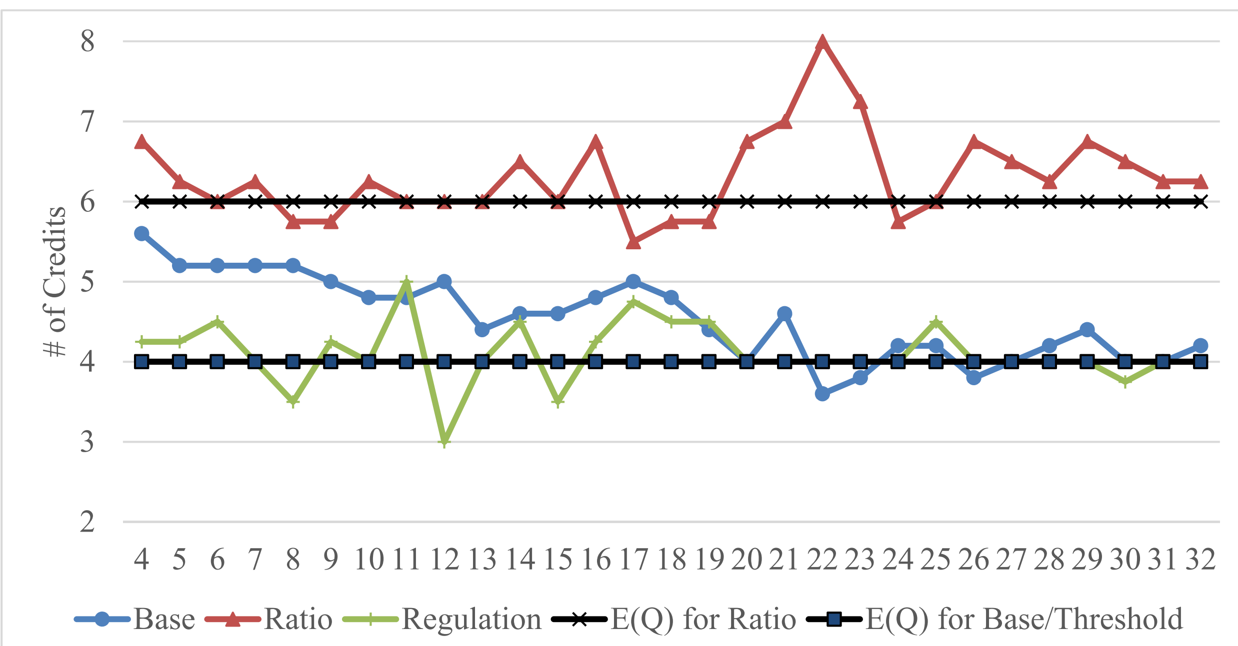

Figure 4.18: Average Number of Credits Traded Over Time by Treatment

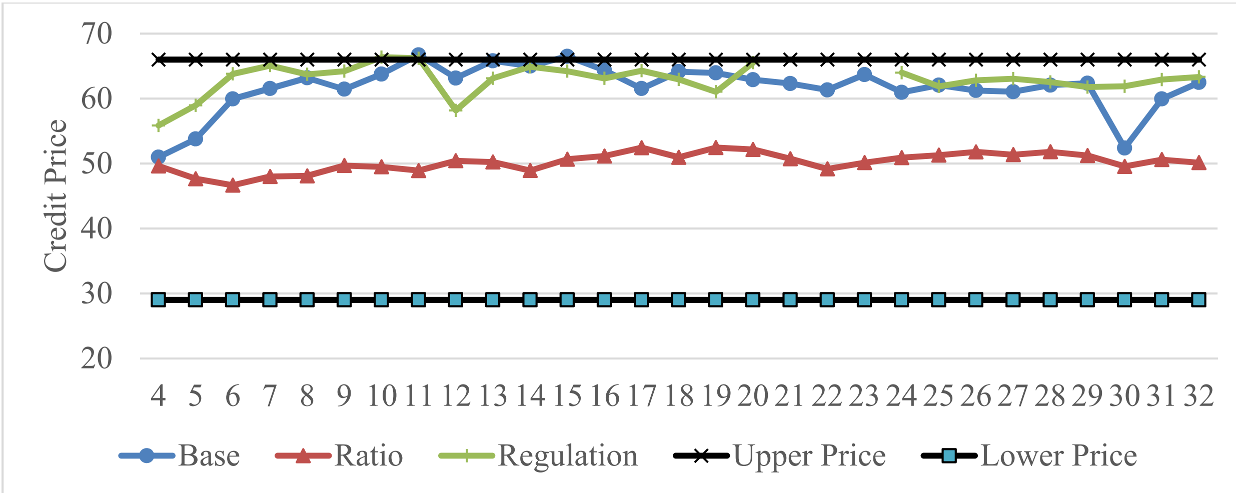

Figure 4.19: Average Trading Price Over Time by Treatment

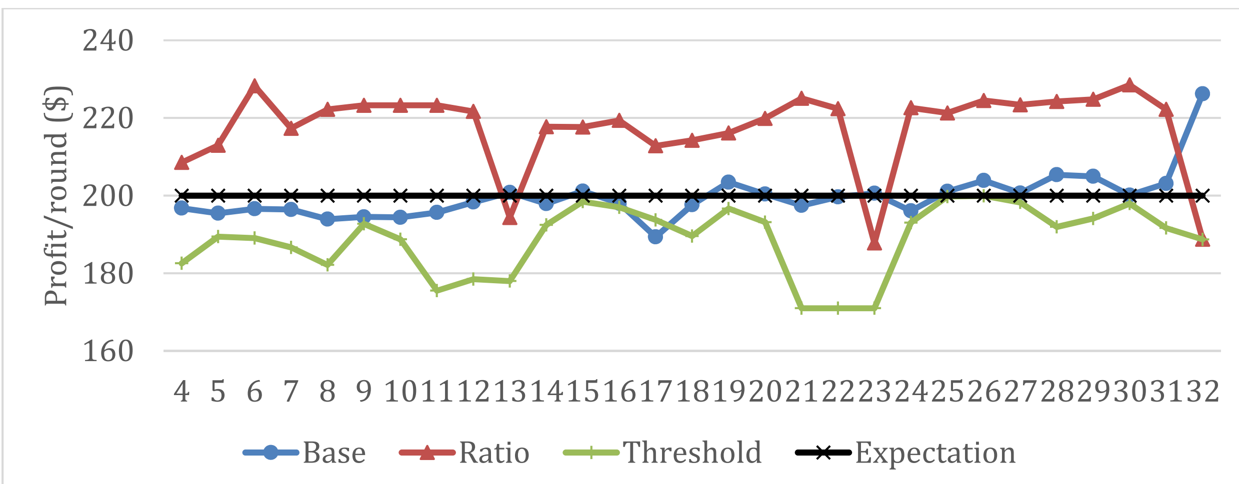

Figure 4.20: Average Profits/Round Over Time by Treatment

In addition to the graphical analysis, pooled regressions were used to determine the statistical difference in these outcomes across treatments (Table 4.7). The average credit prices, quantity transacted and profits served as the dependent variables in pooled regression models with a binary variable for Ratio and Regulation as regressors. This implies the base treatment is captured by the constant in these respective models. Model 5 is the quantity transacted Aggregate Pooled Ordinary Lease Squares (OLS) model. The intercept in this model can be interpreted as the expected quantity transacted in the base treatment. The coefficients for Ratio and Regulation implies how much more or less credits are expected to be traded in a given round. As expected, Ratio had significantly more credits traded whereas Regulation was not significantly different from Base in terms of credits traded in any given round. Model 6 is the Pooled OLS model for credit prices. The coefficients for this model can be interpreted as the expected average price in the base treatment (constant), the Ratio and Regulation treatments. It is clear that Ratio prices were lower (about $11.53/credit lower to be precise) compared to Base. Prices were marginally higher for Regulation compared to Base (based on a p-value of 0.8). Profit differs in all three treatments (model 7); one could expect to earn around $199/year in the base treatment, $19.80/year more in Ratio and $9/year less in Regulation. The treatments explain more of the variation in profit (52%) than the credit prices (23%) or quantity of credits traded (41%). All models are significant at the 1% level or greater.

Table 4.7: Aggregate Econometric Models of Market Activity

Variable	Model 5: Average Quantity	Model 6: Average Price	Model 7: Average Profit
Constant (Base)	4.54*** (0.24)	61.47*** (5.74)	199.03*** (1.80)
Ratio	1.78*** (0.35)	-11.53* (6.29)	19.80*** (2.26)
Regulation	0.36 (0.339)	1.637 (6.32)	-9.29*** (2.83)
Observations	375	375	406
F	20.99***	6.70***	77.72***
R^2	0.41	0.23	0.52
All standard errors in parentheses are cluster robust standard errors. ***Indicates significant at a p-value of 0.01 **Indicates significant at a p-value of 0.05 *Indicates significant at a p-value of 0.10			

Finally, it is important to understand the environmental outcomes of each of the WQT markets. In order to make all treatments comparable, trading ratios are assigned to participants of Base and Regulation in the same proportions as in Ratio (two with the 1:1 ratio, one with the 2:1

