DISSERTATION

LINKED SOCIOPOLITICAL AND ENVIRONMENTAL CONTROLS ON LARGE-SCALE WATER CONSERVATION PROGRAM FEASIBILITY AND EFFECTIVENESS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

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Fall 2025

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ABSTRACT

LINKED SOCIOPOLITICAL AND ENVIRONMENTAL CONTROLS ON LARGE-SCALE WATER CONSERVATION PROGRAM FEASIBILITY AND EFFECTIVENESS

Persistent drought in the Colorado River Basin over the last quarter century continues to strain existing water supplies and challenges the effective management of storage reservoirs and water delivery systems. Projections for the future suggest that these challenges are unlikely to abate. Expected outcomes of changing climate throughout the 21st century include elevated air temperatures and declining snowmelt runoff. Reductions in runoff will limit water storage in reservoirs. At the same time, increased evaporative crop use will increase agricultural water demands. These dramatic and opposing shifts in water availability and water demand portend a period of increasing water scarcity and conflict. Water users in the Colorado River Basin desperately need access to new strategies for managing increasingly constrained supplies.

The body of research described here probes the diverse attitudinal, sociodemographic and geographical characteristics that moderate or enhance agricultural water conservation effectiveness at the regional scale. Three attendant lines of inquiry explore the social and environmental dimensions of water conservation effectiveness in the Upper Colorado River Basin (UCRB). The first line of inquiry explores aspects of the physical-environmental subsystem that moderate the effectiveness of conservation at the field-scale. The second line of inquiry explores the human-behavioral subsystem that controls the likelihood of water user participation in conservation programs. The third line of inquiry integrates outcomes of research into the physical-environmental and human-behavioral subsystems to evaluate potential water conservation outcomes among networks of water users at the basin scale over the long-term. Each line of inquiry utilizes data and information collected across the West Slope region of Colorado, USA.

Research into the physical-environmental controls on conservation outcomes demonstrates how measurable geographical characteristics like soil type and elevation influence patterns of potential consumptive water use reductions under common deficit irrigation practices. Results from a Bayesian hierarchical modeling evaluation of remotely sensed evapotranspiration data show that water savings generated through conservation are highly dependent on elevation and crop type. Notably, conservation on high-elevation grass pasture, a dominant cropping pattern in the UCRB, is significantly less effective at generating meaningful reductions in consumptive water use than on low elevation fields growing other crops. This is particularly evident for conservation strategies that do not require full season irrigation curtailment.

Research into the human-behavioral controls on conservation program participation demonstrates that attitudes toward conservation and tendencies toward risk aversion play a dominant role in driving potential adoption rates among agricultural water users. An exploration of the relationship between attitudes and intention to participate in conservation identified a general, widespread resistance to conservation associated with a low sense of individual responsibility to act and a limited sense of agency in contributing meaningfully to basin-scale water management issues. Analysis of Discrete Choice Experiment results suggest that agricultural water users prefer conservation programs that do not require irrigation curtailment on large fractions of their irrigated lands for the entire irrigation season and that matching West Slope water conservation with reductions in transmountain water diversions to Colorado's Front Ranch may help boost participation rates.

An agent-based framework integrates modeling tools that characterize the physical-environmental and human-behavioral subsystems and explores emergent behaviors among networks of water users distributed across diverse geographies at the basin scale and over the long-term. Monte Carlo simulation results illustrate trade-offs in conservation policy effectiveness and the uncertainty in outcomes associated with any given policy. The most effective policy pathway for generating meaningful amounts of conserved water appears to be one that includes moderate compensation rates (e.g. $600/acre), requires commitment of at least 50% of an irrigated acreage to full season irrigation curtailment, and includes provisions for a 1:1 match of water conserved on the West Slope with forgone transmountain water diversions to the Front Range. The insights and modeling tools generated here should support data-driven water conservation policy development in the UCRB.

ACKNOWLEDGMENTS

Many of the ideas presented in this dissertation were inspired by conversations with Pat McMahon, Rick Lofaro, and and the rest of the staff at the Roaring Fork Conservancy. In particular, Pat's unending enthusiasm for all things related to sustatinable use and management of water for the benefit of both environment and agriculture was a significant motivator for initiating my Ph.D. program. My research was generously supported with funding from the Colorado River Water Conservation District, American Rivers, the Colorado Water Conservation Board by way of the Colorado Basin Roundtable, and Conscience Bay Research. Coordination and administrative support was provided by Roaring Fork Conservancy. Dr. Neil Grigg and the rest of my graduate committee provided critical insights and guidance throughout my tenure as a student at Colorado State University. Dr. Dana Hoag and Dr. Jesse Burkhardt provided critical insights and suggestions for water user survey development and distribution. Through the course of my research, I had opportunity to pursue thought-provoking collaborations with Dr. Daniel Mooney and Dr. Perry Cabot. These collaborations not only inspired me but helped ensure they my work remained relevant to broader discussions about water supply and management challenges in the Upper Colorado River Basin.

DEDICATION

For Jessica, Atlin and Kade, whose enduring patience and steadfast support made this endeavor possible.

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CHAPTER 1

INTRODUCTION

The Colorado River is in crisis. Water from the river provides access to municipal drinking water to 27 million users [1] and irrigation water for two million hectares of farmland [2] spread across seven states and two countries. Water from the Colorado River and its tributaries makes up the majority of the water supplied for human uses in this arid portion of North America. The river is also home to numerous threatened and endangered species [3, 4]. A significant and mounting body of research indicates that changing climatic conditions and growing populations will conspire to place significant pressure on regional water supply [5, 6, 7, 8]. Progressive declines in snowmelt runoff due to rising air temperatures are expected throughout the 21st century [9, 10]. Recent research demonstrates the mechanisms by which a warming climate may reduce annual water yields in the Upper Colorado River Basin (UCRB) by as much as 20% [11]. This potential future is compounded by the fact that demand for water across the basin exceeded supply in recent years [8]. Expected demand trajectories over the next 50-years will serve only to exacerbate this mismatch between the need for Colorado River water and its availability.

Reduced water yields and ever increasing demands foretell a system in crisis. Discussions of doomsday scenarios once relegated to the domain of academics, policy wonks and water managers have spilled into the mainstream media, as evidenced by a spate of recent articles in the New York Times [12, 13, 14, 15, 16, 17], Washington Post [18, 19], and other outlets [20]. Persistent drought over the last two decades significantly reduced the amount of stored water in Lake Mead and Lake Powell and increases the likelihood that Colorado, Utah, Wyoming, and New Mexico (jointly, the "Upper Basin States") will find themselves in violation of interstate and international treaty obligations.

The 1922 Colorado River Compact requires the UCRB (i.e. Colorado, Utah, Wyoming, and New Mexico) to deliver 1.02e+10 m^3 of water to the Lower Colorado River Basin (LCRB) (i.e. California, Arizona, and Nevada) and Mexico on a ten-year rolling average basis [21]. A failure to deliver the required volume of water from the UCRB will result in a "Compact Call"—a legal and administrative process that may require the Upper Basin States to implement non-voluntary curtailments of water use by municipalities, industries, and agricultural producers. No policy frameworks currently exist for responding to a Compact Call, and anticipating the actual impact on individual water uses in Colorado is, thus, challenging. Despite this uncertainty—or because of it—most stakeholders agree that a Compact Call would be severely disruptive and measures should be taken to avoid it, if possible.

The principal means by which water managers in the Colorado River Basin ensure that annual demands for water in each basin are met and that deliveries of water from the UCRB are compliant with respect to the Colorado Compact is through management of a system of jointly managed reservoirs. The two largest reservoirs, Lake Powell and Lake Mead, have a joint capacity of 6.17e+10 m^3, approximately three and a half times the annual flow of the Colorado River [8]. Coordinated operation of these two reservoirs works to significantly "smooth-out" inter-annual hydrological variability of flows below Lake Powell. As diminished winter snow packs produce meager spring runoff with increasing frequency, reserves of water in Lake Powell and Lake Mead continue to fall and the chance of violating provisions of the Colorado Compact become ever more realistic. Even if annual water deliveries required by the Colorado Compact are maintained, dropping water elevations in Lake Powell threaten power generation at Glen Canyon Dam. The Glen Canyon hydroelectric plant produces about five billion kilowatt-hours of low-cost, renewable energy for consumers in Wyoming, Utah, Colorado, New Mexico, Arizona, Nevada, and Nebraska [21]. Revenues generated from the sale of this electricity fund ongoing efforts to protect threatened and endangered native fish populations in the Upper Colorado River and Upper San Juan River basins. Loss of power generation capabilities at Glen Canyon Dam would, thus, impact electricity rates for millions of consumers in the western U.S. and further endanger the tenuous position of several iconic fish species.

In August of 2022, the Commissioner for the U.S. Bureau of Reclamation (USBR) testified to a Senate committee that the seven Colorado River Basin states must identify a means to cut water use by 2.47e+9 - 4.94e+9 m^3 per year to stave off disastrous consequences to the management of water in Lake Powell and Lake Mead [22]. USBR indicated that if the states were unable to develop a satisfactory plan to meet the reduction targets, the federal government would step in and mandate cuts to water use. The Lower Basin states subsequently developed a plan to conserve a total of ~3.70e+9 m^3 of water over the 2023-2026 period.

In recent years, acute reservoir storage conditions, coupled with an ongoing renegotiation of the operational strategies for Lake Powell and Lake Mead [23] prompted a spate of discussions, investigations, and agreements aimed at controlling water demand growth, bolstering storage volumes and temporarily reducing water consumption (e.g., [24, 25, 26]). On March 19, 2019, the seven Colorado River Basin states wrote a joint letter to Congress outlining drought contingency plans (DCPs) for testing new ideas to reduce water demand in the basin. The states also requested federal legislation to authorize the Bureau of

Reclamation to participate and assist in these efforts [27]. The potential for various water conservation practices to result in measurable consumptive use reductions across western Colorado is of critical interest to state and regional water planners. Notably, the Upper Basin DCP action authorized the multiyear storage of up to 1.85e+9 m^3 in Flaming Gorge Reservoir, Navajo Reservoir, the Aspinall Unit, and Lake Powell for the purpose of storing water conserved in the Upper Basin states. The DCP did not define the mechanisms for contributing water to this storage pool.

Critical insights regarding the most strategic conservation approaches capable of meeting multiple water management objectives and minimizing negative impacts on communities are limited at both the local and regional scale. The Colorado River Risk Study [24] characterized the impact of meeting different consumptive water use reduction targets on the risk of passing certain storage and water delivery thresholds at Lake Powell under various hydrological futures. The Upper Basin Demand Management Economic Study in Western Colorado [28] evaluated the potential economic impacts of "Moderate" and "Aggressive" water conservation programs—hypothetical programs differentiated by presumed levels of basin-wide annual consumptive water use reductions. Neither study proposed nor assessed the mechanisms for achieving consumptive water use reduction volume targets at any level.

Voluntary, temporary, and compensated water conservation among agricultural users is gaining traction as an acceptable and viable means for meeting consumptive use reduction goals throughout the Colorado River Basin. The agricultural sector comprises the largest aggregate demand (~68% by volume) for water in the UCRB. Among the four Upper Basin States, Colorado is responsible for approximately 55% (3.45e+9 m^3) of the total depletions to the Colorado River [29]. Within Colorado, the agricultural sector accounts for ~65% of Colorado River water use (Figure 1.1) Excluding transmountain diversions of water to the Front Range, agricultural accounts for ~88% of the use of Colorado River water. Therefore, maximizing the benefits of voluntary and temporary water conservation efforts will likely require broad and sustained buy-in among agricultural water users on Colorado's West Slope. However, a high level of continual participation in water conservation programs by this population is not guaranteed. Furthermore, the consumptive use water savings associated with diverse conservation practices across highly variable geographies are not well understood.

The Upper Basin States enacted the System Conservation Pilot Program (SCPP) to assess opportunities for generating conserved consumptive use (CCU) on agricultural lands. The most recent iteration of SCPP implemented projects across the UCRB in 2023 and 2024 [30]. 2023 SCPP projects yielded approximately 3.35e+7 m^3 of CCU across the Upper Basin states in 2023. Of this total, approximately 2.37e+6 m^3 (6.5%)

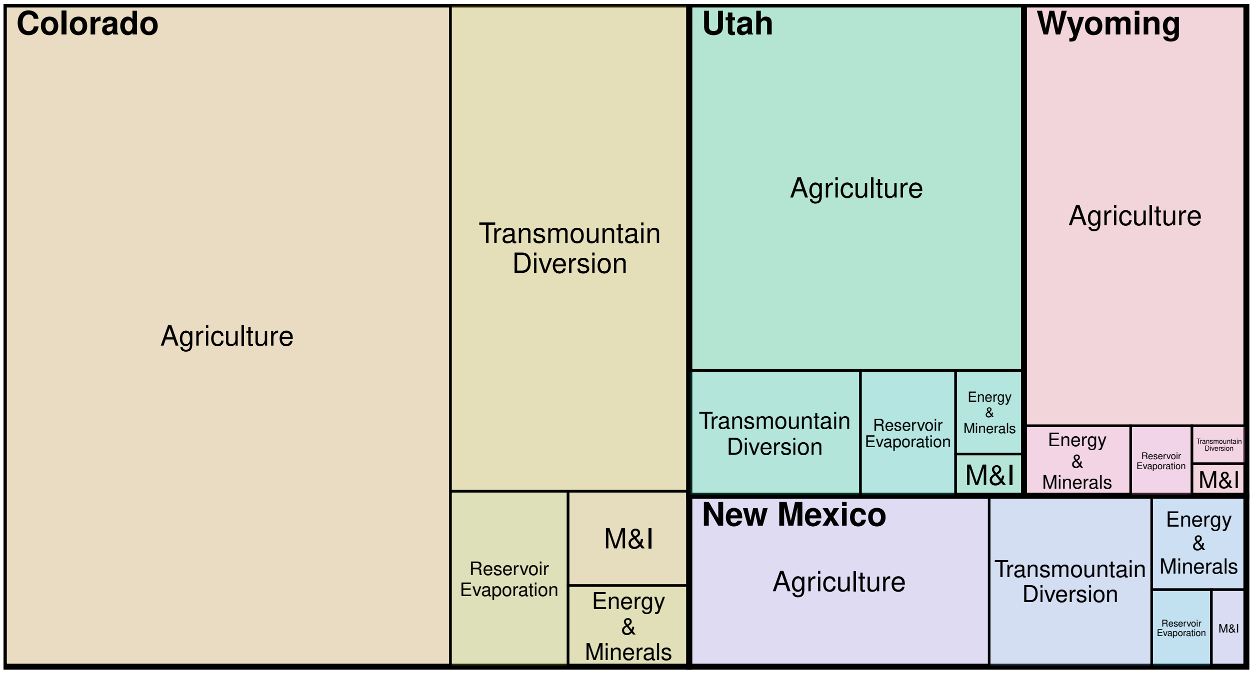

FIGURE 1.1. Proportional average annual allocations of Colorado River use in the UCRB by state and water sector.

came from water users in Colorado. The 2024 SCPP was expected to yield approximately 2.06e+7 m^3 of CCU in the State of Colorado—24% of the total expected CCU for projects approved in the Upper Basin States in that year [31]. However, no post-project CCU verification for 2024 SCPP was available at time of writing.

Modest SCPP participation rates and CCU outcomes observed among agricultural producers on Colorado's West Slope during 2023 and 2024 indicate that open questions remain regarding the factors that drive water conservation decision-making. Pilot studies, water user surveys, modeling, and additional research can provide critical information and support to policymakers as they endeavor to ensure a high return on investment made in water conservation program development or implementation. Developing water conservation programs and policies that lead to meaningful and sustained reductions in consumptive use can be enhanced by elucidating the attitudes, perceptions, social network traits, and policy characteristics that inspire widespread and persistent interannual adoption levels. Integrated planning across water and energy systems elsewhere underscores the need for coordinated conservation strategies [32]. These efforts may be further supported by work that explores the relationships between variability in geography, water conservation practice, and CCU outcomes at the field scale.

1.1 CONCEPT OF OPERATIONS

The human-behavioral and physical-environmental factors expected to promote or constrain water conservation outcomes in the UCRB can be conceptualized as a series of intersecting causal loops (Figure 1.2) where the primary problem response loop defines how a perceived risk for administrative water supply curtailment creates pressure for the enactment of water conservation programs and policies. Enacting these policies is expected to reduce consumptive water use. Over time, these consumptive water use reductions are expected to reduce water supply risks.

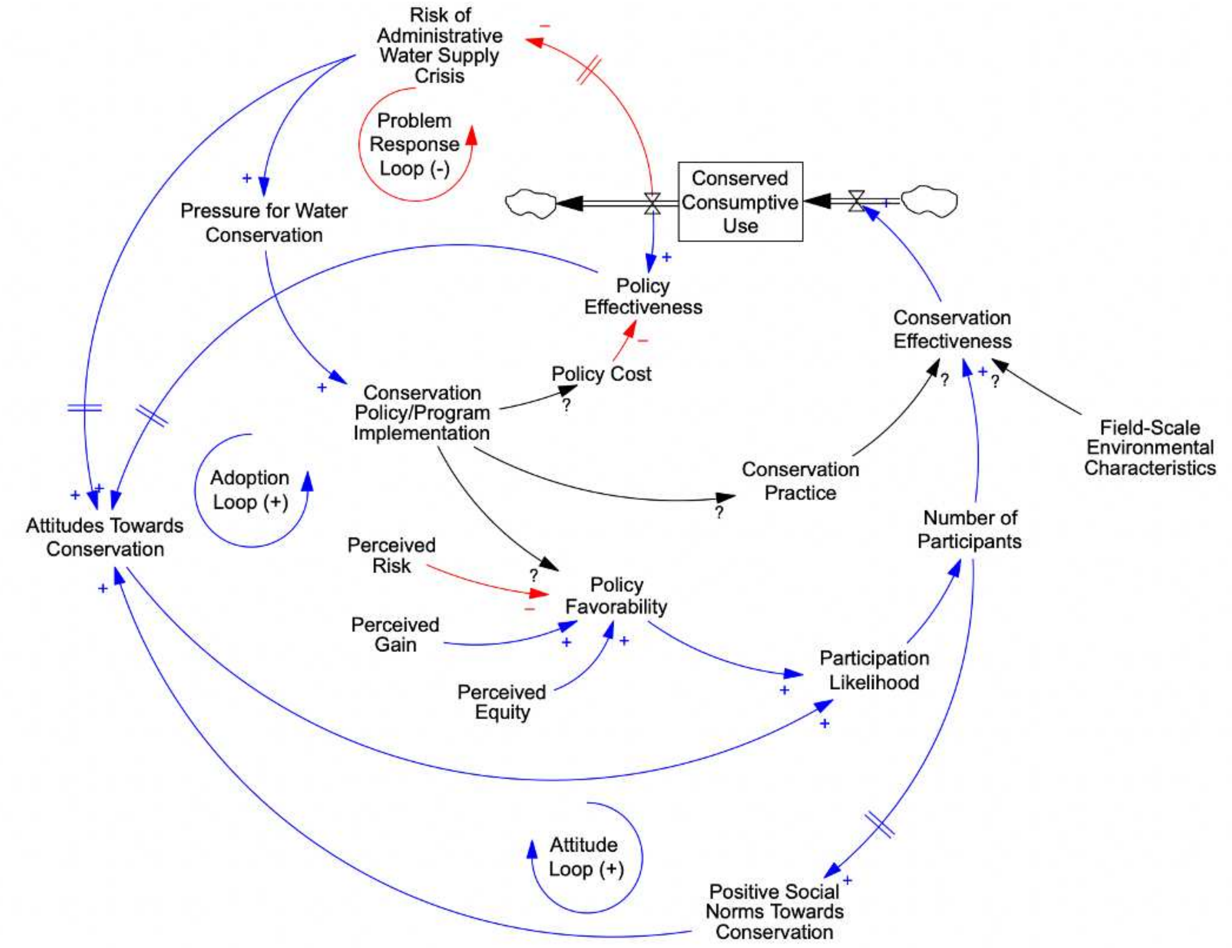

FIGURE 1.2. Causal loop diagram indicating conceptual relationships between human and environmental variables that can moderate or accelerate water conservation effectiveness and the reduction of risk for an administrative water supply crisis.

The response of water users to water conservation programs and policies is described by an adoption loop that relates individuals' attitudes towards conservation, and the attributes of a conservation program or policy related to perceptions of risk, utility, and equity. The effectiveness of water conservation activities is mediated by interactions between the specific conservation practice enacted on a field, the environmental characteristics (e.g. soil type, elevation) of the field, and the number of water users who elect to participate in the program. The effectiveness of a given water conservation policy can then be evaluated as the ratio of the volumetric water conservation gains to the total cost of the policy. Perceived policy effectiveness may generate a positive feedback on water user attitudes where highly effective policies improve attitudes. As the number of water users participating on conservation programs increases, social norms are expected to lead to shifting attitudes toward water conservation. This positive feedback (the "attitude loop") may work to increase conservation program adoption rates over time.

The adoption loop and attitude loop represent a critical human-behavioral subsystem expected to control the number of water users who may participate in water conservation in any given year. Interactions between conservation practices and field-scale environmental characteristics (the "effectiveness link") represent a physical-environmental subsystem expected to constrain the amount of conserved consumptive water use that can be generated by a program. This dissertation decomposes and explores the human-behavioral and physical-environmental subsystems, then integrates models of those subsystems into a decision support tool (Figure 1.3). The integrated system is intended to support data-driven water conservation policy development in the UCRB.

The overarching objective of this research effort is to produce novel insights and develop new tools to assist in the strategic development of water conservation programs that produce meaningful and sustained reductions in consumptive use at the watershed or basin scale. The subsequent chapters in this document are organized into three parts that reflect this objective and the organizational heuristics common to the domain of Systems Engineering.