ratio and one with the 3:1 ratio). In Base and Regulation and for those in Ratio without unverified ratios, trading took place at a 2:1 trading ratio, regardless of the participants' true trading ratio. In order to account for this, the value associated with each unit of abatement sold as a credit or cleaned up voluntarily would need to be discounted based on the actual environmental outcome. Assuming a benefit of $100/unit of abatement, the benefit function for farmer that implemented abatement is given by equation 4.5. "Trading Type" takes on a value of 1 if the true ratio is 1:1, a 2 if the true trading ratio is 2:1 and a 3 if the true trading ratio is 3:1. Credits are the number of credits traded and Quantity is the number of additional units of abatement implemented by farmers. For the Regulation treatment, the mandatory abatement implemented after failure to meet the threshold is also additive to environmental benefit; as farmers are charged for two units of abatement, their contribution is not as discounted as others who implement one practice voluntarily. Any abatement implemented by the WWTP (this will always be the difference in credits and regulatory requirement) are valued at $100/unit (equation 4.6). Total benefit then for each treatment (i) would be the sum of environmental benefits incurred in each time period (t) between farmers and WWTPs (equation 4.7).

$$Benefit_{farmers} = \frac{100}{Trading\ Type} * (Credits + Voluntary) + \frac{2}{Trading\ Type} * Regulation \qquad 4.5$$

$$Benefit_{WWTP} = Abatement * 100 \qquad 4.6$$

$$Total\ Benefit_{i,t} = \sum_{i=1,t=1}^{3,30} [Benefit_{farmers} + Benefit_{WWTP}] \qquad 4.7$$

Figure 4.21 illustrates the environmental benefit associated with each of the three treatments across games. While it is clear that there is some variation in environmental outcomes within treatments due to the composition of the players, in every game, Regulation has better environmental outcomes than the other treatments. This is mostly driven by the mandatory abatement occurring once the threshold is not reached. Clearly, mandatory abatement has better environmental outcomes. However, it was surprising to see that Ratio was consistently greater than the Base. This result may be is driven by a higher volume of trade at true trading ratios. This might imply that market and environmental outcomes benefit from a process of verifying real trading ratios. There is no statistical difference in voluntary abatement based on trading type in the Ratio treatment either implying that even though they may know more about their environmental impact, it does not impact their voluntary abatement behavior.

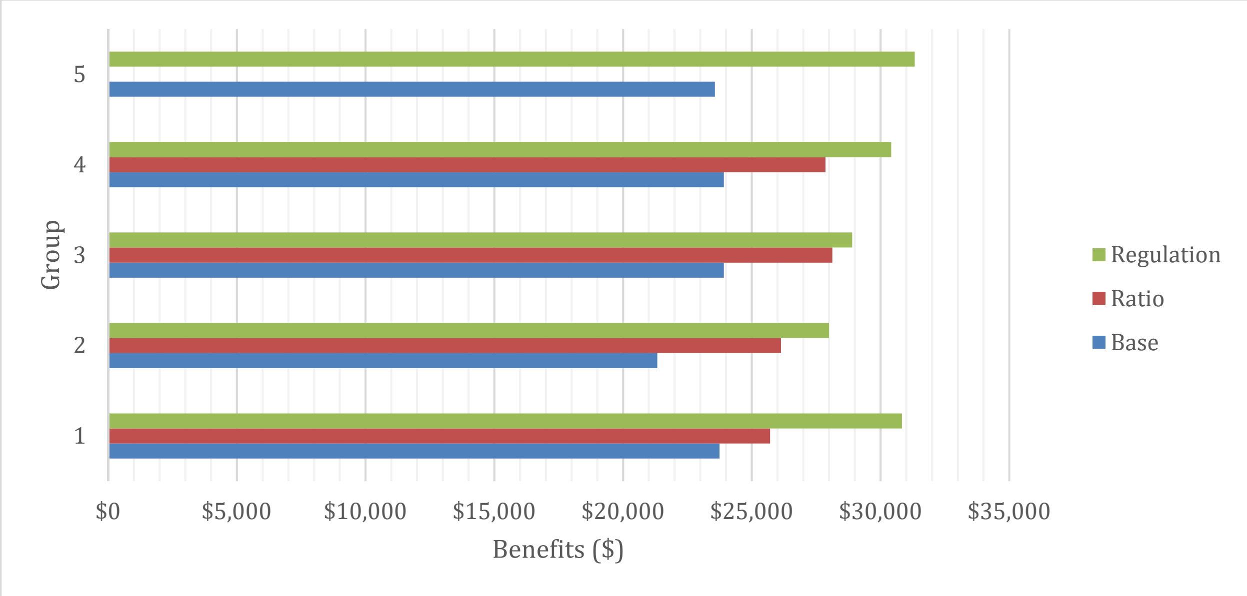

Figure 4.21: Comparison of the Environmental Benefit by Groups in each Treatment

The Ratio treatment performed well in terms of the profits and environmental outcomes. It exceeded the other two market designs in terms of volume of trade and profits for both farmers and WWTPs. This would likely be a popular market design from both sides of the market if implemented in reality. That being said, environmental welfare was best under Regulation. This is driven partly by participants attempting to meet the threshold but also by mandatory abatement post-regulation. Ratio had improved environmental outcomes compared to Base, however, implying that even with more information, environmental outcomes could be improved comparatively.

4.7 Discussion/Conclusion

The results indicate that the market designs introduced through these experiments would have positive impacts on various measures of import to participants in water quality decision making. An over-whelming majority of the time in Ratio treatment, participants eventually verified their trading ratio, even under negative price signals. This indicates that even if firms have a pre-conceived belief about their own ability to reduce pollution, they still want to resolve the uncertainty at some point if given the option. Additionally, profits for farmers and WWTPs increased under this scenario as more trades were able to occur at favorable prices. Voluntary abatement increased under the threat of regulation; however, voluntary abatement was significant in Base and Ratio treatments as well, suggesting that as firms become aware that their activities affect water quality, some are likely to undertake voluntary abatement. Environmental quality was highest in Regulation, however, environmental outcomes were also improved under Ratio compared to Base as trading became more efficient and the firms who could do the most towards pollution control were able to do so.

Voluntary abatement is governed by a propensity by an individual to implement practices and by synergies in the market. This experience seems to confirm that some that engage in pollution control do so for intrinsic motivations and will continue to do so throughout time. However, in terms of characteristics of those individuals who do undergo voluntary abatement, there was no evidence in this experiment that an "environmentalist" was more likely to undertake abatement. Much more at play in this experiment was the institutional design. The ability to trade more in the Ratio treatment allowed for greater degrees of freedom in voluntary pollution control. In Base and Regulation, this was much more of a constraint as farmers that sell more credits in the market have fewer practices available to implement voluntarily. Additionally, abatement does decrease over time (confirming a rich body of public goods literature) but those that were able to meet the threshold in Regulation did so twice implying at least one group was motivated by a threat of regulation. In groups that did not meet the threshold initially, no further concerted effort was made to meet the threshold collapsing the Regulation treatment to that of the Base treatment.