- Part 1 consists of chapters 2-3 that jointly present research into the physical-environmental subsystem discussed above. Chapter 2 provides a baseline dataset of plot-scale remotely sensed evapotranspiration (ET) time series data attributed with various environmental characteristics of the sample plot. This chapter is composed and formatted in accordance with a submission for publication in *Data In Brief*. Chapter 3 presents a hierarchical Bayesian model that predicts consumptive water use reductions as a function of various conservation practices and environmental characteristics (Figure 1.3). This chapter demonstrates the degree to which different knowable geographical characteristics influence the magnitude and variability of potential water conservation gains. Results include a probabilistic model of conserved consumptive water use, given field-scale geographical characteristics and a selected conservation practice. Chapter

3 also introduces a novel time series classification approach for verifying conservation activities using remotely sensed data. This approach hints at scalable verification strategies that might be employed by water conservation program managers who need to monitor and confirm adherence to conservation practices on fields broadly spaced across the UCRB.

- Part 2 consists of chapters 4-5 that jointly present research into the human-behavioral subsystem identified in the causal loop diagram (Figure 1.2). Chapter 4 introduces a quantitative social survey of agricultural water users on Colorado's West Slope. The survey results include outcomes from a Discrete Choice Experiment (DCE). This chapter is composed and formatted in accordance with a submission for publication in *Data In Brief.* Chapter 5 makes use of the survey data to test a conceptual model of human behavior that relates attitudes to intention to participate in water conservation (Figure 1.3). The conceptual behavior model is assessed through development of a Bayesian Belief Network (BBN). This analysis is extended with a hierarchical Bayesian model of choice behavior that predicts water conservation program participation likelihood, given a set of attitude characteristics and a hypothetical water conservation program attributes.
- Part 3 consists of chapters 6-7. Chapter 6 integrates prediction models presented in Part 1 and Part 2 in an Agent Based Model to evaluate potential trajectories for water conservation gains, and the attendant uncertainty associated with those gains, at the basin scale. Potential conservation program outcomes are charted along axes defined by different program attribute compositions, shifts in demographics, and alternative strategies for addressing poor attitudes towards water conservation. This chapter is formatted as a policy whitepaper that aims integrates findings from previous chapters and presents a novel decision-support tool. The formatting and level of technical detail included in this chapter are intended to maximize accessibility among policymakers. In keeping with policy whitepaper format, methodological details for Chapter 8 are relegated to an appendix. The final chapter (Chapter 7) reflects on the complete body of research and discusses the work in the context of the Systems Engineering evolutionary sequential model (the "Vee model").

The collection of applied research discussed in this dissertation delivers important information to organizations and agencies promoting and funding water conservation efforts in the Upper Colorado River Basin. Each chapter in this dissertation is composed with the intention to submit for publication in mind. As a result, some repetition of basic water conservation introductory material is necessary between chapters. Some acronym definitions are similarly repeated. It is my sincere hope that the insights

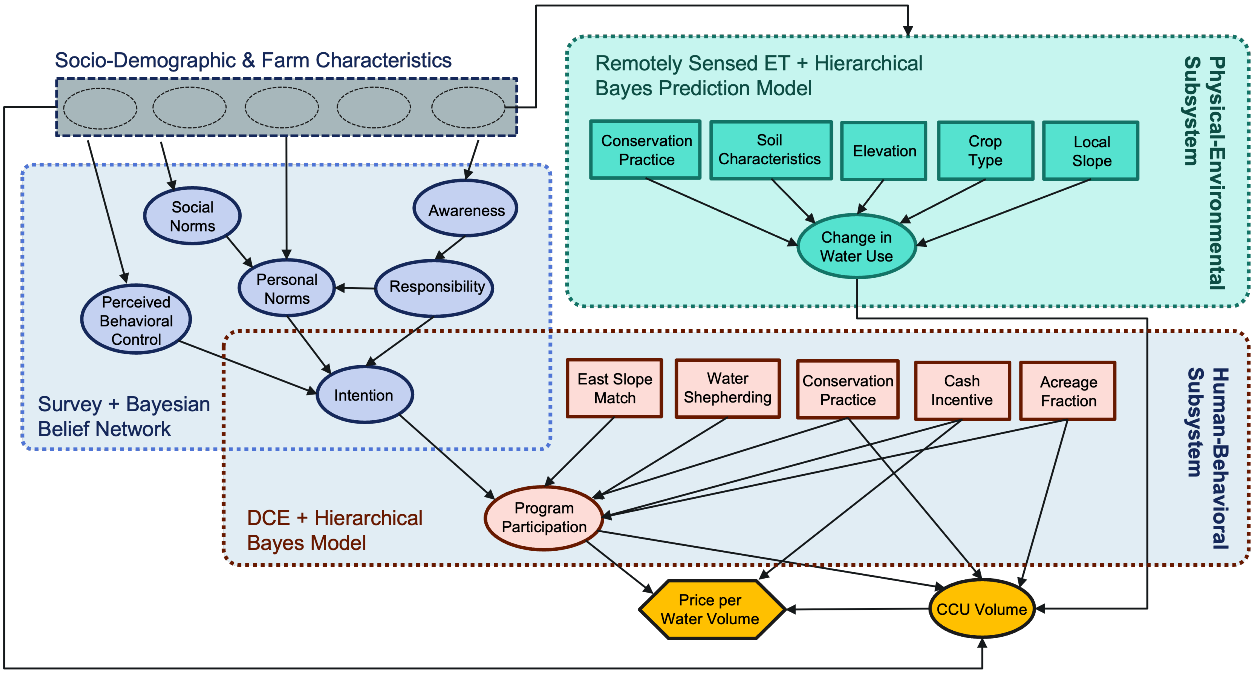

FIGURE 1.3. Architecture of research design responsive to the causal loop diagram and presented in the various sections and chapters of this dissertation.

and tools presented here make their way into decision-making and policy development settings and contribute meaningfully to trade-off analyses and the implementation of new water conservation pilot programs. I also hope this dissertation can serve as an instructive example of application of the Systems Engineering philosophy in the natural resource policy domain.

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PART I

Physical-Environmental Subsystem

CHAPTER 2

AGRICULTURAL EVAPOTRANSPIRATION ON COLORADO'S WEST SLOPE: A DATASET LINKING WATER CONSERVATION PRACTICES, GEOGRAPHICAL FACTORS, AND FIELD-LEVEL OUTCOMES.

This dataset provides a detailed baseline of spatially-explicit relationships between various conservation practices, geographical characteristics of agricultural fields on Colorado's West Slope, and conserved consumptive use (CCU) outcomes associated with water conservation in the 2016-2024 period. Multiyear evapotranspiration (ET) time series are characterized for 21,281 Agricultural Hydropedological Units (AHUs) distributed across 392 agricultural fields. For each AHU, the dataset includes the start and end dates of water conservation activities, the type of conservation activity (e.g., Split Season Fallow), growing season time series of ET and normalized difference vegetation index (NDVI), elevation, soil characteristics (e.g., flood frequency, drainage class, hydrological group), crop type, and irrigation application strategy. This dataset is intended to support research into the environmental controls on water conservation activities across diverse geographies in the Upper Colorado River Basin (UCRB).

TABLE 2.1. Data Specification.

Specifications	
Subject	Earth & Environmental Sciences
Specific subject area	Evapotranspiration time series analysis and estimation of agricultural water conservation impacts across diverse geographies.
Type of data	CSV files of filtered and joined evapotranspiration and geospatial data, GeoPackages of point and polygon data, reports and documents describing the water conservation activities that occurred on each mapped field.

Specifications	
Data collection	This dataset characterizes patterns of evapotranspiration, impacts of water conservation, and hydropedological characteristics of fields in the West Slope Region, Colorado, USA. A total of 392 agricultural field boundaries where water conservation activities occurred in the 2016-2024 period were hand digitized, based on available aerial imagery and paper maps. Within these fields, we randomly sampled 5,275 points. Each point was joined to elevation values from 30 meter Shuttle Radar Topography Mission (SRTM) coverages, classification keys from the gridded National Soil Survey Geographic Database (gNATSGO), and field centroids from the Colorado Decision Support System (CDSS) Irrigated Lands Geodatabase. Sampled points were treated as the centroids for delineating AHUs. AHUs were generated with 30, 60, 90, 120, and 180 meter diameters around these centroids, producing a total of 21,281 potentially-overlapping individual polygons with footprints of varying sizes. The AHUs were the fundamental spatial unit used to extract times series of evapotranspiration, normalized difference vegetation index (NDVI), and precipitation from the OpenET API.
Data source location	West Slope region, State of Colorado, United States of America
Data accessibility	Repository Name: Dryad, Data identification number: 10.5061/dryad.m905qfvf5

2.1 VALUE OF THE DATA

- Provides regional-scale aggregate information on seasonal ET patterns and totals with water conservation actions, and geographical characteristics of a diverse set of fields located on in the West Slope region of Colorado, USA.
- Reduces perceived barriers to entry for researchers who lack the technical skills to programatically retrieve big-data sets and/or relate time series data to geospatial data. Data is organized in a set of tables that include primary keys that will allow users to encode the data in a relational database.
- Researchers can analyze this data to explore and identify meaningful relationships between ET patterns, common water conservation practices (e.g., split season fallow, crop switching, etc.), crop and irrigation types, elevation, and a suite of soil characteristics at varying spatial and temporal scales.
- Researchers and policymakers can make use of this data for bounding expectations for water conservation programs enacted in different geographies in the Upper Colorado River Basin.

2.2 BACKGROUND

Persistent drought in the Upper Colorado River Basin over the last quarter century continues to strain existing water supplies and challenge the effective management of storage reservoirs and water delivery systems [1, 2, 3, 4]. The specter of a water management crisis on the Colorado River is looming larger with each passing month. Regional water administration agencies increasingly look to agricultural water conservation as an important tool for addressing current and future water supply and management challenges in the UCRB [5]. Recent agricultural water conservation pilot projects in Colorado yielded highly variable reductions in conserved consumptive use (CCU) [6, 7]. This variability will likely complicate future efforts to establish long-running water conservation programs designed to generate consistent and reliable volumes of CCU across the UCRB. This dataset provides timely and critical information to researchers interested in exploring the complex relationships between water conservation practices, geographical characteristics, and ET patterns at varying spatial and temporal scales.

2.3 DATA DESCRIPTION

The complete dataset includes CSV files, a ZIP archive containing a directory of PDF documents, and several GeoPackage files. The CSV files are structured to enable table joins as indicated in Figure 2.1. Each file is described below:

File: ahu_centroids.csv: Description: Table of randomly sampled centroid points used to delineate AHUs.

Variables:

- **ahu_centroid (PK):** Unique identifier for AHU centroids
- field_id (FK): Unique identifier for delineated fields
- utm13N_x: Easting in the UTM 13N projection (meters)
- utm13N_y: Northing in the UTM 13N projection (meters)
- elev_m: Elevation (meters) sampled form SRTM 30 m data coverage.
- mukey (FK): gNATSGO map unit key.
- PARCEL_ID (FK): Unique identifier for the mapped fields in the CDSS Irrigated Lands Geodatabase.
- MASTER_ID (FK): Companion identifier for PARCEL_ID.

File: ahu.csv: Description: Table of unique AHU unique identifiers

Variables:

- **ahu_id (PK)**: Unique identifier for individual AHUs.
- ahu_centroid (FK): Unique identifier of the ahu_centroid used to generate the AHU.
- ahu_diameter_m: Diameter of the AHU (meters).

File: ahu_et.csv: Description: Table containing daily time series of ET, NDVI, and precipitation for the 2016-2024 growing seasons for each of the AHUs. Data was extracted from the OpenET API [8].

Variables:

- ahu_id (FK): Unique identifier for individual AHUs.
- time: The date of observation.
- et: Evaoptranspiration computed by the eeMETRIC model (mm)
- ndvi: Normalized difference vegetation index
- eto: Grass reference ET (mm)

- etr: Alfalfa reference ET (mm)
- pr: Precipitation depth estimated by gridMET (mm)

File: fields.csv: Description: Table containing information about conservation activities performed on 392 fields delineated across Colorado's West Slope region.

Variables:

- **field_id (PK)**: Unique identifier for delineated fields.
- field_group: Grouping variable for fields that can be used to cross reference reporting documents contained in Conservation_Programs.zip.
- field_code: Grouping variable for fields that can be used to cross reference reporting documents contained in Conservation_Programs.zip.
- hectares: Computed area of the field (hectares).
- conservation_program: The name of the conservation program that the field participated in. Can be used to cross reference reporting documents contained in Conservation_Programs.zip.
- conservation_year_1: The first year during which water conservation activities took place.
- conservation_activity_1: The type of water conservation practice enacted in conservation_year_1.
- curtailment_start_date_1: The start of irrigation water curtailment during conservation_year_1.
- curtailment_end_date_1:The end of irrigation water curtailment during conservation_year_1.
- conservation_year_2: The second year during which water conservation activities took place.
- conservation_activity_2: The type of water conservation practice enacted in conservation_year_2.
- curtailment_start_date_2: The start of irrigation water curtailment during conservation_year_2.
- curtailment_end_date_2: The end of irrigation water curtailment during conservation_year_2.
- conservation_agreement_crop: The type of crop under irrigation noted in agreements

contained in Conservation_Programs.zip. Values here can be compared to the more complete listing of crop_type included in the cdss_centroids.csv table.

File: field_et.csv: Description: Table containing daily time series of ET, NDVI, and precipitation for the 2016-2024 growing seasons for each of the fields. Data was extracted from the OpenET API [8].

Variables:

- field_id (FK): Unique identifier for individual fields.
- time: The date of observation.
- et: Evaoptranspiration computed by the eeMETRIC model (mm)
- ndvi: Normalized difference vegetation index
- eto: Grass reference ET (mm)
- etr: Alfalfa reference ET (mm)
- pr: Precipitation depth estimated by gridMET (mm)

File: gNATSGO.csv: Description: An extract of the Map Unit Aggregate Attributes (muaggatt) table from gNATSGO. See the gNATSGO documentation for a complete description of table variables [9].

File: cdss_centroids.csv: Description: Table containing information from the CDSS Irrigated Lands Geodatabase for all mapped agricultural fields across the West Slope region of Colorado. See the CDSS GIS data pages for more information [10].

Variables:

- **fid (PK)**: Unique feature ID.
- OBJECTID: CDSS object ID.
- MAPPED_YEAR: The year that the field was mapped for revised in CDSS.
- WATER_DIVISION: The Water Division where the field is located.
- WATER_DISTRICT: The Water District where the field is located.
- PARCEL_ID (FK): A unique Parcel ID for the field.
- MASTER_ID (FK): A companion ID to the PARCEL_ID.
- CROP_TYPE: The CDSS mapped crop type.
- CROP_SOURCE: The source of the crop mapping/assignment.
- PERENNIAL: Perennial crop flag (True/False).
- IRRIG_TYPE: The CDSS mapped irrigation type.

- ACRES: The CDSS computed field acreage.
- SW_WDID1: The Well and Structure Identification Number (WDID) associated with the field's first surface water right.
- SW_WDID2: The WDID associated with the field's second surface water right.
- SW_WDID3: The WDID associated with the field's third surface water right.
- SW_WDID4: The WDID associated with the field's fourth surface water right.
- SW_WDID5: The WDID associated with the field's fifth surface water right.
- COUNTY: The county where the field is located.
- ELEV_m: Elevation (meters) sampled form SRTM 30 m data coverage. This is not an attribute from the CDSS Irrigated Lands Geodatabase.
- mukey (FK): gNATSGO map unit key. This is not an attribute from the CDSS Irrigated Lands Geodatabase.

File: Conservation_Programs.zip: Description: Archive containing public documents associated with the conservation programs referenced in the *conservation_program* field of the *fields.csv* table. Documents may be used to cross reference conservation program details assigned to a *field_id*.

File: cdss_westslope_field_centroids.gpkg: Description: Geopackage containing a point layer of centroids from agricultural field polygons included in the CDSS Irrigated Lands Geodatabase. Data may be used sample additional environmental variables and join them back to the other tables.

File: fields.gpkg: Description: Geopackage containing a polygon layer of delineated fields represented in the *fields.csv* file.

File: ahu_centroids.gpkg: Description: Geopackage containing a point layer of AHU centroids. Layer may be used to sample additional environmental variables and join them back to the other tables.

2.4 EXPERIMENTAL DESIGN, MATERIALS AND METHODS

The assembly of geographical information for agricultural fields on Colorado's West Slope required the collation and joining of datasets from various public data sources [9, 10, 11, 12]. Assembly of the dataset followed three distinct phases: delineation of agricultural fields involved in water conservation activities,

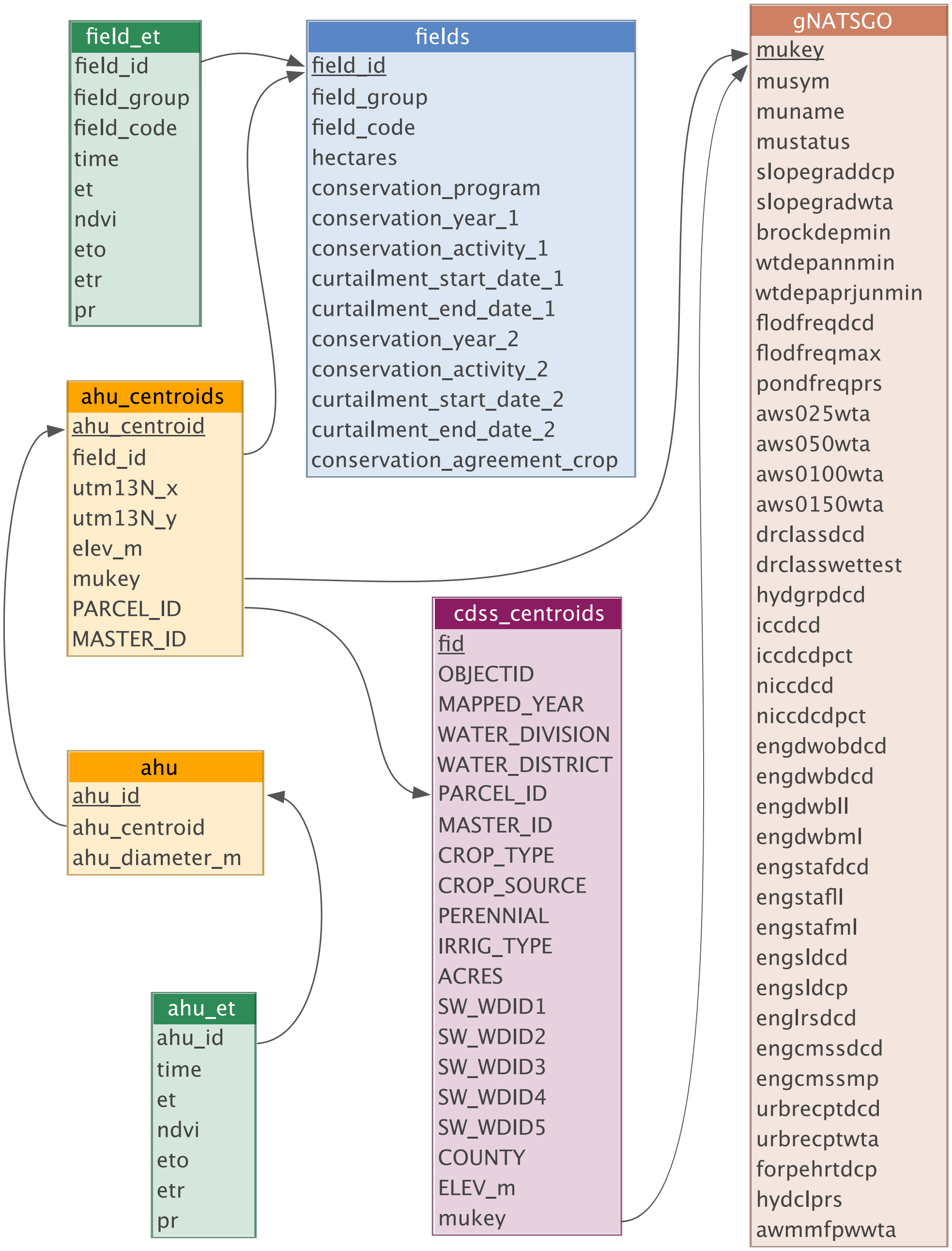

FIGURE 2.1. Entity-relationship diagram of the CSV table structures included in the dataset. Tables may be joined and queried using the Primary Keys (PK) and Foreign Keys (FK) noted in the file descriptions above and depicted in the graphic.

delineation of AHUs, and retrieval of ET time series. All spatial data processing was carried out in QGIS [13]. Programmatic data queries and data formatting tasks were developed and implemented in R [14]. Each phase of the data collection effort is described in the sections below.

2.4.1 FIELD DELINEATION

The effort to delineate fields involved in water conservation activities in the 2016-2024 period began with a search of public document repositories for water conservation agreements and relevant research reports from the focus area. Specifically, we sought documents related to the Grand Valley Conserved Consumptive Use Pilot Project (CCUPP), the System Conservation Pilot Program (SCPP), the Phase IIC Water Bank, the Tomichi Water Conservation Program, a research effort entitled Evaluating Conserved Consumptive Use in the Upper Colorado (Kremmling ECCU), and water leasing programs coordinated by the Colorado Water Trust (CWT). Many documents, including contracts for 2023 and 2024 SCPP projects were available on the Colorado Department of Water Resources Laserfische Weblink electronic document store. Other reports were procured from Colorado State University, via Internet searches, or through direct outreach to individuals and organizations involved in the aforementioned water conservation programs over the period of interest. The set of collated documents related to each conservation program is included in this dataset.

Paper maps, aerial images, and location descriptions in the available documents were used to identify conservation project fields. The boundaries of these fields were then hand digitized in QGIS. While the CCUPP ran in 2017 and 2018, the completed hand-digitization generally did not include fields that participated in 2017. Published maps of fields involved in 2023 SCPP and the Tomichi Water Conservation Program were either of poor quality or were unavailable, making hand digitization impossible. The Upper Colorado River Commission graciously provided a spatial layer for 2023 SCPP projects in Colorado. Trout Unlimited provided a spatial layer for fields involved in the Tomichi Water Conservation Program. Both spatial data layers were refined by hand in QGIS. All digitized fields were attributed with information about the participating water conservation program. Attributes included the year(s) water conservation was enacted and the start and end dates of conservation activities. If conservation program reporting documents mentioned the crop type on a given field, that information was also included. A total of 392 fields (the "conservation fields") were mapped and attributed in this manner (Figure 2.2). Each mapped field was provided a unique ID and two grouping attributes (i.e. field_group, field_code) reflecting names and codes assigned by a conservation program or otherwise referenced in reporting documents.