From a policy perspective, baselines might detract from pollution control and market activity more than they help with pollution resulting in low volume of trades and low profits for all firms. Ratio games saw a much higher trade volume, higher profits and were second in terms of environmental outcomes. While Regulation had better environmental outcomes, it did so at the direct expense of market activity and profit for participants. This provides compelling evidence that more information might benefit WQT programs more than voluntary threat regulations if there is concern over a low volume of trades and uncertain environmental outcomes.

This experiment has some short-comings. First of all, while I used a lot of context for the experiment, I could not test for whether this context mattered as I had no treatment without this context for comparison. Additionally, it would be interesting to see if the context were more important for environmentalists versus non-environmentalists or farmers versus students. Moreover, giving participants an 80% chance of being regulated seemed appropriate as many regulations threaten regulation but casual observation through my research revealed that most firms do not believe they will actually be regulated. It would be interesting to see if by changing this probability we would generate different behavior. From the group that was able to reach the threshold, they indicated that they were motivated by the threat of regulation and "did their part to avoid it" but others who did not meet the threshold indicated that they did not benefit much from avoiding it and they weren't hurt much once they became regulated so there was no point in trying to meet the threshold, especially in the presence of free-riders. It might be interesting to see what firms could accomplish if their own voluntary regulation depended only on themselves and they could receive some sort of reward or punishment for reaching their own private goal. Finally, it may have been the case that the cost to verify one's ratio was too low and was highly discounted as it came at the end of the game rather than at the moment of the decision. For coding, it was easier to have the fee incurred at the end but from a realistic perspective, it might have been a more significant cost in the round the decision was made. Variations on the magnitude and timing of this fee could be explored more to see if perhaps the hurdle set in this experiment was too low and unobtrusive compared to actual implementation in the real world.

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APPENDIX 1: FOCUS GROUP QUESTIONS

Questions for this focus group were drawn heavily from Luloff, et al., 2012, p. 14. The questions were as follows:

1) Every agricultural region is a bit different. What makes the place and people where you live unique?

2) What are the most critical water management issues in your watershed?

3) Given your experience, what do you think are the most commonly used irrigation methods and why? If farmers were informed about the benefits of more efficient irrigation, do you think they would be willing to adopt these technologies?

4) Selenium is known to exceed chronic standards in the Arkansas River Basin. Some practices can be implemented to address this including lining irrigation canals, building up the riparian buffer zone, lease fallowing and reducing water and/or fertilizer application to fields. Which of these practices do you see as feasible? Why or why not?

5) Integrated resource management often takes involvement from all members of a community. For water management, it often involves interaction between ditch companies, irrigators, water utilities, and conservation districts. Is this list inclusive or are there other groups/entities that are relevant for water resource management in your watershed? What potential issues have occurred or may occur in the future from the interactions of these different groups?

APPENDIX 2: MATLAB CODE FOR SIMULATION EXERCISE

```
clear all

clc

%parameters

p=200;

c0=0;

c1=0.99;

f0=31.50;

f1=2.34;

K=154.91;

m=0.177;

e0=0.6;

e1=0.90;

b0=m*e0;

b1=m*e1;

gamma=0.7;

maxyield=9;

avgwater=10;

r=0.04;

rho=0.10;

alpha=(-0.03);

delta=rho-alpha;
```

```
gamma1=(0.63:0.001:0.73);
A=p*(gamma*b1-b0)-(gamma*c1-c0);
f=f1-f0;
sigma=0.15;
varw=sigma^2;
W=(1:1:60);
A1=p*(gamma1*b1-b0)-(gamma1*c1-c0);
Psi=41;
Beta1=(1/2)-((delta-r)/varw)+sqrt((((r-delta)/varw)-1/2).^2+((2*r)/varw));
%NPV Rule
w0=max(0,delta*((f+r*K)/r*A));
W1=max(0,delta*((f+r*K)/r*A1));
%W1=delta*((f+r*K)/r*A1);
NPV=(W*A/delta)-(f/r)-K;
OV=(delta/(Beta1-1)*A)-(W*r/Beta1*(f+r*K));
Sale=(delta/(Beta1-1)*(A-Psi*gamma))-(W*r/Beta1*(f+r*K));


%graph of NPV
% plot(W,NPV,'rs');
% %title('NPV as Water Level Increases');
% xlabel('Water Level (acre inches)');
% ylabel('NPV of Conservation Technology ($/acre)');
```

```
%graph of gamma impact on NPV
% plot(gamma1,W1,'rs');
% grid on;
% %title('Water Level Switch as Gamma Increases');
% xlabel('Gamma');
% ylabel('Cut-off Level of Water (acre-inches)');
%
% %graph of OV Function
% plot(W,OV,'bs');
% %title('Value as Water Level Increases');
% xlabel('Water Level (acre inches)');
% ylabel('NPV of Conservation Technology with OV ($/acre)');
% %legend('Option Value Rule','Sale Value Rule')
%
% %option value threshold
WOV=max(0, (Beta1/(Beta1-1))*delta*((f+r*K)/r*A));
%WOV1=max(0, (Beta1/(Beta1-1))*delta*((f+r*K)/r*A1));
WOV1=max(0,(Beta1/(Beta1-1))*delta*((f+r*K)/r*A1));
%graph of gamma impact on OV
plot(gamma1,W1,'rs', gamma1,WOV1,'bs');
grid on;
%title('Water Threshold as a Function of Gamma');
xlabel('Gamma');
```

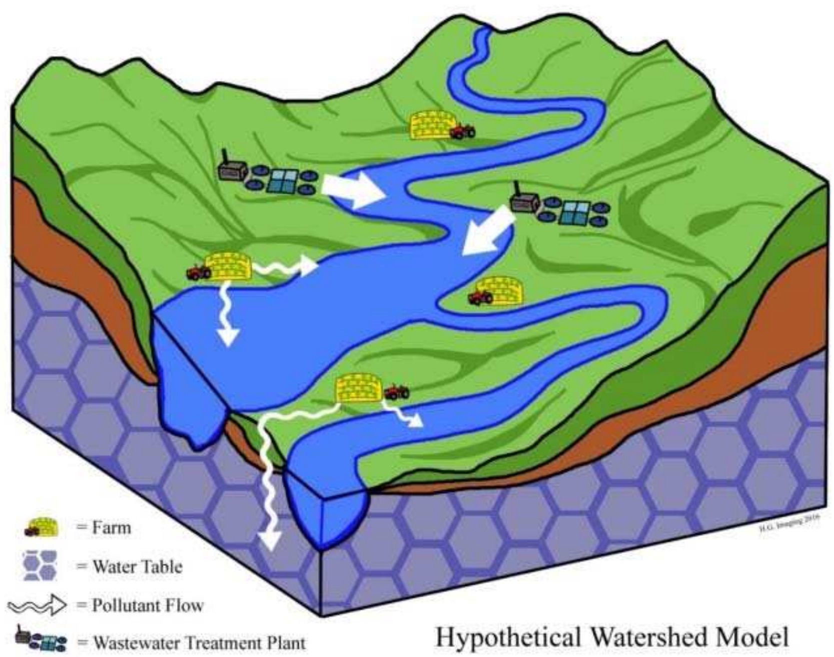
```
ylabel('Cut-off Level of Water (acre-inches)');

legend('NPV Rule','Option Value Rule')

%
```

APPENDIX 3: WWTP INSTRUCTIONS FOR BASE EXPERIMENT

Background

This study involves decision making related to water resources in a situation where activities generate pollution to a water body. Sometimes pollution can be traced back to a specific source, like a wastewater treatment plant (WWTP). Other times, pollution cannot be accurately traced to a specific source, such as runoff from an agricultural field (see Figure 1 below). Farms and WWTPs can both implement practices that reduce pollution flows. Because it is difficult to trace pollution from farms, only WWTPs face limits on the amount of pollution they generate.

Figure 1: Graphic of water pollution process



There is interest in involving farmers in the pollution clean-up process. One approach is to allow farmers to sell "pollution credits" to WWTPs on a voluntary basis, since farmers can often achieve pollution clean-up at lower costs by implementing less costly practices than

WWTPs. Farmers can benefit from this by making money from the sale of credits and WWTPs benefit from lower costs of pollution control.

Experimental Set-up

In this experiment, you will earn money based on the decisions that you and others make, plus an initial payment for showing up. Expected average earnings for participation are $20 plus the $5 show-up fee. You will be assigned a role as either a manager of a wastewater treatment plant or a farm. Two WWTP managers will be randomly paired with four farmers, forming a watershed group similar to what is depicted in Figure 1. Your role as a WWTP manager or farmer will remain the same throughout the experiment as will the members of your group.

You have been provided a “Role Information Worksheet” that defines your role as well as information specific to your operation. Please do not share this worksheet or communicate with other participants in the room; if you have questions, please ask a lab monitor for assistance.

Today’s session will consist of three separate games. Each game will consist of 10 decision rounds that we refer to as years. In order to become familiar with the experiment software, we will begin with three non-binding practice years. After the practice years, we will play the three games back-to-back, followed by a short questionnaire. The games and questionnaire should take about an hour to complete.

Your take-away earnings will be based on only one of the three games, and this game will be chosen randomly at the end of the experiment by drawing a number out of a hat. If the number 1 is drawn, your earnings will be the amount of your earnings in the first game. There is a 100:1 exchange rate between earnings in the game and US dollars. See your role information worksheet for an example. It is in your interest to make the best economic decisions in all games!

Both WWTPs and farms generate revenue in each year. They also generate pollution from their operations and the pollution is costly to clean up with practices. The cost of implementing practices can be found on your Role Information Worksheet. A regulator has determined, however, that this pollution needs to be cleaned up. Specifically, each WWTP is required to clean up four units of pollution. To achieve this clean-up, a WWTP can either buy pollution credits from farms in the water quality trading market or implement practices.

Farmers are not required to reduce pollution but may earn extra money by generating pollution credits which they sell to WWTPs. Due to the uncertainty associated with pollution flows from farms to the water source, regulations typically require 2 conservation practices for every credit generated. Policy makers realize that some farmers may implement practices that are more cost effective due to on-farm characteristics like soil type, distance to the river etc. Prior to the trading round, farmers have an option to verify their trading ratio (see the role information worksheet).

The trading market is the main component of this experiment where participants will spend the most time making decisions about how much to bid to buy credits (WWTPs) and how much to offer to sell credits (farmers). Bids to buy are always called “bids” and offers to sell are always called “offers.” There are two ways that trades can take place in the market:

1- WWTP managers can make bids by specifying the price that they are willing to pay.
  - A farmer may accept any bid from WWTP managers. The farmer gains the bid price less his cost to produce that credit. The WWTP gains the credit at the bid price.
  - WWTP managers can submit as many bids as they like; however, if a farmer accepts a bid, then the WWTP manager automatically purchases the credit and all other bids made by this buyer disappears.