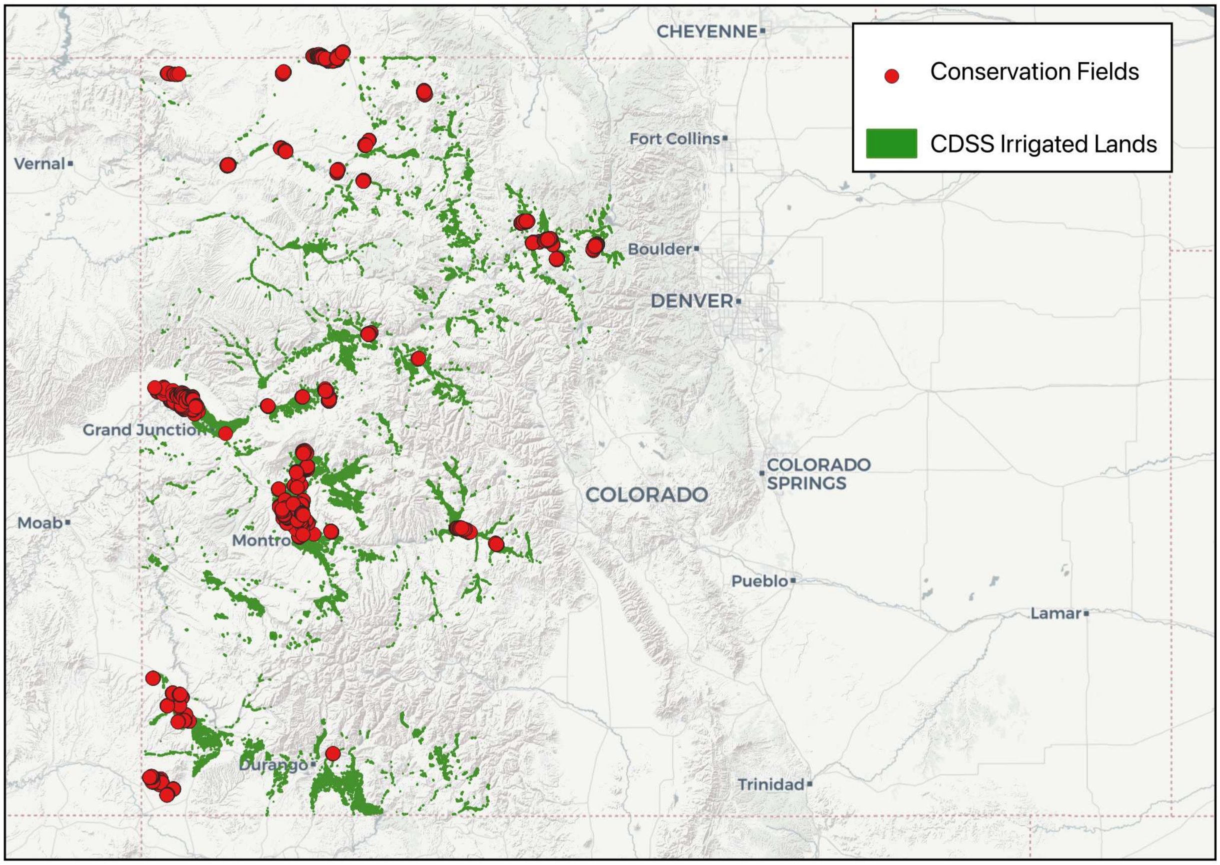

FIGURE 2.2. Delineated conservation field locations (red points) overlaid on fields included in the CDSS Irrigated Lands Geodatabase for Colorado's West Slope region (green polygons).

2.4.2 AGRICULTURAL HYDROPEDOLOGICAL UNITS

The process of delineating AHUs within the mapped conservation fields began by randomly sampling points within the field polygons. This random sampling was restricted to locations at least 45 m from the boundary of a field and at least 90 m from adjacent sample points. Some small fields were thus excluded from the random sampling effort. All random spatial sample processing was carried out in QGIS. Of the 392 mapped fields, only 367 contained random samples. AHUs could not be delineated on 25 small fields due to the restrictions placed on point placement. A total of 5,275 AHU centroids were delineated in this manner. SRTM elevations [12] and gNATSGO mukey values [9] were sampled at each AHU centroid and added as separate attributes. An effort was made to attribute AHU centoids with agricultural land characteristics stored in the CDSS Irrigated Lands Geodatabase [10]. Irrigated lands geospatial data layers were assembled for Water Divisions in the West Slope region. These layers included polygons of agricultural fields (the "CDSS fields") mapped by the Colorado Division of Water Resources.

Where individual AHU centroids intersected with CDSS fields, the PARCEL_ID attribute from the CDSS fields was added as an attribute to the AHU centroid. Addition of this foreign key to the AHU centroid dataset enables data users to perform joins between the two data sets. The centroid of each CDSS field was subsequently extracted and attributed with information from its parent polygon. SRTM elevations [12] and gNATSGO mukey values [9] were separately sampled at each CDSS field centroid and added as attributes to those centroids.

Individual AHUs with 30, 60, 90, 120, and 180 m diameters were delineated around each AHU centroid (Figure 2.3). The footprints of generated AHUs were allowed to overlap with adjacent AHUs but were not allowed to extend beyond the edge of a delineated conservation field. This imposed restriction, coupled with previously discussed restrictions on AHU centroid sampling significantly limited the placement and number of AHUs with diameters equal to 120 and 180 m. AHUs with diameters between 30-90 m were delineated on 367 of the 392 conservation fields. AHUs with 120 m diameters were delineated on only 300 fields, while AHUs with 180 m diameters were delineated on a smaller subset totaling 212 fields. A total of 5,275 AHUs were delineated with a diameters equal to 30, 60, and 90 m. A total of 3,369 AHUs were delineated with a 120 m diameter and only 2,087 were delineated with a 180 m diameter. Each AHU was assigned a unique ID and attributed with its diameter and its parent AHU centroid. The generation of AHUs took place in QGIS [**QGIS**].

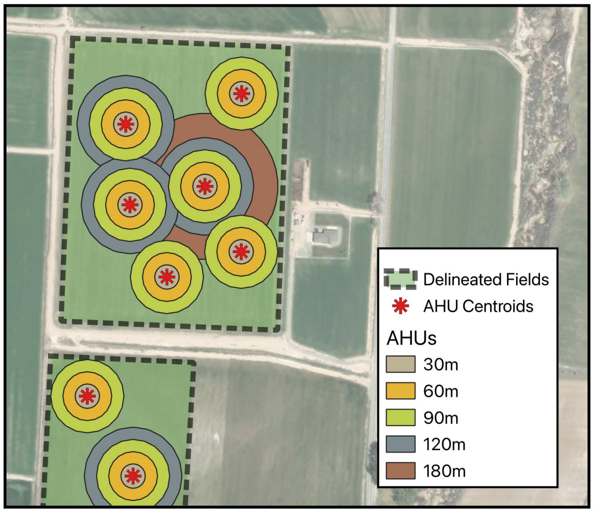

FIGURE 2.3. Example delineation of AHUs on pair of mapped conservation fields.

2.4.3 EVAPOTRANSPIRATION TIME SERIES

Mapped conservation fields and delineated AHUs were used to extract ET time series from the OpenET API [8]. All programmatic data retrieval tasks were preformed in R [14]. Daily time series over the growing season (Apr-Oct) were extracted for years between 2016-2024. Variables returned by the OpenET API [8] for the land areas associated with individual AHUs and for entire fields included NDVI and estimates of ET produced by the METRIC model [15, 16]. Variables returned separately for the footprints of individual fields included reference ET for grass (ETo), reference ET for alfalfa (ETr), and gridMET [17] precipitation (PR) estimates. The ET data for AHUs was joined to the ET data for fields such that each AHU inherited daily ETo, ETr, and PR values from its parent field. All post-processing and data manipulation tasks were performed in R [14]. The resulting post-processed dataset included ET, ETo, ETr, and PR time series for the 2016-2024 growing seasons for 392 fields, 5,275 AHUs with 30 m diameter, 5,275 AHUs with 60 m diameter, 5,275 AHUs with 90 m diameter, 3,369 AHUs with 120 m diameter, and 2,087 AHUs with 180 m diameter (Figure 2.4).

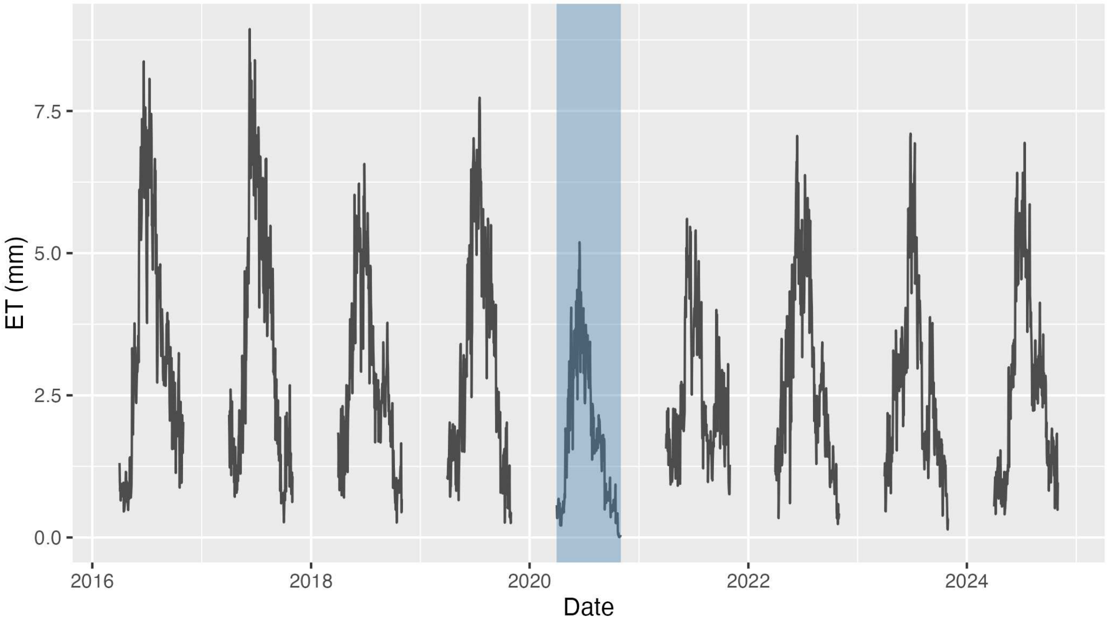

FIGURE 2.4. Seasonal ET time series from a single conservation field. A period of water conservation practice (2020-04-01 to 2020-11-01) is indicated in the blue shaded area.

2.5 LIMITATIONS

Fields subjected to water conservation activities were delineated by hand using maps, figures and aerial images contained in relevant program reports and agreements. Some error in the delineation of field boundaries is possible. Geographical data associated with AHU centroids may not be characteristic of the dominant characteristics of the entire AHU. Some delineated agricultural fields and AHUs did not intersect with irrigated lands mapped in the CDSS. This limited our ability to join the entire AHU dataset to CDSS geospatial data. While we assume that the years noted for conservation program participation in the fields.csv file are the only years in the 2016-2024 period when fields were subjected to water conservation practice, it is possible that conservation activities or other sorts of voluntary or involuntary irrigation curtailment were enacted by agricultural producers on any given field in other years of the record.

2.6 ETHICS STATEMENT

All data collated and published here were procured from public sources. No personal identifiers associated with agricultural fields, beyond those included in public reports and water conservation agreements, were added to the data.

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CHAPTER 3

THE GEOGRAPHY OF CONSERVATION: LOCATION AND PRACTICE DRIVE AGRICULTURAL WATER CONSERVATION OUTCOMES IN WESTERN COLORADO.

3.1 INTRODUCTION

The unfolding water supply and management crisis in the Colorado River Basin is forcing water administrators and policy makers to explore new strategies for managing supplies from a diminishing snowpack and operating reservoirs under a trend of progressive depletion [1, 2, 3, 4, 5, 6, 7, 8]. The challenges at hand affect both the Lower Colorado River Basin (LCRB) and Upper Colorado River Basin (UCRB) differently, but both basins identify water conservation by agricultural water users as an important tool for enhancing the sustainability of water use that supports over 40 million people across numerous sectors. Explicit support for voluntary and compensated conservation activities among agricultural users comes from funding and programs enacted through federal legislation [9] and from commitments articulated in regional water planning documents [10].

Water conservation activities in the LCRB may be an important long-term strategy for addressing the basin's water supply "structural deficit", a term that represents the regular imbalance between inflows and outflows to the major reservoirs that supply Colorado River water to California, Nevada, and Arizona. In any given year, outflows from Lake Mead regularly exceed inflows to the Lake Powell - Lake Mead system. Over the previous quarter century, this imbalance, persistent drought, and operational strategies outlined in the 2017 Interim Guidelines [11] and the 2019 Drought Contingency Plan [12] conspired to substantially reduce storage volumes in both reservoirs [13]. The combined reservoir storage volumes of Lake Powell and Lake Mead fell from near 100% of capacity in the year 2000 to approximately 37% as of August, 2025 [14]. In response to these low reservoir volumes and direction for the U.S. Bureau of Reclamation (USBR) to implement conservation actions to stabilize reservoir storage [15], the LCRB implemented projects that conserved approximately 1.85e+9 m^3 between 2023 and 2024. An additional 1.85e+9 m^3 of conservation is expected between 2025-2026. These efforts include temporary fallowing of agricultural land, deficit irrigation, municipal water conservation, residential turf replacement programs, and conveyance system upgrades. LCRB conservation programs are supported by a one-time 4 billion USD investment from the Inflation Reduction Act [9]. Due to the operational agreements used to manage storage volumes in Lake

Powell and Lake Mead and the geographical orientation of reservoirs, canal systems and points of water use, conservation activities by water users in the LCRB inevitably leads to an accrual of physical water in Lake Mead and becomes available for future use by LCRB water users.

Water use is generally more decentralized in the UCRB than in the LCRB. While numerous large canal systems exist in the UCRB (e.g., Colorado's Grand Valley Project and Uncompahgre Project), most agricultural, municipal and industrial users receive water from direct surface flow diversions from streams and rivers that are not augmented by reservoirs and are thus exposed to inter-annual hydrological variability driven by a changing snow pack. In most settings, upstream reservoirs are not available for storing conserved water for future use. This situation is further complicated by existing water rights regimes and a lack of administrative authorities or legal bases to accrue conserved water in headwaters reservoirs. In 2019, the UCRB states of Colorado, Wyoming, Utah and New Mexico developed a Drought Contingency Plan that allocated 6.17e+8 m^3 of multiyear storage in Colorado River Storage Project (CRSP) reservoirs (i.e. Flaming Gorge Reservoir, Navajo Reservoir, the Aspinall Unit, and Lake Powell) for the purpose of storing physical water generated through conservation activities [16]. This plan was not accompanied by guidance for the implementation or coordination of Demand Management–a term used to describe voluntary, compensated, and temporary water conservation–in the Upper Basin states that would be necessary to contribute water to this storage account. As a result, conservation projects enacted in the UCRB in recent years failed to generate physical water supplies that could be managed to stabilize reservoirs or reduce risks of legal disputes over water delivery obligations outlined in the Colorado Compact.

The UCRB piloted large-scale water conservation efforts under the System Conservation Pilot Program (SCPP) in 2015-2018 and then again in 2023-2024. Water savings in the UCRB in the two most recent years of SCPP implementation were much lower than their counterpart savings in the LCRB. Water conservation projects enacted by Upper Basin agricultural users in 2023 yielded 3.35e+7 m^3 of water savings. SCPP projects were expected to conserve upwards of 8.32e+7 m^3 of water, largely through full season irrigation curtailment, split season irrigation curtailment or crop switching on agricultural fields. The dominance of agricultural water conservation among the mix of projects enacted under SCPP reflects the dominance of that sector of overall water use in the UCRB. Of the approximately 6.39e+9 m^3 of consumed Colorado River water in the UCRB, 4.38e+9 m^3 (~68%) is allocated to agricultural uses. All conserved consumptive water use generated by agricultural water conservation activities under SCPP in the UCRB was reverted to "system water"–water freely available to other upstream or downstream water users. No administrative shepherding of conserved water occurred and no water was accrued into the CRSP reservoir storage account established in the 2019 Drought Contingency Plan.

Unlike the LCRB where the non-use of water due to conservation activities implemented by downstream water users produces a storage accrual that can be readily quantified as equivalent to the reduction in annual reservoir releases from Lake Mead, effective accounting and administration of water generated through conservation activities in the UCRB requires verifiable estimates of changing seasonal consumptive use patterns at the scale of individual fields and the careful tracking of physically and administratively available water from the historical point of diversion to a downstream reservoir, including incidental transit losses along the way. The evaluation of physically and administratively available water at a historical point of diversion, the downstream shepherding of conserved water volumes, and the accounting for and administration of these volumes in storage reservoirs pose unique challenges that, given sufficient investment and attention, may largely be resolved through policy development and application or extension of existing engineering techniques. The quantification of conservation outcomes at the scale of individual fields, however, is a topic that can benefit from applied research that produces new measurement strategies or assessment methodologies.

Agricultural water users in the UCRB who volunteer to participate in temporary and compensated conservation under SCPP receive credit and financial reparation commensurate with the expected conserved consumptive use (CCU) on a field. CCU represents the change in consumptive water use on a field during a period of conservation compared to a typical irrigated condition. No standard for characterizing typical conditions exists in policy or in practice. In its most basic form, estimating CCU is an attempt at closure of a field-scale water balance, nested within a basin-scale water balance. Conceptually, irrigation water applied to a field during the growing season may be partitioned into surface water runoff, infiltration to groundwater, evaporation from free water surfaces, and transpiration from plants. The surface runoff and groundwater infiltration components are considered incidental as they do not remove water from the basin-scale water balance. Evapotranspiration (ET) is the primary component of interest to agricultural water conservation programs, since water evaporated and transpired from a field is considered removed from the basin-scale water balance. In other words, 100% of the water removed from the field through ET is considered lost to the system. Computation of CCU, therefore, can rely on comparisons of seasonal ET volumes accrued during periods of water conservation practice to volumes accrued during typical irrigation practice. Unfortunately, ET is often the most uncertain component of agricultural water balances in semi-arid settings like those prevalent across Colorado's West Slope [17].

The challenges associated with using seasonal ET patterns as the primary surrogate for CCU largely hinge on the characterization of baseline conditions. Measuring or estimating ET in any given irrigation season is relatively straightforward, if technologically demanding. Approximating what ET might have been under typical irrigation in periods when conservation actions are in place is much more philosophically and methodologically challenging. How do we define "typical" irrigation on any given field? Does typical irrigation include periods of abnormally wet or dry conditions? How do we account for or disregard periods of land ownership transition, sickness, economic malaise, or other external drivers that may affect farm or ranch operations, including irrigation strategies, in any given year? Is it better to characterize baseline conditions using the historical record of a given field or establish a nearby reference field as a proxy for reference conditions during the implementation of water conservation projects? If we select the latter, how do we accommodate the potential for non-linear differences in inter-annual CCU variability between operations on the conservation field and the selected reference field. In the absence of robust research into the reliability of different methodologies for establishing baseline conditions, clear policy direction on the matter is unlikely.

The selection of robust conceptual, spatial and temporal frames of reference for the establishment of baseline conditions is critical for evaluating the effectiveness of various conservation strategies across broad and diverse geographies. Furthermore, the failure to marry a methodology for baseline condition establishment with coherent prediction frameworks for site-specific CCU outcomes will continue to vex efforts to anticipate the return on investment for any given water conservation project. This point is illustrated by the differences between anticipated and observed CCU outcomes for SCPP projects enacted across the UCRB in 2023. The total CCU volume for all UCRB projects enacted under 2023 SCPP was 19% lower than estimates used during contract development for conservation activities [18]. For individual projects, the volume of water conserved per hectare was 1,832 +/- 303 m^3 lower than expectations set forward in conservation contracts. The mean contracted price for conserved water under 2023 SCPP was 0.38 USD/m^3. The lower than expected CCU volumes increased the realized cost of contracted water across most projects, in some cases, significantly (Figure 3.1).