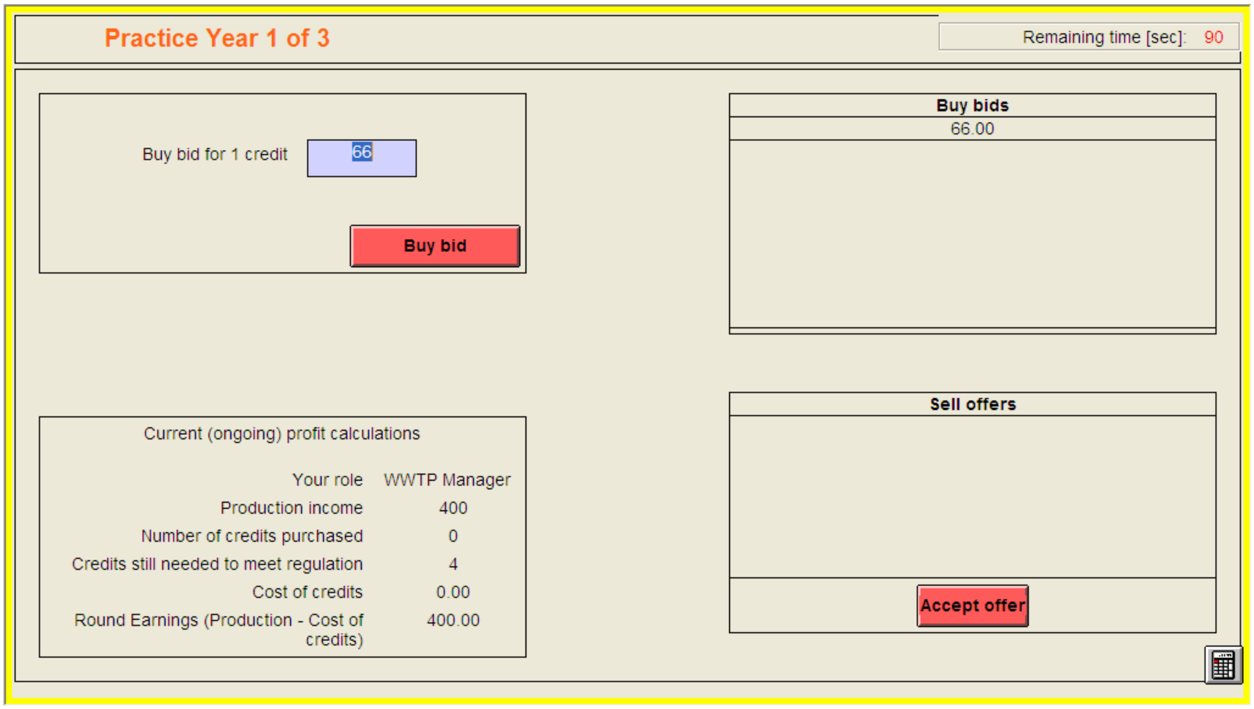
- New bids must be higher than all bids available and lower than all offers available.

2- Farmers can make offers by specifying the price they would be willing to accept.

- WWTP managers can accept any offer, resulting in the purchase of a pollution credit for the offer price. The farmer again gains the offer price less his cost to produce the credit.
- Farmers can submit as many offers as they like; however, if a WWTP manager accepts an offer, then the farmer automatically sells the credit and this deletes all other offers made by the same farmer.
- New offers must be lower than all offers available and higher than all bids available.

Figure 2 contains a screen capture of the trading market in the experimental software from the WWTP perspective. The upper left contains the box where WWTPs enter bids. In this example, the WWTP has entered a bid for $66 which has appeared in the upper right hand box labeled "buy bids." A farmer is able to accept bids resulting in the WWTP buying a credit and the farmer selling a credit. The lower box shows offers made by farmers. WWTPs can click on any sell offers and click "accept offer" in order to buy a credit at that price. Whether a farmer selects the bid or a WWTP accepts the offer, all other bids and offers made by the two participants making the trade are deleted. This allows each participant to make multiple offers without worrying about over-committing to credit generation. With the exception of the three practices years, trading will take place for a period of 90 seconds. A clock is in the upper right corner of your screen, a calculator on the lower right.

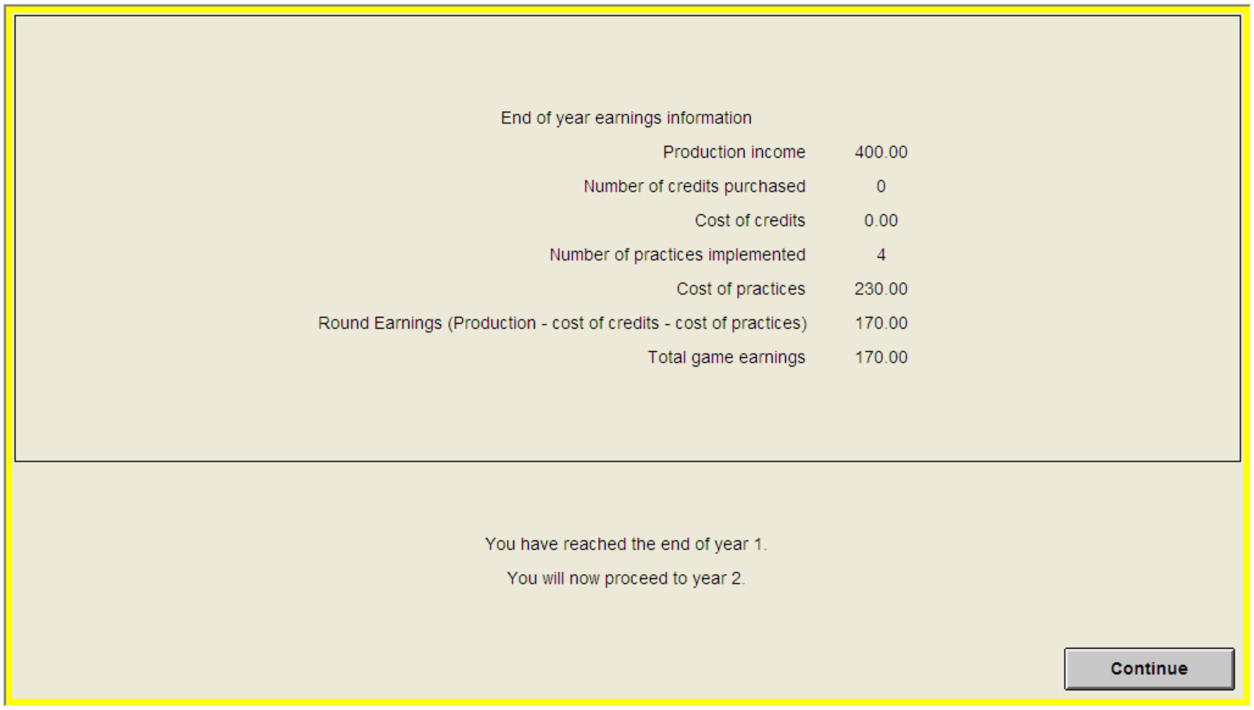
Figure 2: Example screenshot of a trading market as seen by a WWTP manager



In your “Current (ongoing) profit calculations” box (lower left of figure 2 above) you can see how many credits you have bought, the number of credits needed to meet the regulation, the cost of buying credits and your total earnings from the year. WWTPs are required to clean-up 4 units of pollution. If a WWTP purchases fewer than 4 credits during the trading period, they will incur the cost necessary to implement practices after the trading round is over. For example, if one credit is purchased, then the WWTP will be automatically charged for the 3 practices needed to get to 4 units of clean-up.

At the end of each year, you will have an opportunity to see the results of the year. This provides information on your earnings for the year, the number of pollution credits you bought, the cost of practices implemented (automatically), and your cumulative earnings up to that point in the game (figure 3). Once you are done reviewing this information, please click on the “Continue” button to move on to the next year. Recall that each game is made up of 10 years and we will play 3 games. At the end of the 3 games, one game will be chosen randomly to be the game that determines your final earnings.

Figure 3: Example screenshot of end of year earnings information for a WWTP



Summary: You will participate in a water quality trading market in order to buy enough credits to meet a regulation. If you do not have enough credits at the end of the trading round, practices will be implemented automatically in order to meet the regulation according to your cost schedule on your “Role Information Worksheet.”

APPENDIX 4: FARMER COST INFORMATION SHEET FOR BASE, RATIO, AND REGULATION TREATMENTS

Base:

Role: Farmer

Yearly Production Earnings: $200

Yearly Pollution: 4 units

Regulation: Farmers are asked to clean-up pollution voluntarily. They are also given the option of implementing conservation practices to generate credits for WWTP in a water quality trading market. For farmers, two units of clean-up are required to generate 1 credit for sale to WWTPs (2:1). Therefore, if a farmer sells one credit in the market, two practices are implemented. This would leave two practices should a farmer choose to implement any practices voluntarily.

Cost Schedule:

Practices	Per-Unit Cost of Clean-up	# of Credits	Total Cost of Practices
1	11	--	11
2	18	1	11 + 18 = 29
3	37	--	11 + 18 + 37 = 66
4	74	2	11 + 18 + 37 + 74 = 140

Tips on trading: you should be willing to accept any price over the cost of the credit you sell. So if you sell one credit, you should be willing to accept any value over $29 as that is the cost to create that credit.

Earnings Example: A farmer begins each year with $200 in production income. Through trading, suppose you accept a bid for $40 for one credit. The two practices required to generate that credit are implemented automatically at a cost of $29. The total earnings for this year would be:

$$Round\ earnings = Production\ income - Cost\ of\ practices + sale\ of\ credits$$

$211 \quad = \quad 200 \quad - \quad 29 \quad + \quad 40$

Using the same example above, if this were the outcome in each of the 10 years, at the end of the game, he would have earned $211 * 10 = 2110$. With an exchange rate of 100:1 the earnings for participating will be $21.10 under this scenario.

Ratio:

Role: Farmer

Yearly Production Earnings: $200

Yearly Pollution Flows: 4 units

Policy: All farmers begin each game (including the practice game) with an option to sell credits to WWTPs at a trading ratio of 2:1; this implies two units of clean-up are required to generate one credit. In this experiment, farmers are given the opportunity to have their ratio verified (see screenshot below) prior to each trading round. If farmers choose to have their ratio verified, they must pay 50 experimental dollars ($0.50 with a 100:1 exchange rate) which is charged at the end of the game. Having your ratio verified is always optional and this option continues to be available to you every year before the trading round until you choose to verify; once you have chosen to have it verified, your true trading ratio is revealed to you and it becomes the permanent trading ratio for the rest of the game. You do not know which trading ratio applies to your farm and your ratio for trading purposes will remain 2:1 until you verify it. In each game, two of the four farmers have a 1:1 trading ratio (one unit of clean-up is required to generate one credit). One farmer has a 2:1 trading ratio. One farmer has a 3:1 trading ratio. The cost schedules for the all trading ratios are below. In the next game, your trading ratio will reset to 2:1 and you will again have to verify your ratio which may not be the same as in the previous game.