Discrepancies between expected and realized CCU volumes produced through contracted conservation program activities carry a two-fold risk. First, persistent bias in CCU expectations, particularly where expectations are higher than outcomes can make it challenging to calibrate program efforts enacted to meet a specific conservation target. Second, where contracted compensation rates are set based on expected CCU outcomes, one of the contract parties bears a risk for lower than expected returns. In the

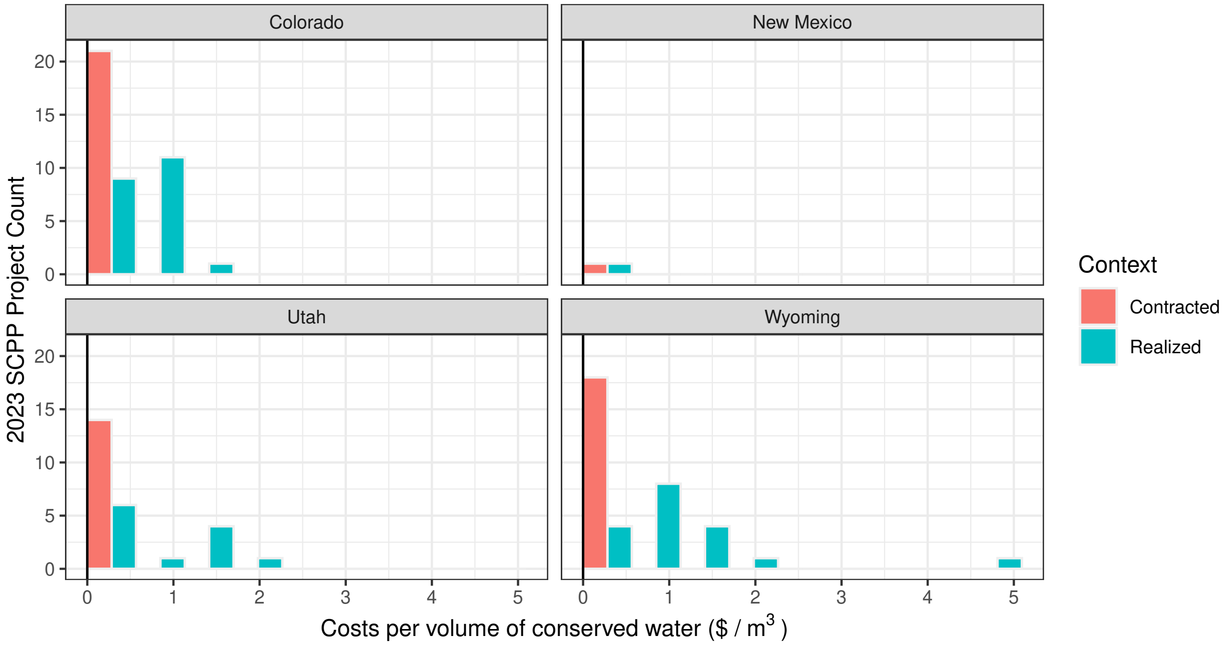

FIGURE 3.1. Contracted vs. realized costs for water conserved by SCPP projects in the UCRB in 2023.

case where CCU outcomes underperform expectations, the state or the entity funding the conservation activities bears the risk of overpayment for conserved water. In the case where CCU outcomes outperform expectations set forward in conservation contracts, the water user bears the risk of lower than expected compensation for conservation activities on a per-volume basis. In this way, a lack of a priori information about potential CCU outcomes inhibits efficient allocation of scarce resources in the water conservation marketplace. The development of new methodologies for more accurate prediction of CCU outcomes under different water conservation practices at the field scale is needed to avoid sub-optimal water conservation market conditions in the UCRB.

The observed differences between expected and observed CCU outcomes associated with 2023 SCPP projects in the UCRB suggest that opportunity exists to improve upon methodologies currently employed for characterizing baseline conditions and evaluating changes in CU patterns during periods of conservation. This work explores the influence of different conservation practices and environmental factors that govern CCU outcomes on agricultural fields in the UCRB. The intention is to move beyond a simple evaluation of whether or not water conservation activities actually save water, as reported elsewhere [19], to a more detailed exploration of the mechanistic controls on conservation outcomes. This topic is structured as a two-stage exploration guided by a pair of linked hypotheses:

- H1: The suite of conservation practices typically applied to agricultural fields create statistically identifiable temporal patterns in seasonal ET data.

- H2: Between-field variability in CCU outcomes can be explained by interactions between varied conservation strategies and measurable environmental factors.

The first hypothesis establishes a foundational question: can time series ET data be used to meaningfully differentiate one water conservation strategy from another (e.g., full season fallow vs split season fallow) and from periods of normal irrigation practice. If conservation strategies cannot be differentiated from each other or from typical irrigation activities, then any further efforts to evaluate the environmental controls on CCU at the field scale will be highly uncertain. The second hypothesis moves from pattern detection to explanation and guides the use of seasonal ET time series data to explore the various environmental and geographical controls on the magnitude of consumptive water use reductions associated with commonly employed conservation strategies.

3.2 Focus Geography and Primary Data Sources

Among the Upper Basin States, Colorado consumes the greatest portion of Colorado River water in any given year. The largest water use sector for Colorado River water within the state of Colorado is irrigated agriculture. As a result, the areas of primary interest to this study include agricultural parcels on Colorado's West Slope. Among these West Slope fields, those that participated in some type of water conservation program in recent years are particularly well suited to this study.

Several water conservation programs were available to agricultural water users in western Colorado in recent years, including the Grand Valley Conserved Consumptive Use Pilot Project (CCUPP), the System Conservation Pilot Program (SCPP), the Phase IIC Water Bank, the Tomichi Water Conservation Program, a research effort conducted near Kremmling, CO [20], and water leasing programs coordinated by the Colorado Water Trust (CWT). Mapping the individual fields that participated in these efforts provided a rich feature set for evaluating ET patterns that manifest under different conservation strategies. Hand digitization of individual fields was carried out in QGIS [21]. Attribute tables were populated for each field indicating the start and end dates of water conservation practice. A total of 392 fields spanning a diverse set of geographies were mapped and attributed in this manner (Figure 3.2).

A set of 21,281 distinct Agricultural Hydropedological Units (AHUs) were delineated across the set of mapped fields. The delineation of AHUs began with a random placement of points within each field boundary. Locations were constrained such that they did not occur within 45 m of a field boundary. Each

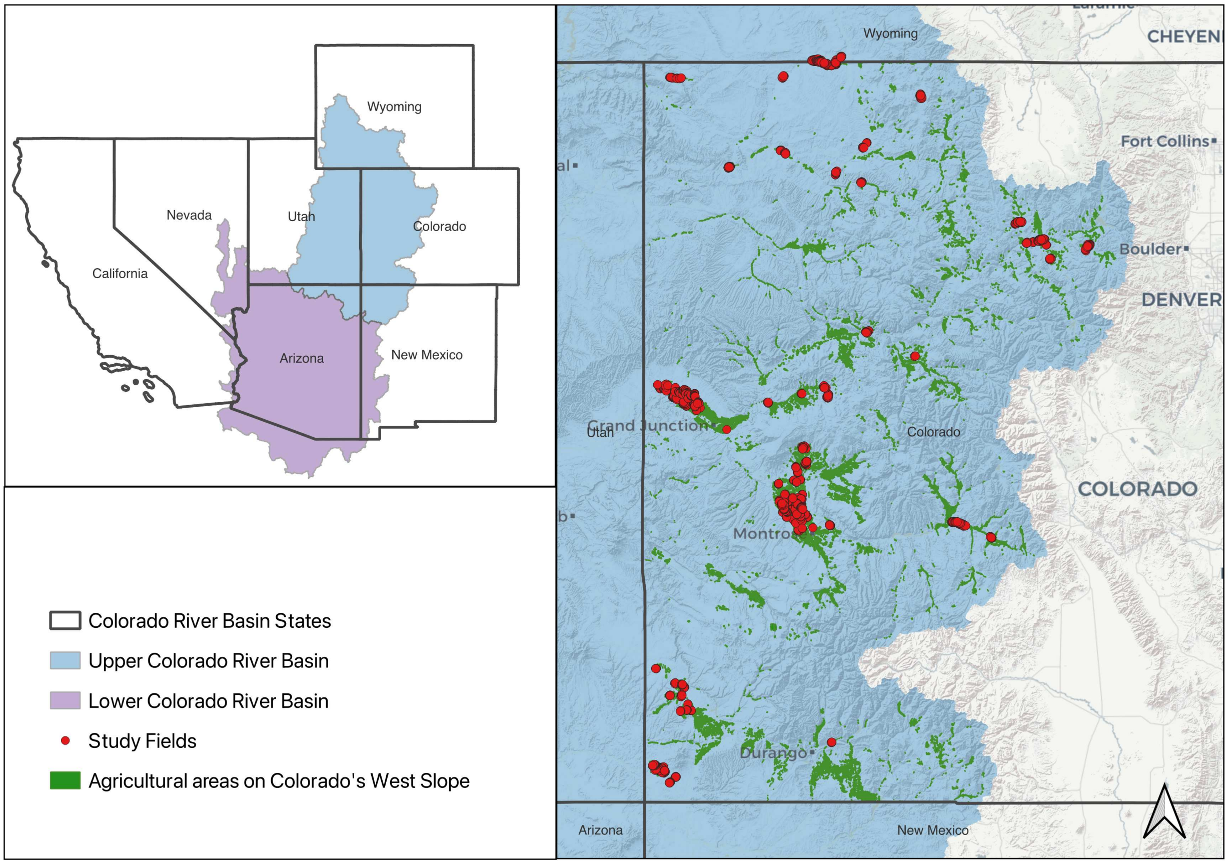

FIGURE 3.2. Study fields positioned within the UCRB on Colorado's West Slope include diverse geographies that span multiple sub-basins.

sample point was attributed with SRTM elevations [@ShuttleRadarTopography2000] and gNATSGO mukey values [22]. Concentric circular polygons with diameters of 30, 60, 90, 120, and 180 m were subsequently delineated around each of the sample points. These polygons were established as AHUs (Figure 3.3). Each AHU was joined with the attribute information for its centroid point. Any AHU that extended beyond the bounds of its parent field was removed from the dataset. All spatial operations were carried out in QGIS.

The dataset included fields subjected to various water conservation practices. A relatively small number of fields implemented crop switching. These fields were removed from the analysis due to the lack of representation across diverse geographies. The remaining fields implemented some form of irrigation curtailment in one or more years, differentiated by the start and end dates of the practice. Three distinct conservation practice categories were defined for this analysis. Field-year pairs where irrigation curtailment began on or before week 20 and lasted for at least 23 weeks were classified as Full Season Curtailment (Full Season). Field-year pairs where irrigation curtailment began on or before week 20 but lasted less than 23 weeks were classified as Split Season Early Curtailment (Split Season Early). Where and when irrigation curtailment began after week 20, field-year pairs were classified as Split Season Late Curtailment (Split Season Late). All other field-year pairs were classified as Normal Irrigation.

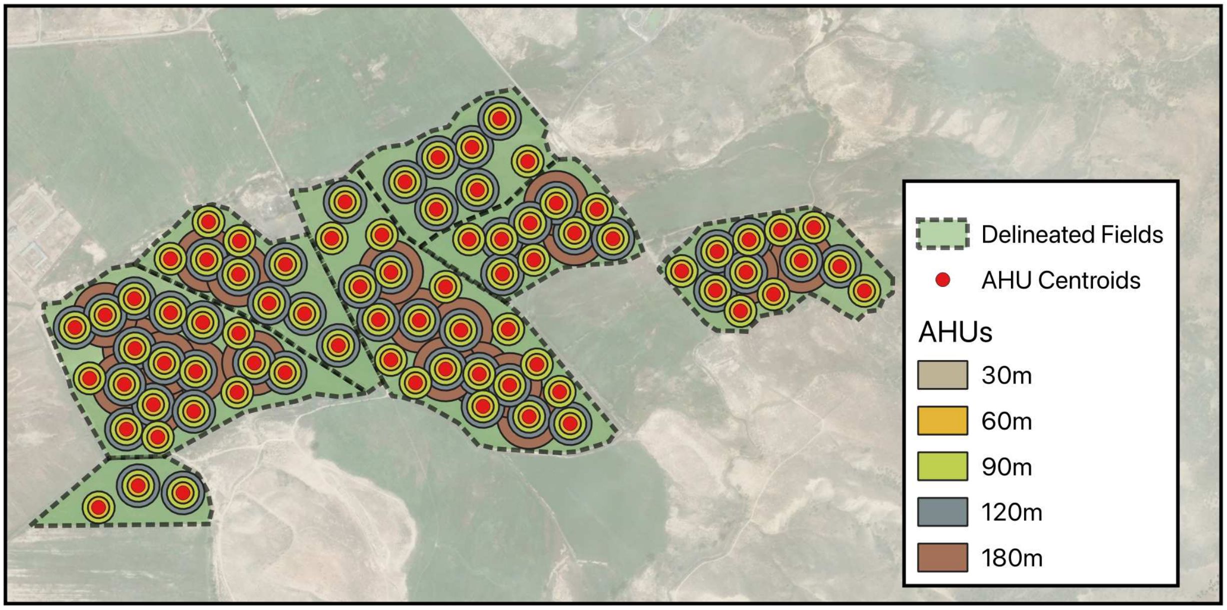

FIGURE 3.3. Nested orientation of AHUs with varying diameters randomly placed within fields that participated in water conservation activities in at least one year in the 2018-2024 period.

3.3 METHODS

Data analysis tasks carried out on data collected in Colorado's West Slope region included an initial characterization of ET time series using metrics of CCU and seasonal anomalies of ET and precipitation. A time series pattern recognition and classification effort was carried out using the computed CCU metrics. Finally, a Bayesian hierachical model was fit to the available data in order to assess the degree to which various conservation practices and environmental variables influence seasonal consumptive use reductions.

3.3.1 COMPUTATION OF ET METRICS AND ANOMALIES

Seasonal ET rates on a given field are expected to reflect irrigation activities, cropping patterns, soil characteristics, and seasonal temperature profiles. Reliable estimates of ET, a typical surrogate for consumptive water use, over irrigated croplands are, thus, necessary to characterize CCU outcomes associated with water conservation practices. Historically, practitioners and water managers in the UCRB relied on the empirical, coefficient-based Blaney-Criddle method to calculate reference ET (ET_{ref}) for different drop types (e.g., grass and alfalfa). ET_{ref} approximates the consumption of water by a crop under optimal irrigation conditions. More recently, the mechanistically based Penman-Monteith method began to displace Blaney-Criddle as the dominant means for computing ET_{ref} in many semi-arid agricultural regions [23]. Both methods are relatively easy to implement and require limited and widely available meteorological data from nearby weather stations. In semi-arid irrigated lands where water conservation entails fallowing an annual crop (e.g., corn), the presumed ET during the fallow period is near zero. The conserved consumptive use volume can then be approximated by integrating the ET_{ref} time series for the irrigation season. This approach hinges on a key assumption that actual ET in a conservation period would be equivalent to ET_{ref} under normally irrigated conditions. The validity of this assumption in high elevation mountainous settings is questionable. This approach also leads to verification challenges since it is largely a desktop method that is not reliant on data collected at the field of interest. Neither is this method well-suited to estimating consumptive water use reductions where water conservation measures are applied to perennial crops like grass or alfalfa that dominate agricultural landscapes across the UCRB. In these cases, the actual ET during a fallow period is non-zero, since the plants continue to grow and extract water from the soil column. ET must be measured or estimated at the field scale to ascertain consumptive water use reduction volumes for perennial crops. Measuring actual ET at the field scale requires the application of direct measurements or remote sensing techniques.

Direct, field scale estimates of ET under typical irrigated conditions and during the implementation of water conservation activities can be procured through the installation of weighing lysimeters or eddy covariance towers. These measurement techniques typically generate highly accurate ET estimates [24]. However, their scalability is limited by the high financial costs and personnel required for the installation, operation, and maintenance of the equipment. Emerging technologies are enabling accurate point-based estimates of ET across large spatial domains. Recent advances in remote sensing image analysis yielded a suite of algorithms that estimate ET across large land areas using readily available satellite imagery. Algorithms like Surface Energy Balance Algorithm for Land (SEBAL) [25] and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) [26, 27, 28] solve the energy balance for individual 30-meter pixels in a satellite image. These algorithms estimate ET as the residual between available energy and sensible heat flux [17]. ET estimates can be generated for a given field at the frequency of imagery collection from Landsat satellites, approximately every 8 days. Application of these methods represents a powerful means for accurately and reliably estimating reductions in crop consumptive use at the field scale during the performance of various water conservation activities.

The OpenET platform implements several ET estimation algorithms, including SEBAL and METRIC, and makes ET data accessible and widely available to the research community and the public at large [29]. Volk, et. al [30] evaluated ET estimates from the suite of OpenET's algorithms and an ensemble model and found that the convenience and cost-effectiveness of remotely sensed approaches to ET estimation come at the cost of some degradation in accuracy. Fortunately, the same research found that the OpenET algorithms performed best in semi-arid settings common across much of irrigated land in the UCRB. Recent work conducted by researchers near Kremmling, Colorado, showed that, among the algorithms provided by OpenET, the METRIC model performed best when assessed against data collected from a locally installed eddy covariance tower [20]. Time series ET data procured from OpenET was selected as an efficient means for characterizing CCU outcomes on individual AHUs delineated on agricultural fields on Colorado's West Slope.

Daily ET time series data extending between January 2016 and December 2024 were retrieved from the OpenET API [31] for the areas defined by each AHU. Data retrieved for each AHU included reference ET for grass (ET_o), reference ET for alfalfa (ET_r), GridMET precipitation totals (P), and actual ET estimates from the METRIC model. Incomplete records for numerous fields for the 2016 - 2017 period led to exclusion of those years from the analysis.

A series of data processing steps were implemented to isolate the portion of the ET time series signal driven by consumptive use of irrigation water. Effective precipitation (P_{eff})-the fraction precipitation available for consumption by crops–was computed for each AHU at each monthly time step using the commonly employed USDA-SCS method, as parameterized for alfalfa and grass hay fields in the UCRB by Aboutalebi et al. [32] (Equation 3.1).

$$P_{\text{eff},t} = 0.87(1.253P_t^{0.824} - 2.935)(10^{0.001ET_t}) \tag{3.1}$$

Where:

- P_{eff} (mm) was computed on GridMET estimates of total precipitation (P), aggregated to the monthly time step in keeping with the data requirements of the empirically derived equation.

Monthly P_{eff} values were then disaggregated back down the weekly and fortnightly time scales based on the fractional allocation of precipitation estimated for each time step. The final metric values represented an estimate of crop water deficit (D)–the amount of water (mm) consumed by a crop that was not supported by precipitation–at each time step (Equation 3.2, Equation 3.3).

$$D_t = max(0, ET_t - P_{\text{eff},t}) \tag{3.2}$$

$$D_{\text{baseline},t} = \text{median}(D_t \mid t \in \text{Normal Irrigation Years}) \tag{3.3}$$

Where:

- ET is the METRIC model estimate of evapotranspiration (mm) measured across the AHU at time step t. Positive values for D represent the portion of crop water use supported by irrigation or depletion of soil moisture. In order to ensure numerical stability in the calculation of the $D_{baseline\text{-}ratio}$ (Equation 3.5) in the presence of low baseline crop water deficit values, the data set was programatically truncated to remove the 5th percentile of samples producing the lowest annual D totals. Remaining values for D were normalized to ET_{ref} (mm) where ET_{ref} was set to the reference ET for grass (ET_o) or alfalfa (ET_r), based on the crop grown on the AHU's parent field (Equation 3.4).

$$D_{\text{ratio},t} = D_t / ET_{\text{ref},t} \quad \text{where} \quad ET_{\text{ref},t} = \begin{cases} ETo_t & \text{if crop} = grass \\ ETr_t & \text{if crop} \neq grass \end{cases} \tag{3.4}$$

Where:

- D_{ratio} is the relative water deficit for a given time step t.

Annual time series for each AHU were partitioned between years when conservation activities occurred and years when normal irrigation practices were in place. Baseline conditions for D_{ratio} were established using summarized data from normal irrigation years (Equation 3.5). Baseline conditions for P (Equation 3.6) and ET_{ref} (Equation 3.7) were established using summarized data from all years between 2018 and 2024.

$$D_{\text{baseline-ratio},t} = \text{median}\{D_{\text{ratio},t} \mid t \in \text{Normal Irrigation Years}\} \tag{3.5}$$

$$P_{\text{baseline},t} = \text{median}\{P_t \mid t \in \text{All Years}\} \tag{3.6}$$

$$ET_{\text{ref-baseline},t} = \text{median}\{ET_{\text{ref},t} \mid t \in \text{All Years}\} \tag{3.7}$$

For sub-annual time steps and in years where conservation activities occurred, anomalies in crop consumptive use were assessed as the difference between the D_{ratio} observed at a given time step and the $D_{baseline\text{-}ratio}$ computed over the years when normal irrigation practices were in place (Equation 3.8).

$$D_{\text{anomaly},t} = D_{\text{ratio},t} - D_{\text{baseline-ratio},t} \tag{3.8}$$

Where:

- $D_{anomaly}$ is a unitless ratio representing the change in percentage points of crop water deficit compared to the same time step under typical conditions for the same AHU.

The $D_{anomaly}$ metric characterizes the change from baseline conditions in the amount of water consumed by a crop relative to the total atmospheric demand for water. A value of zero indicates a crop water deficit that is equivalent to baseline conditions, while a negative value indicates an increasing crop water deficit and a reduction in consumptive water use. The use of an additive ratio was selected over other potential strategies for normalizing the crop water deficit to expectations under the baseline condition. The $D_{anomaly}$ calculation (Equation 3.8) was deemed superior to other approaches due to its sensitivity to the effects of unique weather conditions in any given time step, while avoiding statistical instability that would result from use of a multiplicative ratio in cases where $D_{baseline\text{-}ratio}$ was near zero. This metric was of primary interest for time series pattern detection and classification since it is well suited to understanding the change in crop consumptive use at individual time steps across a year, while normalizing for the time-variant impacts of changing atmospheric conditions.

The calculation of annual total impacts of water conservation activities proceeded in a slightly different manner. The primary metric of interest at annual time scales was the total change in consumptive water use within an AHU. The annual change in irrigation water Consumptive Use within an AHU, CU_{diff} was computed relative to baseline conditions (Equation 3.9).

$$CU_{\text{diff},Y} = \sum_{t \in Y} (D_t - D_{\text{baseline},t}) \tag{3.9}$$

Where:

- $CU_{diff,Y}$ is a representation of the annual change in the depth of irrigation water (m) evapotranspired from a given AHU in year (Y).

This metric allowed us to characterize the cumulative seasonal impact of different water conservation practices. It also served as the response variable of interest for for Bayesian Hierarchical model development. The primary drawback of this metric compared to $D_{anomaly}$ is the lack of normalization to variable meteorological conditions. Annual precipitation anomalies ($P_{anomaly}$) (Equation 3.10) and reference ET anomalies ($ET_{anomaly}$) (Equation 3.11) were computed as companion metrics to account for the seasonal impacts of evaporative demand and precipitation on CU_{diff}.

$$P_{\text{anomaly,Y}} = \sum_{t \in Y} \left(P_t / P_{\text{baseline},t} \right) - 1 \tag{3.10}$$

$$ET_{\text{anomaly,Y}} = \sum_{t \in Y} \left(ET_{\text{ref},t} / ET_{\text{ref-baseline},t} \right) - 1 \tag{3.11}$$

3.3.2 Time Series Pattern Detection and Classification

Time series classification was performed on seasonal $D_{anomaly}$ values computed at varying spatial and temporal scales in order to identify the optimal reference frame for detecting unique water conservation practices from ET time series data. Time series classification proceeded for all combinations of distinct AHU diameters (i.e. 30, 60, 90, 120, and 180 m) and time intervals used in the characterization of consumptive use anomalies (i.e. week, fortnight, and month). Individual seasonal time series (Apr - Nov) of $D_{anomaly}$ (Equation 3.8) values computed for each AHU in each year of the record were treated as the basic temporal series input for the classification engine.

Seasonal AHU time series were partitioned by AHU diameter and time interval and subjected to data standardization and cleaning protocols. The modal value for seasonal time series length was computed for each partition. Any series shorter or longer than this modal value were removed from the partition. This step ensured that fragmented series were excluded from the time series classification and that the analyzed series were all of equivalent length. Each partition was then split into five folds. Imbalances among the number of individual time series characterizing Normal Irrigation, Split Season Early, Split Season Late, and Full Season present in each fold were resolved through down-sampling. The conservation activity class with the smallest number of seasonal records was identified. Random down-sampling from the other conservation activity classes proceeded until all classes exhibited the same number of seasonal records. This rebalancing approach was used to ensure that the classification engine did not disproportionately weight the time series characteristics of the Normal Irrigation category.

A Dynamic Time Warping (DTW) algorithm from the *dtwclust* and *proxy* libraries in R[33] was used to characterize the similarity in the time series patterns present within each fold. Application of DTW to seasonal time series data provides a means for identifying similar time patterns, even if those patterns are out of phase. DTW identifies similarities by warping the time axis and computing the minimum cumulative cost distance between the warped points in two series [34, 35]. This approach is particularly well suited to identifying and clustering similar time series where the underlying signal of interest is predominately expressed as unique shape. The conservation activities of interest to this study are expected to manifest as unique patterns in the ET time series data. For example, Full Season is expected to produce a $\mathrm{D}_{\mathrm{anomaly}}$ series that drops at the beginning of the irrigation season and remains low through the end of the season. $\mathrm{D}_{\mathrm{anomaly}}$ patterns associated with the Late Season Curtailment are expected to reflect Normal Irrigation early in the season, then drop near the end of the season. Differences among the start and end dates of similar conservation practices (e.g., August 1st vs. August 15th for Late Season Curtailment) implemented on different fields is expected to shift the temporal position of the characteristic $\mathrm{D}_{\mathrm{anomaly}}$ behavior for a given conservation activity.

The employed classification algorithm used a k-NN approach to classify time series in each fold of the partitioned data where an individual $D_{anomaly}$ series in a test fold was assigned to the majority conservation activity class of its three nearest neighbors (in DTW space) in the corresponding training fold. The performance of the individual classification models (e.g., 30 m fortnightly model vs. 90 m monthly model) was assessed on the cross-validation outputs. The balanced accuracy of each model was computed using the *yardstick* library in R. The balanced accuracy metric provides a combined measure of model specificity and sensitivity where sensitivity is the proportion of true positives identified by the model and specificity is the proportion of true negatives identified by the model [36]. The classification skill of the best performing model was further evaluated through examination of confusion matrices and plots of the conservation activity class barycenters.

3.3.3 BAYESIAN HIERARCHICAL MODEL DEVELOPMENT

The interplay between water conservation strategies, environmental factors, and CCU outcomes was explored by fitting the $CU_{diff,Y}$ data from each AHU to a Bayesian hierarchical model. A hierarchical model structure was selected to accommodate the nested data structure where a set of AHUs are nested within a field. This structure reflected a governing assumption that all areas within a field were generally subjected to similar irrigation or water conservation practices with a given year and that the within-field environmental characteristics were more similar than between-field environmental characteristics. Model development and fitting was carried out using the *brms* library in R.

The $CU_{diff,Y}$ data was randomly partitioned into training and test data sets where 80% of the data was placed in the training set. The partitioning was stratified along the conservation activity factor so that equal proportions of each class fell into the training and test sets. A wide array of model structures were evaluated. Model structures variously incorporated AHU soil characteristics, topographic characteristics, vegetation type (e.g., alfalfa vs. corn) and irrigation practices (e.g., sprinkler vs. flood) on a field. The performance of each model structure was evaluated through computation of various goodness-of-fit measures and through visual assessment of the alignment between posterior probability distributions and the distributions of the training data split along the main and interactive effects included in the fitted model structure. This iterative process resulted in the selection of a preferred model structure for observation i on field j undergoing conservation activity k (Equation 3.12).

$$\begin{aligned}
y_{ijm} &\sim \text{Student-t}(\mu_{ijm}, \sigma, \nu) \\
\mu_{ijmk} &= \beta_{0,k} + \beta_{1,k} \cdot \text{Crop}_i + \beta_2 \cdot \text{Hydric}_i + \beta_3 \cdot \text{Elevation}_i + \beta_4 \cdot \text{Slope}_i \\
&\quad + \beta_5 \cdot \text{Sprinkler}_i + \beta_6 \cdot \text{AWS}_i + f(P_{\text{anomaly},i}, ET_{\text{anomaly},i}) + \alpha_j + \gamma_m \\
\alpha_j &\sim \text{Normal}(0, \sigma^2_{\text{field}}) \\
\gamma_m &\sim \text{Normal}(0, \sigma^2_{\text{year}}) \\
f(\cdot) &\sim \text{GP}(0, k)
\end{aligned} \tag{3.12}$$

Where:

- y_{ijm} is the consumptive water use change for observation i in field j and year m.
- μ_{ijmk} is the modeled mean water savings for an observation belonging to conservation strategy k.
- $\beta_{0,k}$ is the group-specific intercept for conservation activity k.
- $\beta_{1,k}$ is the group-specific slope for crop type, given conservation activity k.
- β_2 through β_6 are the population-level fixed effects.
- α_j is the random intercept for field j.
- γ_m is the random intercept for year m.
- σ and ν are the scale and degrees-of-freedom parameters of the Student's t-distribution.

The predictor variables included in the model reflect first-principals expectations for the primary drivers of crop water use in the UCRB. A crop type categorical variable (Crop) was included to differentiate consumptive water use outcomes associated with different vegetation types. Perennial crops like grass pasture were expected to produce more modest consumptive use reductions than annual crops like corn. Crop type was assigned to each AHU from the Colorado Decision Support System (CDSS) database [37] and modified, where possible, with more specific information from water conservation agreements. Only three crop types were included. All crops other than grass pasture or alfalfa were aggregated into a single "Other" category. A continuous variable indicating the likelihood of hydric soils (Hydric) was used as a proxy for sub-irrigation. The *hydclprs* attribute in the gNATSGO dataset [22] provided the modeled values. The elevation above mean sea level (Elevation) and slope (Slope) of each AHU were derived form the SRTM 30m elevation dataset [@ShuttleRadarTopography2000]. Irrigation type (Sprinkler) was included as a binary categorical variable where all irrigation strategies other than sprinkler irrigation were lumped into a single category. Continuous numerical values for Available Water Storage (AWS) in the upper 100 cm of the soil column were derived from the *aws0100wta* attribute in the gNATSGO dataset. Precipitation and crop evaporative demand anomalies, $P_{anomaly}$ and $ET_{anomaly}$, respectively, were included in the model as a Gaussian process to control for inter-annual variability in atmospheric conditions. A random intercept for each field J was included to accommodate the spatially nested structure of the sample data where each AHU is a child of a parent field. The model was fit to the training data using a non-centered parameterization and weakly informative priors.

3.4 Results and Discussion

3.4.1 Time Series Classification

The time series pattern recognition and classification approach applied here successfully identified the temporal "fingerprint" of each conservation strategy. The best spatio-temporal reference frame for identifying distinct patterns in the time series data was evaluated by comparing balanced accuracy scores (Table 3.1) and examining confusion matrices for the k-fold cross-validation results for each AHU diameter / time window pair (Figure 3.4). Within each AHU diameter set, increasing the temporal resolution of the time series data always improved balanced accuracy scores. At the coarser temporal resolutions, larger AHUs generally produced better classification outcomes. As the temporal resolution increased, better classification outcomes were achieved at finer spatial resolutions.

TABLE 3.1. Balanced accuracy scores for the classification results produced for the range of AHU diameters (columns) and time windows (rows).

Time Window	30 m	60 m	90 m	120 m	180 m
Month	0.79	0.81	0.82	0.83	0.86
Fortnight	0.86	0.87	0.88	0.89	0.90
Week	0.96	0.96	0.96	0.95	0.94

A clear co-dependent relationship between AHU size and time window resolution emerged from these results. The observed patterns in classification performance suggest that as time scales of evaluation get coarser, it is necessary to coarsen the spatial context in order to smooth over site specific variability in the $D_{anomaly}$ data. It becomes increasingly difficult to classify time series consisting of relatively few data points if the variance in the underlying signal is large. The balanced accuracy scores for all spatial resolutions decreased with increasing window size. This suggests that as one moves form a characterization of weekly data to monthly data, an increasingly coarse spatial scale must be selected in order to maximize classification performance. The clearest temporal signal for conservation activity classification was achieved at a weekly time scale for 60 or 90 m diameter AHUs. It is possible that increasing the AHU size beyond 180 m, perhaps to the scale of entire fields, for the fortnight or monthly time windows will result in comparable scores to the 30 m weekly data. However, the spatial reference frame required to achieve comparable classification performance at a coarse temporal scale (e.g. monthly) may exceed the area of individual fields. This is a potential area for future investigation.

All subsequent analyses utilized data from 90 m AHUs aggregated at the weekly time scale. A more nuanced view of classification performance for $D_{anomaly}$ data generated for this spatio-temporal reference frame was assessed through examination of a confusion matrix (Table 3.2). The classification engine assigned time series to the correct conservation practice in a vast majority of cases. This is confirmed by the large values on the main diagonal of the confusion matrix. Normal Irrigation time series were correctly identified in 88% of cases. The highest success rate was observed for the Split Season Late class. This may reflect the fact that a limited number of fields in a fairly restricted geography utilized this water conservation strategy. This small sample size exhibiting limited geographical diversity may result in very similar temporal patterns for the Split Season Late conservation strategy.

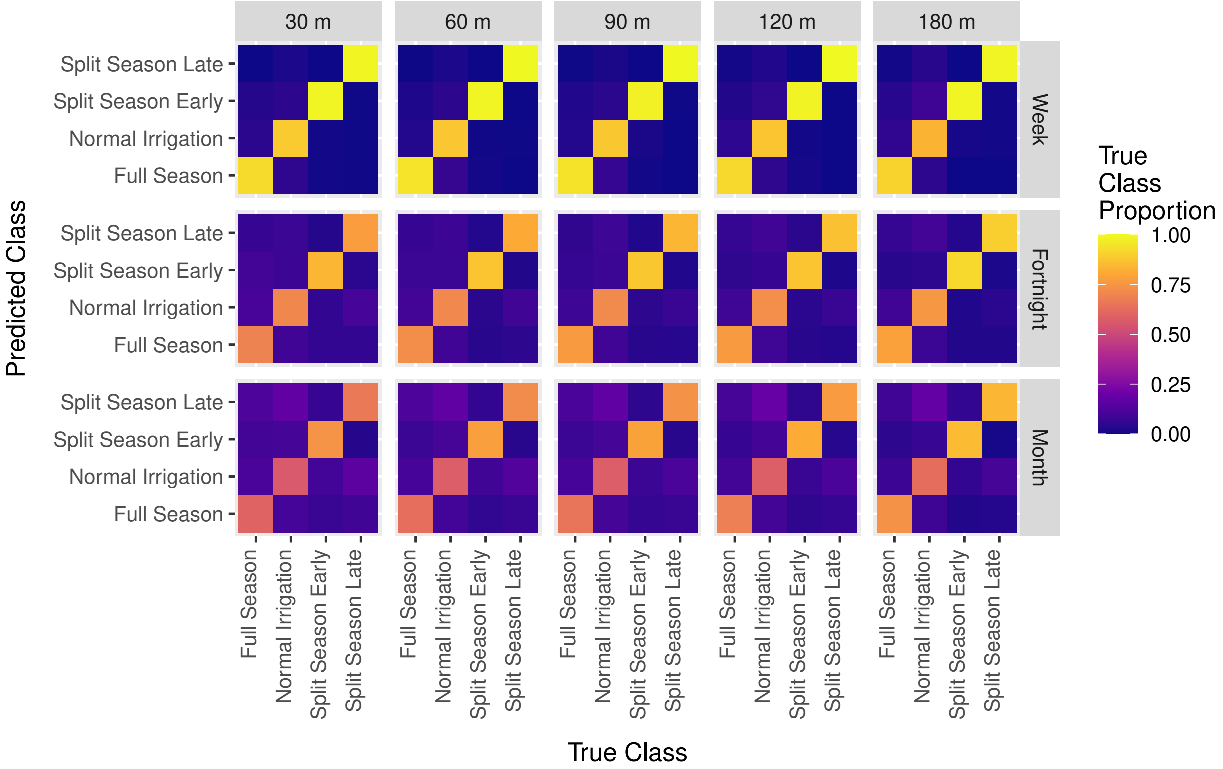

FIGURE 3.4. Confusion matrices for each time step and AHU size pair evaluated through k-fold cross-validation. Symbolized values are normalized to the total size of the samples in each true class.

TABLE 3.2. Confusion matrix of classification results for 90 m AHUs assessed at the weekly timestep where columns indicate the true classes and rows indicate the predicted classes. Results are provided as raw counts and as percentages, normalized across a given class.

Predicted Class	Full Season	Normal Irrigation	Split Season Early	Split Season Late
Full Season	1141 (95%)	1557 (6%)	3 (1%)	0 (0%)
Normal Irrigation	34 (3%)	21292 (88%)	1 (1%)	0 (0%)
Split Season Early	26 (2%)	1066 (4%)	357 (98%)	0 (<1%)
Split Season Late	1 (<1%)	383 (1%)	0 (0%)	513 (99%)

A review of the off-diagonal values in the confusion matrix indicate some interesting error patterns. The misclassification rates for Split Season Early (1.9%) and Split Season Late (0.2%) are very low. The misclassification rate climbs to 5.3% for Full Season and is highest for Normal Irrigation (11.9%). The relatively high misclassification rate for Normal Irrigation points to the challenge in relying on time series patterns alone for identifying instances of and differentiation among different classes of water conservation practice. The greatest fraction of misclassifications for Normal Irrigation time series was for Full Season. Conversely, the greatest fraction of misclassifications for Full Season were in the Normal Irrigation Class.

The specific arrangement of errors reflect the challenges of classifying data with the DTW algorithm. DTW is sensitive to the shape of time series but not to differences in absolute magnitude from some shared baseline datum. Normal Irrigation and Full Season are both expected to produce relatively flat time series. The Normal Irrigation time series should be centered around a $\mathrm{D}_{\mathrm{anomaly}}$ of zero. The Full Season time series should also be fairly flat, albeit centered on a somewhat lower $\mathrm{D}_{\mathrm{anomaly}}$ value, reflecting the persistent reduction in irrigation across the entire irrigation season. The DTW algorithm likely struggles to differentiate these two patterns from one another. The observed misclassifications of the Normal Irrigation series may also hint at the potential existence of confounding environmental variables. For example, the seasonal ET signal generated for a field undergoing normal irrigation practice in an extremely dry year may be indistinguishable from similar seasonal ET patterns evident for a field undergoing some form of irrigation curtailment.

The unique shape of the time series signals associated with each of the conservation practices was qualitatively evaluated by extracting a random subset (n = 200) of the time series from each class and calculating the time series pattern that roughly occupies the centroid of the ensemble (Figure 3.5). These prototypical time series at the center of mass of the ensemble were identified via the DTW Barycenter Averaging (DBA) algorithm in the *dtw_clust* library in R. The DBA algorithm searches for the optimal time series pattern that minimizes the cumulative cost distance between all series in a class.

The plotted time series data exhibits unique patterns between the conservation strategy classes Figure 3.5. Time series belonging to the Normal Irrigation class are tightly centered on a $D_{anomaly}$ value of zero throughout the growing season. Although an increasing degree of variance is visible in the late fall period. This pattern suggests my strategy for characterizing baseline conditions is a reliable method. The Full Season pattern is distinguished by an early drop below the zero $D_{anomaly}$ line, relatively little variability through the majority of the growing season, and a subtle recovery in $D_{anomaly}$ after week 40. The relatively high degree of variability observed among the time series ensemble early in the season probably reflects my allowance for the Full Season class to include any field that implemented irrigation curtailment prior to week 20. The similarity in the temporal patterns of the Normal Irrigation and Full Season classes provides confirmatory evidence of my hypothesis about the drivers of the classification error structure discussed previously.

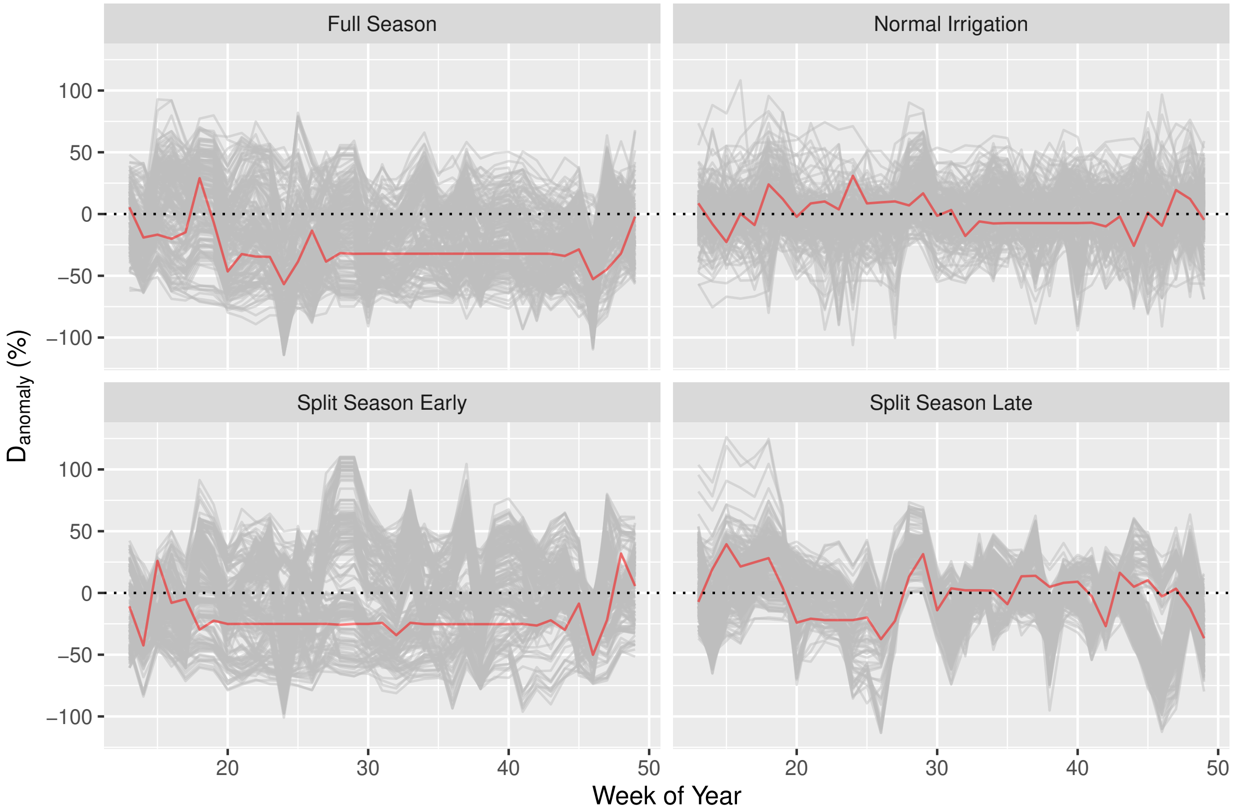

FIGURE 3.5. Prototypical weekly time series (red lines) identified through DTW Barycenter Averaging on a subset of time series (gray lines) from each conservation strategy class.

The barycenter for the Split Season Early time series is characterized by a shape that is similar to the Full Season class. While the barycenters for the two classes are similar, the dominant behaviors evident in the respective ensembles for each class are quite different. The Split Season Early time series display a much greater degree of variability than the Full Season data, particularly after week 25. Some of this variability may be a product of the way that I defined the Split Season Early class. A qualitative visual review of the platted data also suggests that there may be distinct sub-classes within this class. Time series tend to cluster in divergent parts of the $D_{anomaly}$ space during different weeks of the year. More rigid definitions of of the Split Season Early class may reduce some of these effects. This is a potential area for future investigation.

The Split Season Late time series are the most tightly clustered of all the classes. The seasonal pattern began at a $D_{anomaly}$ value near zero, followed by a modest drop after approximately week 25. The general shape of the seasonal pattern conformed to my expectations that curtailment of irrigation late in the season should produce a negative $D_{anomaly}$ value but that value should be higher than similar split season irrigation curtailment strategies implemented earlier in the season. When irrigation is curtailed late in the season the soil column is expected to exhibit relatively high volumetric water content. Crops can draw from this reservoir through the remainder of the growing season, obscuring the ET signal of irrigation curtailment. Conversely, when irrigation is curtailed earlier in the season, when temperatures are warming and plant growth is vigorous, early spring soil water content may be quickly depleted and higher crop water deficits are expected.

The evaluation of seasonal ET time series data confirmed my first hypothesis that water conservation practices common to the UCRB create statistically identifiable temporal patterns. Furthermore, the prototypical $D_{anomaly}$ time series shapes largely conform to first principles expectations for the effect of different conservation practices on seasonal patterns of consumptive water use. These findings may help water managers in the UCRB contemplate scalable strategies for conservation program compliance monitoring. If conservation program participation rates increase substantially in the future, regular in-person compliance monitoring at all participating field may prove unreasonably time consuming and resource intensive. The ability to classify remotely-sensed seasonal ET time series in a post-hoc manner may become a valuable tool for supplementing limited or irregular in-person verification visits to a project site. While time series classification may represent a powerful tool for determining type of conservation activities taking place on a given field during a given year, the approach is not appropriate, on its own, as a means for quantifying differences in consumptive water use in conservation periods vs. normal irrigation periods.