Screenshot of a farmer’s trading ratio verification option

Would you like to pay $50 (50 cents off your final payout) in order to verify your trading ratio for the remainder of the game? ○ Verify ○ Not now

Cost Schedule:

Practices	Per-Unit Cost of Practices	Total cost of practices	Credit (1:1)	Cost per credit (1:1)	Credit (2:1)	Cost per credit (2:1)	Credit (3:1)	Cost per credit (3:1)
1	11	11	1	11	--	--	--	--
2	18	11+18 = 29	2	18	1	29	--	--
3	37	11+18+37 = 66	3	37	--	--	1	66
4	74	11+18+37+74 = 140	4	74	2	111	--	-

Tips on trading: you should be willing to accept any price over the cost of the credit you sell. If you have a 2:1 ratio (because you did not verify your ratio or you did verify it and it is 2:1) then you should be willing to accept a price above $29 for the first credit and so on.

Earnings Example: Each year begins with $200 in production income. Through trading, suppose you accept a bid for $40. The cost for that credit is $29. Total earnings for this year would be:

$$Round\ earnings = Production\ income - Cost\ of\ practice(s) + sale\ of\ credits$$

$$211 \qquad = \qquad 200 \qquad - \qquad 29 \qquad + \qquad 40$$

If this were the outcome in each of the 10 years, you would have earned $211 * 10 = 2110$. With an exchange rate of 100:1 the earnings for participating will be $21.10 under this scenario. Take away would be then $26.10 with the $5 show-up fee.

REMINDER: Please do not communicate with other participants. Ask the proctor if you have any questions.

Regulation:

Role: Farmer

Yearly Production Earnings: $200

Yearly Pollution Flows: 4 units

Policy: After each trading round, farmers are asked to implement practices voluntarily to reduce water pollution in the system. If farmers collectively hold 28 credits by the end of the 7th year, they will not be regulated. This threshold could be met if every farmer undertook one unit of clean-up each year to contribute to this voluntary threshold. If the agricultural sector does not meet this threshold, then there is an 80% chance that they will be regulated in future years. If regulated, each farmer would be required to implement 2 units of clean-up in years 8-10 and will not be able to participate in trading those final 3 years.

Trading Ratio: Two practices are required to generate 1 credit for sale to WWTPs (2:1). One practice counts as one credit towards the farm sector threshold (1:1).

Cost Schedule:

Practices	Per-Unit Cost of Practices	Total Cost of Practices	Credit generation (2:1)	Cost per credit for trading (2:1)	Cost per credit for threshold (1:1)
1	11	11	--	--	11
2	18	11 + 18 = 29	1	29	29
3	37	11 + 18 + 37 = 66	--	--	37
4	74	11 + 18 + 37 + 74 = 140	2	111	74

Tips on trading: you should be willing to accept any price over $29 for the first credit as that is the cost to create that credit. If you have sold one credit in the trading market and decide to contribute to the threshold, the cost of the credit for the threshold would be $37 (because you have already used the first two practices to generate the credit for trading). If you do not trade at all, then the cost of generating a credit for ones threshold would be $11, and the cost of two credits would be $29.

Earnings Example: A farmer begins each year with $200 in production income. Through trading, suppose the farmer earns $40 for a credit that cost him $29 to generate. Suppose also that after trading he implements one practice to contribute to the threshold, costing him $37 to generate. The total earnings for this year are:

$$Round\ earnings = Production\ income - Cost\ of\ practices + sale\ of\ credits - fines$$

$$174 \qquad = \qquad 200 \quad - \quad 66 \quad + \quad 40$$

Using the same example above, if this were the outcome every year, at the end of the game, you will have earned $174 * 10 = 1740$. With an exchange rate of 100:1 the earnings for participating will be $17.40 under this scenario.

APPENDIX 5: WWTP COST HANDOUT

Role: Wastewater Treatment Plant Manager

Yearly Production Earnings: $400

Yearly Pollution: 8 units

Regulation: Must reduce pollution by 4 units at the end of each year; you may implement practices to generate units of clean-up or purchase pollution credits from farmers to meet this regulation.

Cost Schedule:

Units of Clean-up	Per-Unit Cost of Clean-up	Total Cost of Clean-up
1	51	51
2	54	51 + 54 = 105
3	59	51 + 54 + 59 = 164
4	66	51 + 54 + 59 + 66 = 230

Tips on trading: You should be willing to pay any value less than your most expensive unit of clean-up. So for the first credit you buy, you should be willing to pay any price less than $66. For your second credit to purchase, you should be willing to pay any price less than $59, and so on.

Earnings example: A manager begins each year with an income of $400. The manager pays for a combination of practices and credit purchases from farmers. If he buys 2 credits and cleans up 2 units (mandatory to meet regulation), his cost of practices is $105 and if he buys two credits for $40 each, his cost of credits is $80. The total earnings for this year are:

$$Round\ earnings = Production\ income - Cost\ of\ practices - Cost\ of\ credits$$

$$215 \qquad = \qquad 400 \qquad - \qquad 105 \qquad - \qquad 80$$

Using the same example above, if this were the outcome every year, at the end of the game, you will have earned $215 * 10 = 2150$. With an exchange rate of 100:1 the earnings for participating will be $21.50 under this scenario.