3.4.2 TEST OF DIFFERENCE FOR ANNUAL CONSUMPTIVE USE ANOMALIES

The classification of sub-annual $\mathrm{D}_{\mathrm{anomaly}}$ time series data confirmed that distinct temporal ET patterns exist for each of the conservation strategies of interest. However, some uncertainty in the time series pattern recognition approach was evidenced by misclassification errors between Normal Irrigation and Full Season. Clustering of some time series among each class ensemble suggested the presence of sub-populations or the influence of unobserved forcing variables. The complex relationships between conservation practices, environmental characteristics, and consumptive water use reductions that may be better elucidated through multivariate modeling. Unfortunately, time series vectors are not suitable as a response variable for multivariate models. The CU_{diff} metric was established as a means for collapsing seasonal time series data into a single value that reflects the cumulative impact of water conservation at the scale of an individual AHU. While some nuanced information about the time variant impacts of different water conservation strategies is inevitably lost by aggregating values to the yearly timescale, the primary information of interest to water managers and conservation program participants is related to the cumulative seasonal total water savings achieved by conservation.

The CU_{diff} metric was deemed useful for evaluating the interplay between seasonal consumptive use outcomes as they are affected by different conservation strategies and various environmental factors. A pair of non-parametric tests were employed to determine whether the conservation strategy classes of interest were statistically identifiable by the CU_{diff} metric. Results from a Kruskal-Wallis rank sum test ($\chi^2(3) = 3802.83$, p-value < 0.001) suggested with a high degree of confidence that differences exist between the conservation strategy classes. A Dunn's Test of pairwise differences was subsequently performed in R using the *dunn.test* library. The Dunn's test detected significant differences between all classes except between the Split Season Early and Split Season Late irrigation curtailment classes (Table 3.3).

TABLE 3.3. Dunn's pairwise test results for yearly CU_{diff} where p-values are adjusted for multiple comparisons using the Bonferroni method

Comparison	Z-score	Adjusted p-value
Full Season vs. Normal Irrigation	-58.83	< .001
Split Season Early vs. Normal Irrigation	-13.85	< .001
Split Season Late vs. Normal Irrigation	15.55	< .001
Full Season vs. Split Season Early	-15.88	< .001
Full Season vs. Split Season Late	17.97	< .001
Split Season Early vs. Split Season Late	-0.14	1.00

The results of both non-parametric tests provided confidence in the CU_{diff} metric as a viable response variable for more detailed multivariate modeling. The lack of a statistically significant difference between the Split Season Early and Split Season Late classes is notable. The differences between the two classes evident in the seasonal patterns of $D_{anomaly}$ supported successful time series classification with relatively low error rates. Without the detailed information provided by full time series, non-parametric evaluation of CU_{diff} was unable to differentiate the two types of split season curtailment, indicating similar median end-of-season consumptive water use reduction outcomes. This runs counter to expectations that late season irrigation curtailment should produce lower consumptive water use reductions and motivates more detailed analysis.

Characterization of the full distributions of CU_{diff} values (Figure 6.1) for each conservation strategy shows distinct patterns within each class and illuminates the Dunn's test failure to differentiate between the two split season curtailment classes. The mean behavior of the Split Season Early and Split Season Late distributions are very similar. However, while the Split Season Late distribution is nearly Gaussian, the the Split Season Early distribution exhibits a multi-modal behavior with significantly wider tails than the Split Season Late class. The presence of multiple distinct peaks in the Split Season Early distribution hint at the presence of distinct sub-groups within this class, something noted previously upon qualitative detection of clustered time series within the Split Season Early ensemble (Figure 3.5). The Full Season class is centered at a lower CU_{diff} than either of the split season classes. Strong bi-modal behavior is evident in this distribution, providing the strongest evidence yet for the likely presence of sub-populations within each class.

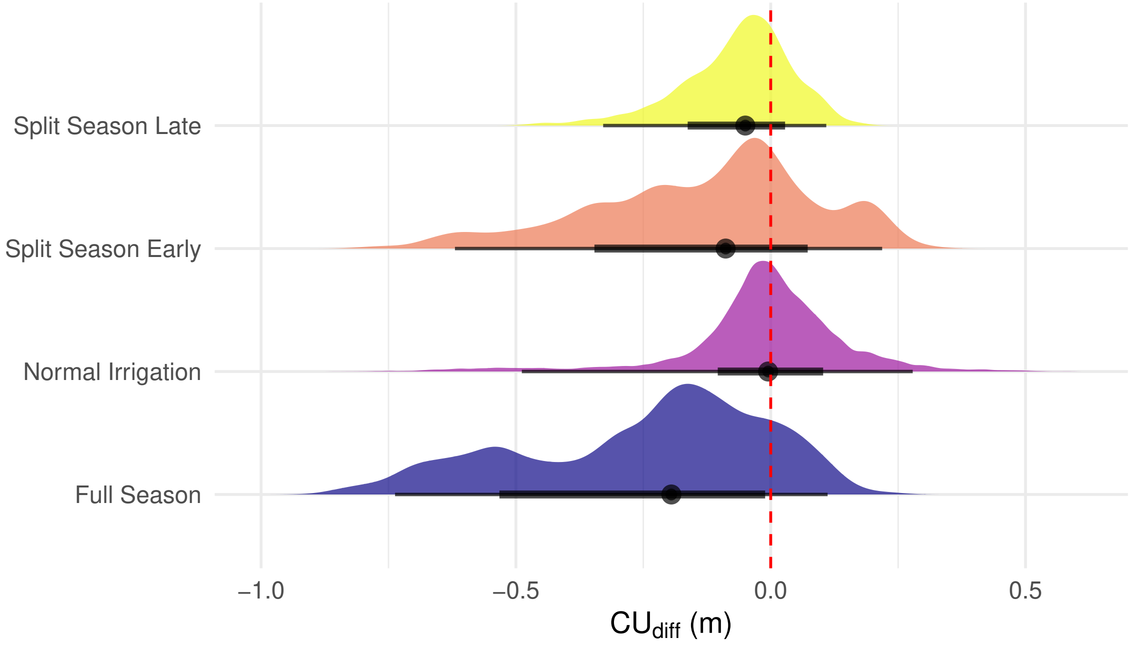

FIGURE 3.6. Distributions of CU_{diff} by water conservation strategy class.

The multi-modal distributions for Split Season Early and Full Season CU_{diff} hint as the presence of distinct subgroups within each class. This non-Gaussian behavior and the relatively long tails confirm that the mean of the observed CU_{diff} values for each class is an unreliable metric for understanding the likely consumptive use outcomes associated with one or more conservation strategies on a given field. This is notable and highly relevant for water users and water managers involved with water conservation programs in the UCRB. In some cases, the Split Season Early strategy appears to drive significant reductions in consumptive water use, relative to Normal Irrigation. In other cases, Split Season Early is likely to produce outcomes that are statistically indistinguishable from Normal Irrigation. In still other cases, the Split Season Early strategy may actually drive more consumptive use than the Normal Irrigation strategy. The distinct shapes of the Split Season Early and Full Season CU_{diff} distributions may reflect within-class timing differences for the onset and cessation of irrigation curtailment (Figure 3.7). Alternatively, interactions between conservation practice and one or more environmental variables may drive these complex patterns. For example, water conservation applied to perennial grass pasture may produce distinctly different outcomes from the same strategy applied to annual crops. An enhanced understanding of the environmental and management circumstances that drive consumptive use patterns one direction or another will support the water managers and policy makers charged with developing programs and strategies for meeting consumptive water use reduction targets in the UCRB. Such information would also be be valuable to the individual water users faced with the choice of water conservation program participation where compensation rates are based on realized (rather than predicted) consumptive water use reductions. These considerations motivated a detailed multivariate modeling exploration of the drivers of end-of-season consumptive water use outcomes.

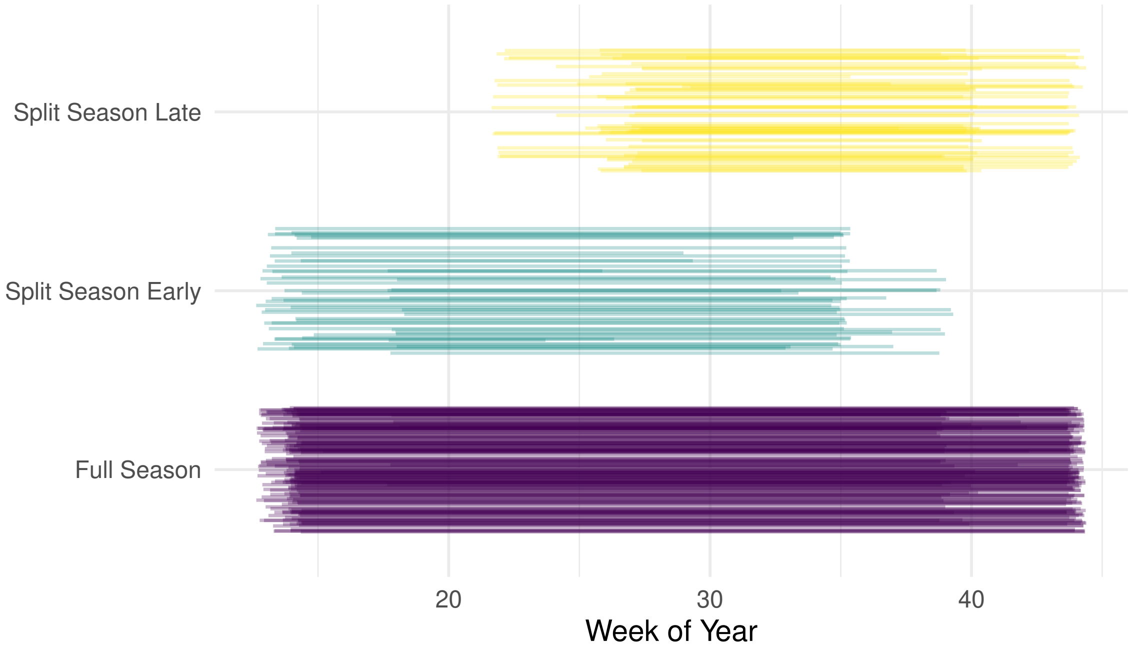

FIGURE 3.7. Water conservation start weeks and end weeks within each water conservation strategy class. Each horizontal line represents a single-year conservation period for a single field.

3.4.3 BAYESIAN HIERARCHICAL MODEL PERFORMANCE

The Bayesian hierarchical model fit to yearly consumptive use anomalies provides a nuanced understanding of the interplay between conservation strategies and several mitigating environmental variables. Successful model convergence was evidenced by R-hat values ~1.0 for all main effects, interactions, and random effects. A suite of goodness-of-fit metrics were used to evaluate the model's overall explanatory power. The fixed effects included in the model were able to explain 71% of the overall CU_{diff} variance (Marginal R^2 = 0.71). The inclusion of field level random effects explained an additional ~21% of the observed variance (Conditional R^2 = 0.92). These results confirmed my second hypothesis. However, they also indicated that a significant portion of the between-field variability in CCU outcomes may be driven by interactions between conservation strategies and untested environmental variables. Identification and evaluation of these variables should be pursued in future studies.

The goodness-of-fit measures for the overall model belie non-uniform model performance across the different water conservation strategy classes (Table 3.5, Table 3.4). Model performance was strong across all conservation activity classes when random effects for fields were included. Removal of the random effects unevenly degraded the model fit by class. The conditional fit (i.e. fixed effects only) was best for the Split Season Early and Full Season conservation strategies, indicated by relatively high R^2 and Ratio of Performance Deviation (RPD) scores. Other measures of fit were fairly consistent between classes. The model struggled the most with the Split Season Late class. The low performance scores among this class were a drag on the characterization of conditional performance for the full model. The model's struggle with the Split Season Late class stands in contrast to results from the time series classification. While the unique time series patterns in the ET data promoted highly-accurate classification of this conservation strategy, the unique temporal features of the class were less apparent in the seasonal magnitudes of the CU_{diff} data. The poor model performance for the Split Season Late class may reflect low overall variance among CU_{diff} values compared to the Full Season, Split Season Early and Split Season Late classes (Figure 6.1). The R^2 and RPD metrics reflect the model's ability to explain variance in CU_{diff}. Where the within-class variance is low, these goodness-of-fit measures may give unhelpful impressions of model performance.

TABLE 3.4. Conditional goodness of fit measures subset by conservation strategy

Conservation Strategy	R2	RMSE	MAE	RPD	CCC
Full Season	0.82	0.10	0.07	2.39	0.90
Split Season Early	0.84	0.09	0.06	2.47	0.92
Split Season Late	0.78	0.05	0.04	2.15	0.88

TABLE 3.5. Marginal goodness of fit measures subset by conservation strategy

Conservation Strategy	R2	RMSE	MAE	RPD	CCC
Full Season	0.67	0.14	0.11	1.73	0.79
Split Season Early	0.61	0.13	0.10	1.60	0.77
Split Season Late	0.53	0.07	0.05	1.48	0.72

Visual examination of the fit of posterior probability distributions to the distribution of the raw CU_{diff} training data provides an alternative view of model performance (Figure 3.8). The multi-modal nature of the CU_{diff} data characteristic of the Full Season and Split Season Early classes were expected to present challenges to model fitting. However, the visual check of posterior probability distribution alignment against the test data suggest that the model was well-calibrated to the mean CU_{diff} behavior across the full set of conservation strategies. This outcome may be attributed to the diverse set of fixed effects and interactions included in the model structure.

Faceting the posterior probability distributions across conservation strategies and crop type provided further insights into model calibration. The model was well calibrated across all conservation strategies–the observed distributions of CU_{diff} fell inside the posterior prediction envelope for each crop (Figure 3.9). However, the Split Season Early class exhibited elevated uncertainty, characterized by the wide posterior prediction envelopes for each crop type. The model successfully accounted for the bi-modal distribution of CU_{diff} values for alfalfa crops within Split Season Early and Full Season classes. Prediction envelopes for the Full Season conservation strategy class were generally tighter than among the other two classes. The relatively tight and zero-centered distribution for the the Split Season Late strategy on grass pasture indicated that this combination consistently produced no meaningful reductions in seasonal consumptive

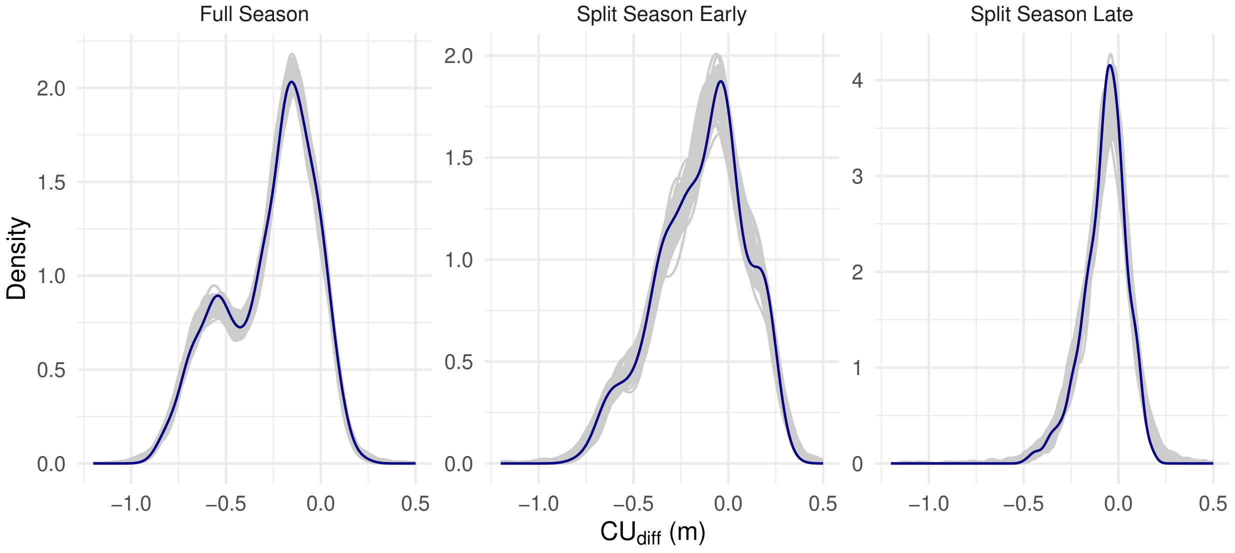

FIGURE 3.8. Model posterior probability distribution draws of CU_{diff} (gray areas) overlaid with the observerved distribution of the training data (blue lines) and faceted by conservation strategy.

water use. Among all the classes, alfalfa appeared most successful at generating the largest consumptive use reductions and grass pasture was least successful. The ability of the model to capture complex variance structures drove high quantitative goodness-of-fit metric scores (Table 3.5, Table 3.4).

3.4.4 INFLUENCE OF ENVIRONMENTAL AND MANAGEMENT FACTORS ON PATTERNS OF CONSUMPTIVE WATER USE

The fitted Bayesian hierarchical model provides a robust characterization of the influence that environmental characteristics and conservation strategies have on consumptive water use reductions. Specifically, the model presented here contemplates the interplay between three distinct water conservation practices, defined by seasonal start and end dates, hydrological soil characteristics, topographic features, crop type, and irrigation strategy. The total effect sizes of the various environmental variables and their interactions with the conservation strategies were assessed through consideration of the regression coefficient estimates and companion conditional effect plots. The ability of the model to account for the effects of the environmental variables on the variance structure of the CU_{diff} metric was also assessed through visual interpretation of posterior probability distributions drawn along modeled interaction terms. Regression coefficient estimates quantified the mean strength and directionality of the modeled fixed effects on CU_{diff} (Table 3.6). The 95% credible interval (CI) for each coefficient were determined by sampling the the

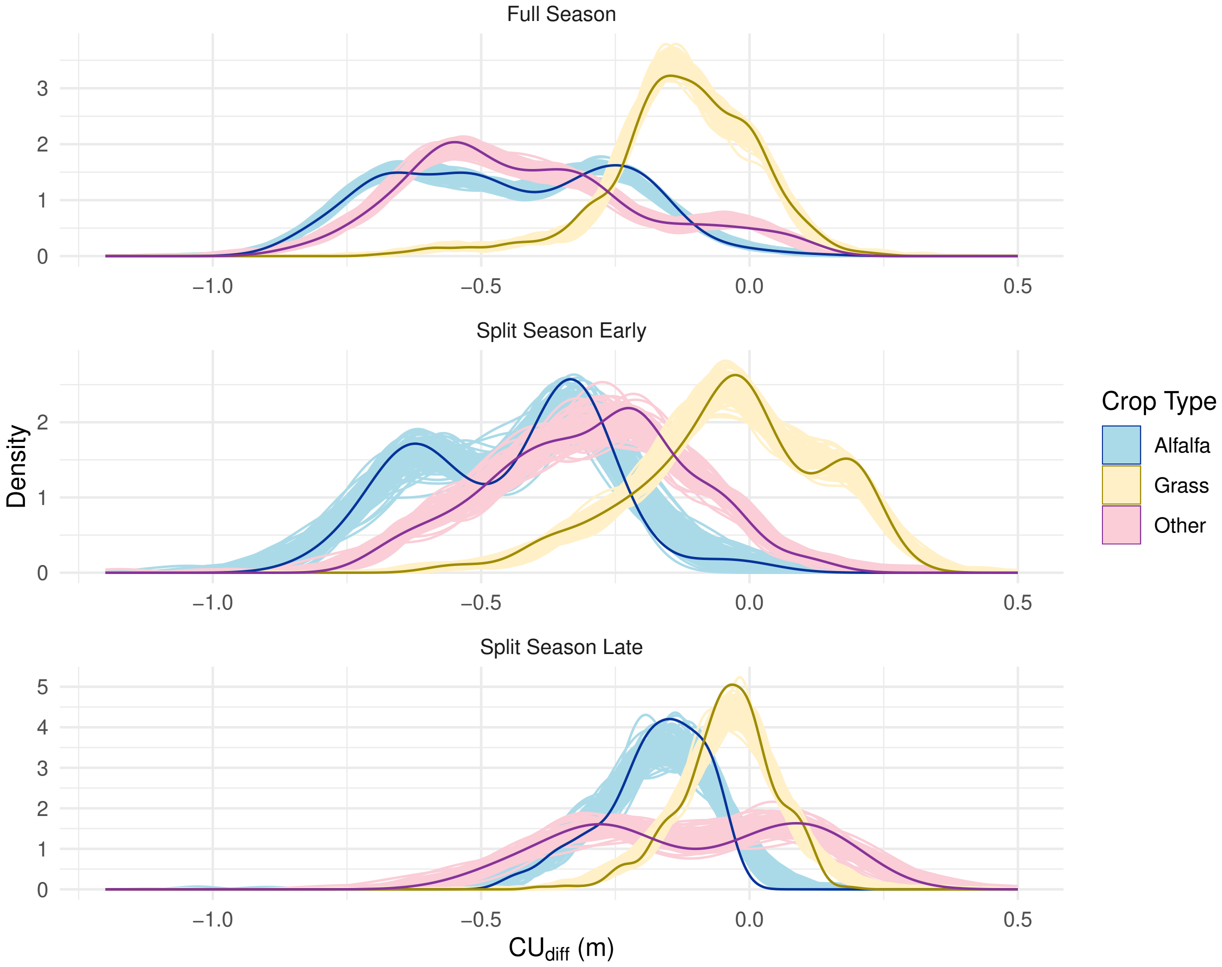

FIGURE 3.9. Posterior probability distribution draws of $D_{anomaly,Y}$ (shaded areas), grouped by conservation strategy and overlaid with the observerved distributions of the training data (solid colored lines).

coefficient's posterior distribution and computing the 2.5th percentile and 97.5th percentile of the ordered values.

The model fit was zero-centered. Therefore, coefficient estimates for the conservation strategies reflect the mean condition of other continuous variables (i.e. average elevation, average precipitation anomaly) and the reference level for categorical variables (i.e. Sprinkler = False). The CU_{diff} response variable indicates a divergence from baseline conditions where an increasingly negative value meant greater conserved water quantities used under conservation.

TABLE 3.6. Regression coefficient estimates and 95% credible intervals for the Bayesian hierarchical model. Rhat for all coefficients = 1.0

Regression Coefficient	Estimate	Lower 95% CI	Upper 95% CI
Full Season	-0.70	-0.90	-0.49
Split Season Early	-0.61	-0.83	-0.39
Split Season Late	-0.47	-0.69	-0.24
Crop, Grass	0.13	0.06	0.22
Crop, Alfalfa	0.03	-0.01	0.06
Hydric Soils (%)	0.02	0.00	0.03
Slope (%)	0.00	0.00	0.00
Sprinkler, Yes	-0.13	-0.21	-0.05
Elevation (km)	0.23	0.11	0.35
AWS (cm)	-0.37	-0.49	-0.25
Split Season Early x Crop, Grass	0.01	-0.10	0.12
Split Season Late x Crop, Grass	-0.16	-0.28	-0.04
Split Season Early x Crop, Alfalfa	-0.06	-0.17	0.05
Split Season Late x Crop, Alfalfa	0.01	-0.10	0.12
Gaussian Process Marginal SD	0.15	0.12	0.18
Gaussian Process Length Scale	0.01	0.00	0.01
Residual SD (σ)	0.05	0.04	0.05
nu	3.78	3.26	4.42
Field ID Random Effect (SD)	0.13	0.12	0.14

The model identified the largest conservation strategy effect size for the Full Season class. Full Season irrigation curtailment generated an average seasonal water savings of 0.70 m. The Split Season Early strategy produced comparable results, averaging 0.61 m of seasonal water savings. The effect size for Split Season Late was much smaller, yielding an average of 0.47 m of conserved consumptive water use. The coefficients for the effect size and direction of the conservation strategies aligned with the general direction and magnitude of the effects evident in the distributions of the raw CU_{diff} data (Figure 6.1). Average baseline consumptive use for all samples across the study area totaled 0.63 m/yr. The Full Season strategy generated an average savings commensurate with this average water use, suggesting that the average effect of the Full Season and Split Season Early strategies were equivalent to baseline consumptive irrigation water use. The estimated effect size for the Split Season Early strategy amounted to ~75% of the baseline water use. The overall magnitude of each effect in any given year was moderated by crop type, a suite of environmental factors, and seasonal weather conditions.

3.4.4.1 THE CRITICAL ROLE OF CROP TYPE

Understanding the differences in conserved consumptive use outcomes among grass pasture and alfalfa fields is critical since they dominate the agricultural landscape in the UCRB. Model regression coefficients confirm that the influence of crop type on CU_{diff} varied among the conservation strategies. Grass pasture had the expected moderating effect on consumptive use reductions. For the Full Season strategy, grass pasture reduced estimates of water savings by 0.13 m, relative to the Other crops category (e.g., corn and small grains). This difference reduced the overall effectiveness of Full Season irrigation curtailment to a more modest total seasonal savings of 0.57 m. The effect of the interaction between Split Season Early strategy and grass pasture was insignificant, meaning the effect size was indistinguishable from the Full Season effect. In this case, grass pasture reduced total water savings for the Split Season Early class to 0.48 m (Figure 3.10). Grass pasture had modest impact on the effectiveness of the Split Season Late strategy, suggesting this strategy is more effective at conserving water on grass pasture than on Other crops. The effect of alfalfa on conservation strategy outcomes was, generally, not statistically significant. Alfalfa was, thus, indistinguishable from the Other category used as the crop reference level. The practical implications of this finding are that two crop categories, one for grass pasture and one for all remaining crop types is likely sufficient for predicting conservation outcomes on fields in the study area.

The diversity in predicted CU_{diff} effect sizes for the Full Season and Split Season Early strategies (Figure 3.10) highlights the importance of understanding geographical context when endeavoring to predict water conservation outcomes in the UCRB. The Full Season irrigation curtailment strategy produced the largest individual effect on conserved consumptive use and was still more effective than the Split Season Late strategy in the presence of grass pasture. However, the benefits of the Full Season strategy relative to the Split Season Early strategy depended on crop type. The model predicted reduced water conservation benefits from the Full Season strategy on grass pasture when compared to the Split Season Early strategy on fields growing alfalfa or other crops. Given the opportunity to enact water conservation on two alternative settings, one with irrigated grass pasture and the other where irrigation supports annual crops, greater or commensurate water savings might be achieved, potentially at a lower cost, through application of the Split Season Early strategy on the non-grass pasture.

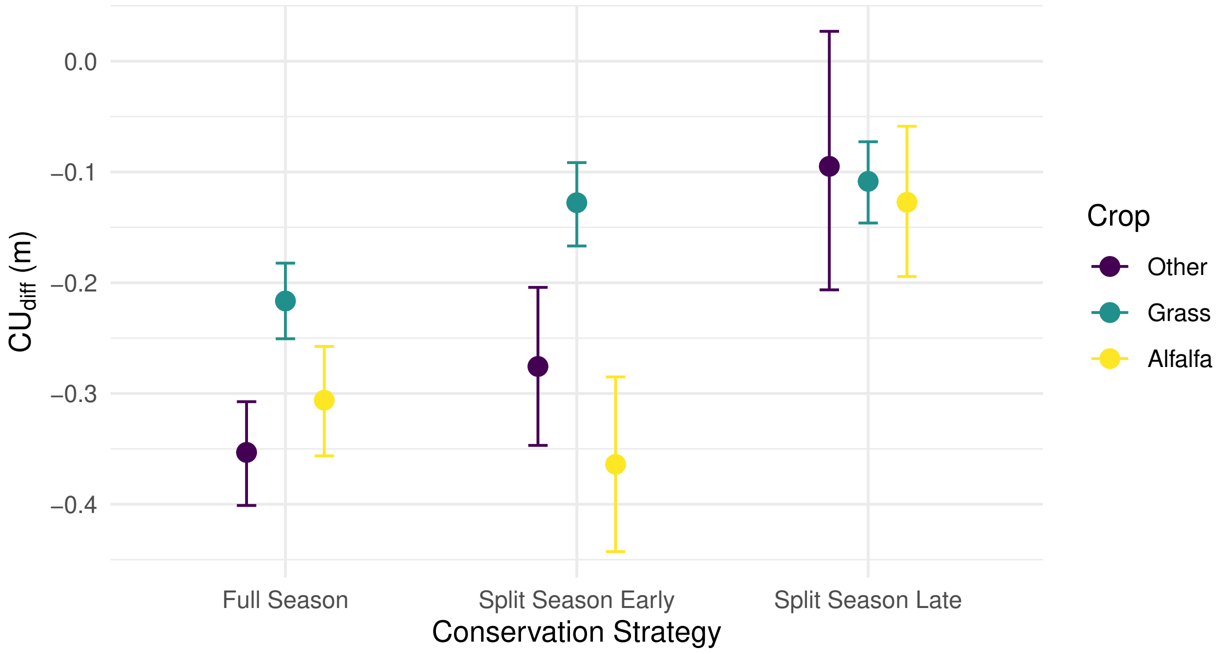

FIGURE 3.10. Conditional effects of conservation strategy and grass pasture. The estimated effect size is centered on the points. Vertical bars indicate the 95% CI of the estimated effect size.

3.4.4.2 EFFECTS INDUCED BY LANDSCAPE CHARACTERISTICS AND MANAGEMENT

The physical, biological, and hydrological conditions present on any single field can be highly variable. Macro-scale variability in slope and aspect, heterogeneity in crop density and species composition, anisotropy in soil conditions, the unique arrangement of local topographic depressions and high points, and many other factors are all expected to drive within-field and between-field variability in CCU. The anticipated effect of environmental variables and farm or ranch management practices on conservation outcomes was evaluated through inclusion of model terms that reflected dominant topographical characteristics, soil hydrological attributes, and typical irrigation application practices.

The influence of topography was assessed through the model terms for local slope and elevation. Increasing slope was expected to drive increasing consumptive water use reductions. However, the modeled effect size for slope was zero. Either slope exerted little to no effect on water savings or the resolution for local slope calculations (30 m) was too coarse to capture meaningful impacts from microtopography. The effect size of elevation was consistent. The fitted model indicated that seasonal consumptive use savings droped by 0.23 m for every 1000 m of increasing elevation. The practical impact of increasing elevation was determined by the different intercepts of the conservation strategy main effects (Figure 3.11). Each of the conservation strategies evaluated here was shown to be much more effective at reducing consumptive water use at low elevations than at high elevations. At high elevations (> 2200 m) , the CU_{diff} outcomes for the Split Season Late class approached the normal irrigation baseline condition. At high elevations, water conservation outcomes associated under Full Season irrigation curtailment achieved similar consumptive water use reductions as the Split Season Early strategy implemented at the low elevations (< 1600 m).

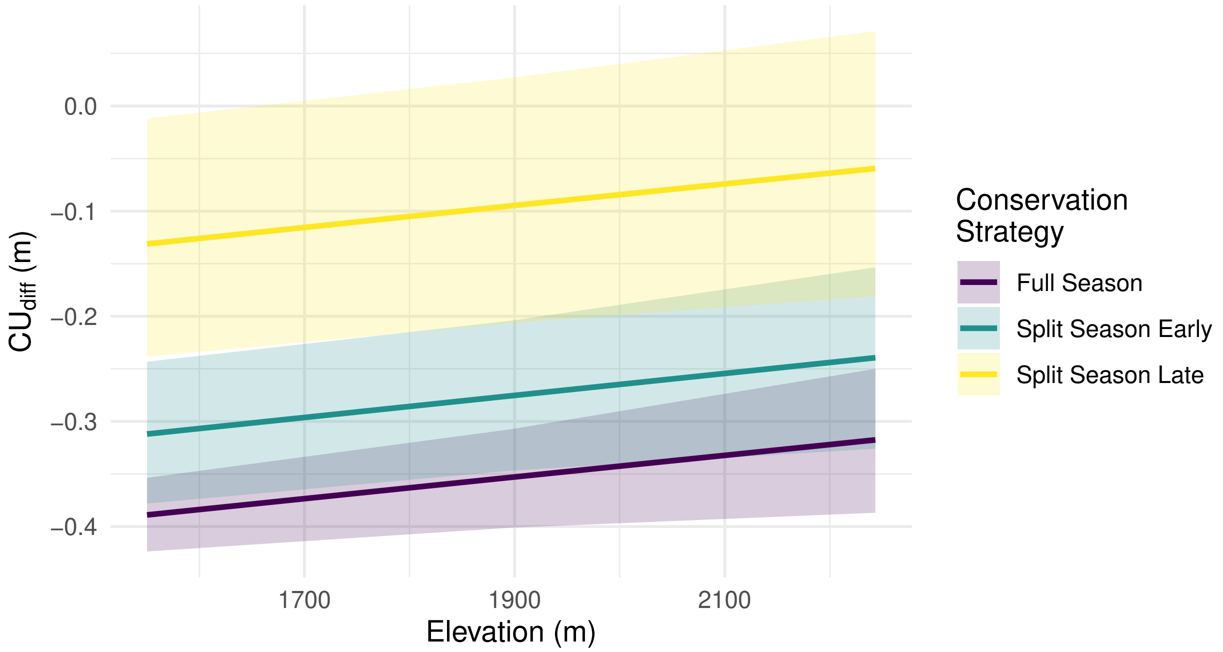

FIGURE 3.11. Conditional effects of conservation strategy and elevation. Elevation values are unscaled in the plot to aid interpretation.

The model included two terms related to soil hydrology. The AWS variable represented available water storage in the upper 1.0 m of the soil column. Low AWS values reflect sandy, well drained soils while high AWS values reflect soils with finer textures and higher clay content. Model results indicated that finer soil textures were associated with increased CCU. Soils with higher clay content generally have greater plant available water than coarser textured soils. This greater water availability in any given year likely supports more vigorous plant growth than on fields with sandy soils. As a result, the baseline water use on fine textured soils was likely higher than the baseline use on sandy soils and, thus, the potential for water savings was greater for fine textured soil.

Some grass pasture fields in the data set were located on wide, low-elevation terraces near low-gradient streams and rivers. In these settings, significant portions of the crop water demand could have been supported by an underlying alluvial aquifer. The effect of water conservation in these settings was likely diminished. No comprehensive mapping of river bottomlands were available for this study. Instead, the Hydric variable was incorporated to reflect the likelihood of encountering hydric soils within an AHU, where hydric soils were an assumed proxy for the presence of sub-irrigation. The model indicated a weak effect, where each percentage point increase in the likelihood of encountering hydric soils was accompanied by a 0.02 m decrease in conservation gains. The direction of the effect conformed to expectations but the small effect size may reflect challenges with using a probabilistic indicator as a predictor variable. The inclusion of non-probabilistic metrics of river adjacency or sub-irrigation may enhance this effect and help account for some of the unexplained variance in observed consumptive water use reductions.

The model showed that irrigation type had significant effect on CCU. The inclusion of this term reflected the assumption that more efficient water application methods would be associated with higher consumptive use gains. The model term that indicated the presence of sprinkler irrigation affirmed this expectation. The effect for sprinkler irrigation was an 0.13 m increase in CCU. The presumed mechanism for this effect was the relationship between soil water storage and irrigation application method. More efficient application methods (e.g., sprinklers) supply water to the soil approximately equal to the crop's demand for water. The applied water is quickly converted to ET and little remains stored in the soil column. Less efficient application methods like flood irrigation produce greater soil saturation at depth. Some of this deep stored water is, presumably, available for crop use during periods of irrigation curtailment. The effect of irrigation application method is likely conditioned on conservation strategy where the presence of sprinklers is less consequential for full season fallow than for irrigation curtailment that starts later in the summer months. However, no such interactive effect was evaluated here.

The model included a random effects term that captured persistent inter-annual differences between fields. The random effects term accounted for approximately ~21% of the variance in the CU_{diff} data. This finding suggests that some fields were consistently wetter or drier than others and that the suite of environmental variables included in the model could not fully account for these differences. However, the fact that the model was able to identify persistent field level differences within the dataset suggests that they are likely sourced from some unobserved physical or management condition and not due to random noise in the data. Further work to identify the drivers of the between-field random effects is warranted.

3.4.4.3 COMPLEX WEATHER INTERACTIONS

The model revealed complex interactive effects for precipitation and evaporative demand. These two weather-related drivers of consumptive water use were included as precipitation and ET anomalies where an increase in the precipitation anomaly ($P_{anomaly}$) indicated wetter than typical conditions and an increase in the ET anomaly ($ET_{anomaly}$) indicated hotter and windier than typical conditions. These terms were included in the model to control for variability in CU_{diff} outcomes driven by inter-annual differences in weather. The effect size for the interaction between the weather terms was significantly larger than any other term. This is an intuitive outcome. Water conservation outcomes in a drought year are expected to deviate from outcomes observed in a cool, wet year. The model identified patterns that support this intuition.

When interpreting the model results for ET and precipitation anomalies it is critical to reflect on the construction of the CU_{diff} response variable. CU_{diff} reflects a change in consumptive use of *irrigation water* from baseline conditions. In a hot and windy year (i.e. elevated $ET_{anomaly}$), baseline evaporative demands are high and baseline consumptive water use is also very high. In a cool year (i.e. depressed $ET_{anomaly}$), baseline evaporative demands are low and baseline consumptive water use is also low. In wet years (i.e. elevated $P_{anomaly}$), effective precipitation (P_{eff}) is high and a crop relies less on irrigation to support evaporative demands than it does in dry years (i.e. depressed $P_{anomaly}$) when effective precipitation is low. As a result, baseline consumptive use of irrigation water is lower in wet years than in dry years, even if total consumptive water use remains unchanged between the two years.

The conditional effects plot of the interaction precipitation anomaly and ET anomaly illustrates the complexity of the relationship (Figure 3.12). Hot and wet conditions ($P_{anomaly} > 0.25$ and $ET_{anomaly} = 0.25$) are associated with lower consumptive water use reductions than hot and dry conditions ($P_{anomaly} < 0.25$ and $ET_{anomaly} = 0.25$). In years when conditions are simultaneously cooler and drier than usual ($P_{anomaly} < 0.25$ and $ET_{anomaly} = -0.25$), consumption of irrigation water is lower than typical, primarily due to the depressed evaporative demand. Conversely, in cool and wet conditions ($P_{anomaly} > 0.25$ and $ET_{anomaly} = -0.25$) consumptive use of irrigation water appears higher than typical. This result does not conform to my conceptual understanding of the system and is likely a purely mathematical outcome driven by limited data available for the Gaussian process fit used by the model to interact the two anomalies. The effects in this quadrant are extrapolations that do not appear physically plausible.

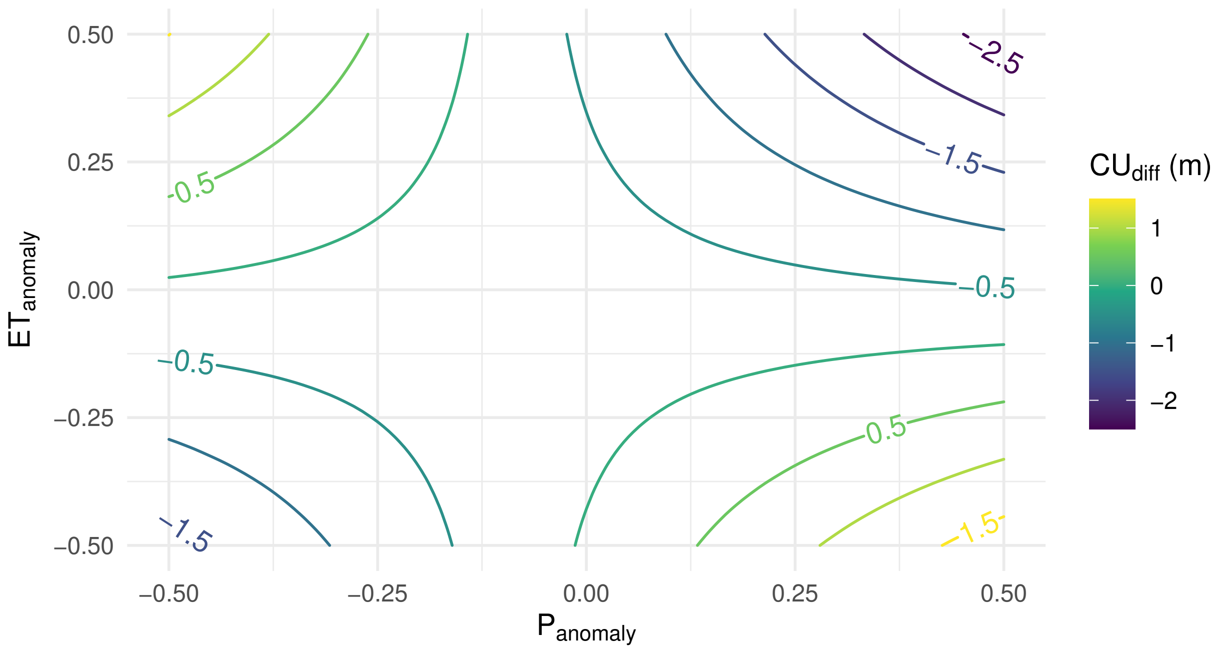

FIGURE 3.12. Conditional effects of ET anomaly and precipitation anomaly where anomalies greater than 100% indicate hotter or wetter than usual conditions, respectively.

3.4.5 POLICY AND MANAGEMENT IMPLICATIONS

This research was performed in response to perceived information gaps in the water conservation policy and management domains. Most related work performed to date focuses on tabulating volumetric consumptive use reductions following conservation projects [18, 19, 38, 39]. As the prospect of sustained efforts to generate agricultural water conservation at the basin scale increases, it becomes increasingly important for water managers and policy makers to have access to insights that can help 1) optimize decision-making about where to prioritize specific types of conservation, 2) predict field-scale conservation outcomes given a set of observable geographical characteristics, and 3) deploy scalable techniques for verifying conservation practice implementation across large geographies. The analyses and findings presented here respond to each of these needs

The role that cropping pattern played in moderating consumptive use reductions was of particular interest to this study. The dominant agricultural economic activity on Colorado's West Slope is the production of feed for livestock. Significant acreages of perennial grass and alfalfa are required to support this economy. In fact, grass pasture and alfalfa are ubiquitous agricultural land cover types in the UCRB. This basin-scale pattern is mirrored in the study area where ~65% of the mapped agricultural fields were grass pasture, ~27% were alfalfa, ~4% were corn, and the remaining 4% were divided up among orchards, small grains, dry beans, and other crops [37]. The largest uncertainties in potential consumptive water use reductions are also associated with these perennial croplands.

The perennial nature of grass pasture (and many alfalfa fields in the the UCRB) means that some water consumption is inevitable, even in cases where irrigation curtailment is applied across the entire growing season. This affect was noted by other researchers studying water conservation impacts in the UCRB [20]. The posterior probability distributions, conditioned on crop type, showed the strongest differences between the CU_{diff} distributions on grass pasture fields and fields growing alfalfa. Other crops appeared in the Full Season and Split Season Early classes (Figure 3.9). In both cases, the presence of grass pasture diminished the CCU outcomes associated with conservation practice. The results presented here help establish a quantitative basis for the otherwise anecdotal expectations that water conservation on grass pasture is less effective than on fields growing other crops.

My model suggests that the moderating influence of grass pasture on consumptive water use reductions is non-linear across conservation strategies. Grass pasture incurred the greatest differentiation in CCU outcomes for the Split Season Early strategy (Figure 3.10). Other researchers documented the potential for rapid recovery of productivity and ET in high-elevation grasslands following a period of drought or deficit irrigation [40]. The recovery of grasslands from water stress early in the growing season may be a function of a general lack of physiological drought response among grasses until soil moisture deficits drop to very low levels [41, 42]. This may result in persistent growth under early season irrigation curtailment as grasses draw down available soil moisture. A period of vigorous plant growth may follow a mid-season irrigation re-start. In some settings, this period of vigorous growth and elevated ET may significantly offset the signal of depressed ET from earlier in the growing season. Alternatively, the observation of a sub-population of positive CU_{diff} values for the Split Season Early classes among grass pastures may result from the "drought-paradox" noted by others [43], where conservation periods that coincide with above normal summer temperatures and below normal precipitation may experience ET rates elevated above baseline conditions.

The success of sustained basin-scale water conservation programs or policies will inevitably require participation by farmers and ranchers who own or manage grass pasture. My results suggest that full season irrigation curtailment is the most promising strategy for optimizing CCU on grass-pasture. The probability that consumptive water use on grass pasture mirrors the normal irrigation baseline condition increases significantly for the other conservation strategies (Figure 3.9). Model results evaluating the effects of elevation further restrict the management and policy space, especially for grass pasture. Conservation at higher elevation generated less CCU than conservation at lower elevations. Larger areas of high-elevation irrigated grass pasture will be required to generate the same CCU outcomes as conservation projects implemented on other crop types at lower elevations. Model results suggest that achievement of equivalent conservation outcomes in a high elevation (2100 m) grass pasture will require approximately five times the land area as a low elevation (1600 m) field cultivating corn, all other conditions being equal.

The model identified strong interactive effects between precipitation and evaporative demand. In relatively wet-cool years, when farmers and ranchers with senior water rights may be more willing to participate in conservation due to a lower perceived risk, conservation will net less CCU than in hot and dry years. The stochastic nature of seasonal weather patterns means that irregular temporal implementation of conservation projects in the UCRB will increase uncertainty in basin-scale conservation outcomes. Presently, funding for programs like SCPP is authorized by the U.S. Congress in annual federal budgets. No guarantee exists for program funding in any given year. As a result, numerous conservation projects are enacted in some years while other years see none. If a year when conservation projects are implemented happens to coincide with hot and dry conditions, CCU from conservation gains will be relatively high. Conversely, if conservation projects are implemented in a cool and wet year, conservation gains will be modest. The best strategic approach for maximizing conservation outcomes and minimizing uncertainty over the long term, given the strong influence of seasonal weather, is consistent annual implementation of projects. This long-term, strategic approach will help smooth over the effects of infrequent but consequential outlying seasonal weather conditions.

Significant uncertainty exists in characterizations of water use reductions under conservation. Even after accounting for the presence of numerous interacting environmental factors, the model presented here was only able to account for 71% of the variance in CU_{diff} when applied in a predictive context. The mean effects, absent some explicit characterization of uncertainty, are likely to provide unreliable estimates of CCU outcomes across diverse geographies in western Colorado or, more broadly, across the UCRB. Therefore, any future efforts to incorporate findings presented here into decision support systems should utilize a probabilistic framework that can explicitly present uncertainty in predictions.

3.5 DATA LIMITATIONS AND OPPORTUNITIES FOR FUTURE WORK

A large number of individual AHUs were used as training data for the hierarchical model. However, the total irrigated area captured in the data is relatively small compared to the total irrigated area in the UCRB.

Additionally, the sampled fields may not cover the full range of geographical characteristics that might affect water conservation outcomes at the basin scale. Fields considered in this study were exclusively located in western Colorado. No fields from Utah, Wyoming, or New Mexico were represented in the sample. The drivers of consumptive use reductions under water conservation may be distinct in type and magnitude in these locations.

The relative position of individual AHU's within a field may have produced some error. AHUs with a 90 m diameter were selected for computation of CU_{diff}. The placement of AHU centroids at least 45 m from a mapped field edge should have prevented cases where pixels included in the ET dataset were contaminated by field edge effects. One or more 30 m pixels used by OpenET to compute AHU ET time series for a given AHU may have captured some portion of the ET signal from outside of the conservation field. Inaccuracies in field delineations may have produced similar cases. These edge effects may contribute noise to the data used to fit the model. Data contamination may also artificially mask or enhance the assessed impact of water conservation.

Crop type assignments for a given field and its nested AHUs were based on publicly available data from the CDSS [44]. These assignments were modified where specific information about cropping patterns was available from contracts for water conservation activities on a given field. It is possible that some of the crop type assignments do not match actual cropping patterns over the period of interest. It is also possible that some fields mapped as grass pasture were put into different cultivation at some point in the period of interest. These potential sources of error may contribute to uncertainty in the effect of grass pasture on CU_{diff}. Future work expanding on the methods presented here will benefit from a rigorous effort to validate crop types on conservation fields throughout the baseline and conservation periods.

Most of the conservation documented in the dataset occurred in a limited number of years, primarily in 2023 and 2024. Despite my attempt to control for precipitation anomalies, specific meteorological or antecedent soil moisture conditions unique to these years may have exerted influence on measured water conservation effects. The calculation of baseline conditions utilized a relatively short time window–most fields underwent normal irrigation in five out of the six years in the observation period. This may be an insufficiently long window to capture true baseline irrigation patterns across a diversity of hydrological year types. A relative lack of diversity in year types available across the baseline period or the performance of most conservation in outlying year types may have affected computations of $ET_{anomaly}$, $P_{anomaly}$ and baselines used for computation of CU_{diff}.

As longer observational periods become available through OpenET or similar services, it may be possible to establish more stable and representative baseline conditions, which may support deployment of better performing models. However, if the goal is to quantify the effects of conservation consumptive water use, then some tension may exist between the desire to increase the length of the baseline period and the need to represent typical conditions and irrigation practices in a contemporary setting. For example, use of a 30-year record for the computation of baselines, those periods may overlap with change points in farm or ranch management accompanied by step changes D_{ratio} (e.g., due to a shift in irrigation frequency, magnitude, or location with a field). Future work should evaluate the role of shifting baseline time window length on the characterization of water conservation outcomes.

The diversity of enacted conservation practices captured by the dataset were not applied equally across all geographies. Some practices were restricted to limited geographies or cropping patterns. This feature of the data may be improved in future years through strategic implementation of field scale experiments that test a variety of conservation practices on different field types, situated across different geographical contexts in the UCRB. As more evidence of conservation practice comes available in publicly-available remotely sensed ET data, it may be possible to improve upon the modeling results presented here.

3.6 CONCLUSION

Persistent drought and depleted reservoir storage continue to challenge management of Colorado River water in the Colorado River Basin. In the UCRB, voluntary, temporary and compensated reductions in water use are promoted as a viable tool for partially addressing some of these challenges. The proportional allocation of water among various water use sectors suggests that agriculture will need to provide most of this conservation. Maximizing the beneficial impacts of agricultural water conservation depends on water managers ability to verify where conservation happened (and where it did not) in any given year. It also depends on elucidation of the geographical factors that drive greater or lesser CCU outcomes in one location vs. another. The work presented here responds to both of these needs.

I present a time series pattern recognition and classification approach that confirms conservation practices leave a detectable fingerprint on remotely sensed ET data, confirming my first hypothesis. I propose a novel metric for the computation of crop water use, normalized to time-varying evaporative demands and baseline consumptive water use across a given time step. I deploy this metric and the DTW algorithm to identify the optimal spatial and temporal scales for classifying ET time series. I expect that this work can support future efforts to efficiently validate conservation project implementation across large landscapes.

My work to construct a Bayesian hierarchical model confirms my hypothesis that between-field variability in CCU outcomes can be explained by interactions between conservation strategies and measurable environmental factors. Results presented here quantify the magnitude and direction of these effects and characterize the specific geographical conditions and conservation strategies likely to produce the greatest and least consumptive water use reductions. My approach for predicting CCU outcomes as a function of observable environmental variables provides water managers and policy makers with a pathway for anticipating consumptive use outcomes on a given field, in a particular hydrological year type.

Combining the insights and information presented here with characterizations of water conservation's economic consequences in different settings can provide a coherent framework for strategically maximizing conservation outcomes while minimizing adverse economic impacts. I also perceive opportunity to integrate these findings with evaluations of participation likelihood among agricultural producers when presented with alternative conservation program structures and attributes. This integration would permit probabilistic characterization of annual CCU totals at a spatial scale of interest.

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PART II

Human-Behavioral Subsystem

CHAPTER 4

PRODUCER PREFERENCES FOR WATER CONSERVATION PROGRAM ATTRIBUTES: A QUANTITATIVE SOCIAL SURVEY DATASET FROM COLORADO'S WEST SLOPE.

This dataset provides survey responses generated among agricultural water users on Colorado's West Slope. The dataset characterizes water users' demographics, farm and ranch characteristics, attitudes towards water conservation activities, and stated preferences for water conservation program or policy attributes (Table 4.1). Survey responses were collected in 2023 and 2024 over the Internet using the Qualtrics survey platform and through distribution of paper surveys to addresses associated with agricultural lands in Colorado counties located west of the Continental Divide. The dataset consists of responses from 573 individuals self-identified as agricultural water users.

TABLE 4.1. Data Specification.

Specifications	
Subject	Social Sciences
Specific subject area	Agricultural water users' attitudes towards water conservation and stated preferences for specific conservation program or policy attributes
Type of data	PDF file, CSV files

Specifications	
Data collection	A quantitative social survey was deployed among agricultural water users on Colorado's West Slope. The survey included questions about a water user's demographic characteristics, farm or ranch characteristics and attitudes toward water conservation. The survey also included a discrete choice experiment. Surveys were administered using the Qualitrics survey platform and through distribution of paper copies via the U.S. Postal Service. Survey responses were deidentified and reformatted in R.
Data source location	West Slope region, State of Colorado, United States of America
Data accessibility	Repository Name: Dryad, Data identification number: 10.5061/dryad.m905qfvf5

4.1 VALUE OF THE DATA

- Provides information on agricultural water users attitudes about water conservation and stated preferences for specific water conservation policy or program attributes.
- Supplements recent qualitative survey efforts among water users with results from a discrete choice experiment that permit quantitative evaluation of water user preferences and likelihood of participation in conservation programs characterized by a specific attribute set.
- Researchers can reuse this data to establish statistical linkages between observable demographic and farm or ranch characteristics, latent variables related to water user attitudes, and results from the DCE.
- Policymakers in the Upper Colorado River Basin and, specifically, in the State of Colorado, may use this data to support or develop data-informed water conservation policy.

4.2 BACKGROUND

Voluntary, temporary, and compensated water conservation on agricultural lands in the Colorado River Basin are receiving increasing attention as an important tool for addressing ongoing water supply and management challenges on the Colorado River [1, 2]. Pilot projects testing the effectiveness and feasibility of this type of conservation in the Upper Colorado River Basin (UCRB) attracted modest participation [3] relative to average annual rates of basin-wide water consumption [4]. Hard evidence supporting different theories for low conservation program participation rates among agricultural water users in the UCRB is limited. Most existing information is anecdotal. The limited published findings that explore the issue are either qualitative in nature [5] or do not contain sufficient detail to support development of predictive models of water conservation program participation, given a set of observable demographic characteristics and a set of proposed or hypothetical water conservation policy or program attributes. The dataset contained here intends to fill this important data gap and support the generation and testing of predictive models and decision support tools that can subsequently inform robust policy development.

4.3 DATA DESCRIPTION

The complete dataset includes four files organized as follows:

File: Paper_Survey.pdf: Description: A paper version of the survey distributed to agricultural water users on Colorado's West Slope.

File: survey_headers.csv: Description: This file contains the mapping of the header values present in the complete_deidentified_responses.csv file to the text of individual questions administered in the survey.

Variables:

- *question_ID*: The ID of the question included in the survey.
- *question_text*: The text of the question associated with the ID.

File: complete_deidentified_responses.csv: Description: This file contains the full set of deidentified survey responses, including results from the DCE in wide format. Each row in the file contains a set of responses from a single survey respondent.

Variables:

- *resp.id*: The unique identifier for each respondent.
- See survey_headers.csv for complete description of remaining file headers.

File: dce_results_long_format.csv: Description: This file contains the DCE results in long format for ease of use in analysis.

Variables:

- *resp.id*: The unique identifier for each respondent. This is the primary key for joining to other data files.
- *question*: the ID of the choice sets (1-12) presented to the respondent.
- *alternative*: the ID of the choices (1-3) contained within the choice set where choice #3 was always the status-quo or no-action alternative.
- *conservationPractice*: The irrigation reduction activity that would be contracted and enacted for a single irrigation season.
- *compensationPerAcre*: Payment for each acre of land placed under water conservation.
- *committedAcreage*: The portion of typically irrigated acreage allocated to water conservation program activities.
- *eastSlopeMatch*: Whether any conserved consumptive use will be matched in volume by curtailment of transmountain water diversions to the Front Range.
- *waterShepherding*: Whether any conserved consumptive use water will be shepherded downstream past all other water users and controlled by the Upper Basin states to reduce risks of a Compact Call on the Colorado River.
- *alternativeSelected*: The ID of the alternative selected from the choice set.
- *optOut*: Flag indicating whether the respondent elected the status quo option from the choice set.

4.4 EXPERIMENTAL DESIGN, MATERIALS, AND METHODS

The relevant decision-making variables that influence water conservation program participation among diverse groups of agricultural water users on Colorado's West Slope were explored by aggregating relevant information from existing reports and workshop proceedings, conducting one-on-one interviews with diverse groups of water users, and via consultation with professionals in the water management sector who currently or previously managed or implemented voluntary water conservation programs. This information collection exercise provided a body of knowledge that was used to inform development of a survey questionnaire that consisted of two primary parts. The first part of the survey included questions that probed the demographics characteristics and attitudes of individual respondents.The second part of the survey consisted of a DCE where respondents were asked to indicate their willingness to participate in alternative water conservation programs characterized unique sets of attributes. DCEs are common tools used for evaluating stated-preferences for competing goods or services [6]. DCEs are gaining traction as viable tools for assessing environmental valuations among non-market goods [7] and for characterizing preferences for trade-offs in agricultural and water resource management contexts [8, 9, 10, 11].

4.4.1 DEMOGRAPHICS

Demographic questions included inquires about county of residence, age, gender, ethnicity, adjusted gross income, and political affiliation. Most respondents who reported age, sex, and ethnicity were white males who fell between 55-84 years old Figure 4.1, Figure 4.2, Figure 4.3. Republicans and Independents dominated among reported political affiliations Figure 4.4. A majority of respondents reported adjusted gross income (AGI) less than $150,000 Figure 4.5. Farm income generally comprised less than 25% of AGI.

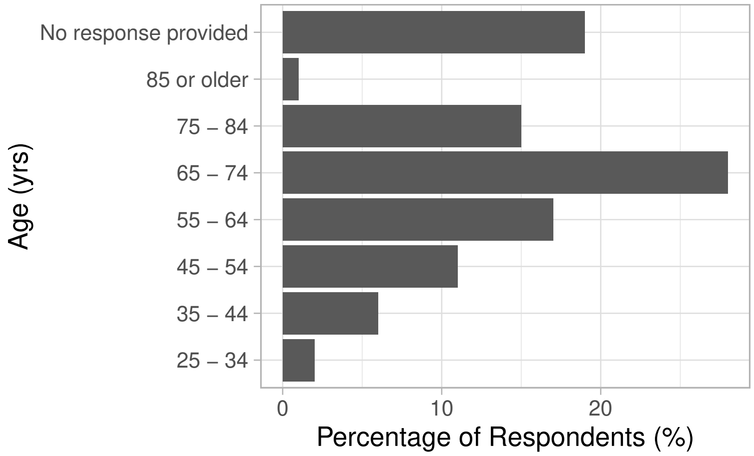


FIGURE 4.1. Age of survey respondents.

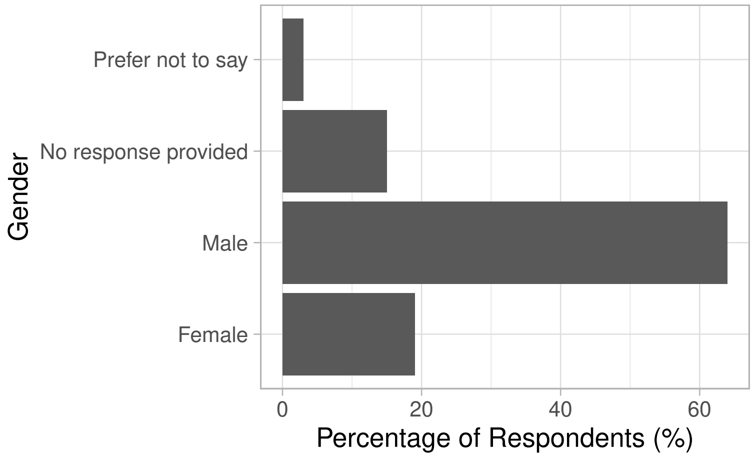


FIGURE 4.2. Gender of survey respondents.

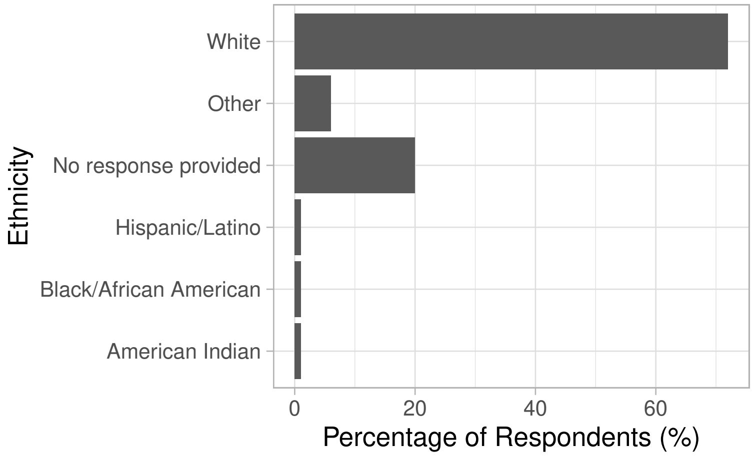


FIGURE 4.3. Ethnicity of survey respondents.

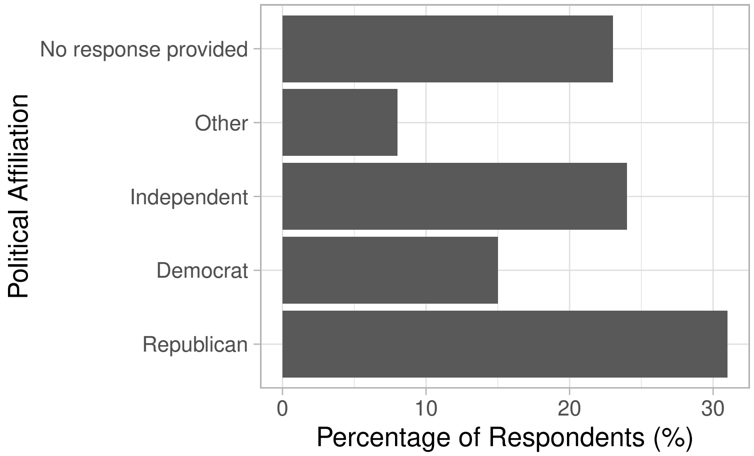


FIGURE 4.4. Political affiliation of survey respondents.

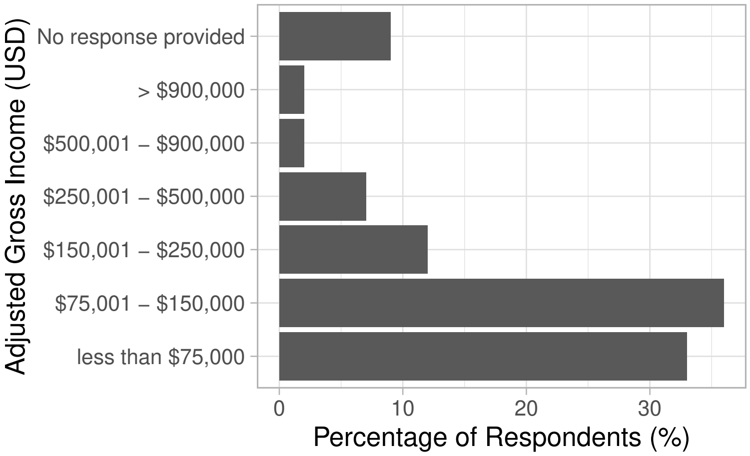


FIGURE 4.5. Survey results for annual adjusted gross income.

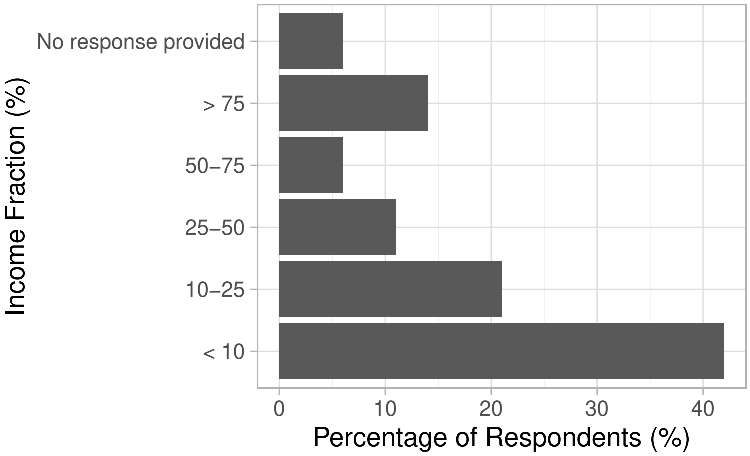


FIGURE 4.6. Percentage of adjusted gross income derived from agricultural production.

4.4.2 FARM AND RANCH CHARACTERISTICS

Questions about farm and ranch characteristics captured information about the size of a respondent's agricultural operation, the crops produced under irrigation, the on-farm activities related to income-generation, the relative seniority of water rights, and water availability under different hydrological year types. The most common reported irrigated acreage fell between 11-50 acres Figure 4.6, but farms and ranches up to 300 acres were not uncommon Figure 4.7. Nearly 80% of respondents reported using irrigation water to produce hay/grass pasture Figure 4.8. This aligned with the dominance of livestock sales and forage sales as the primary farm or ranch revenue source Figure 4.9.

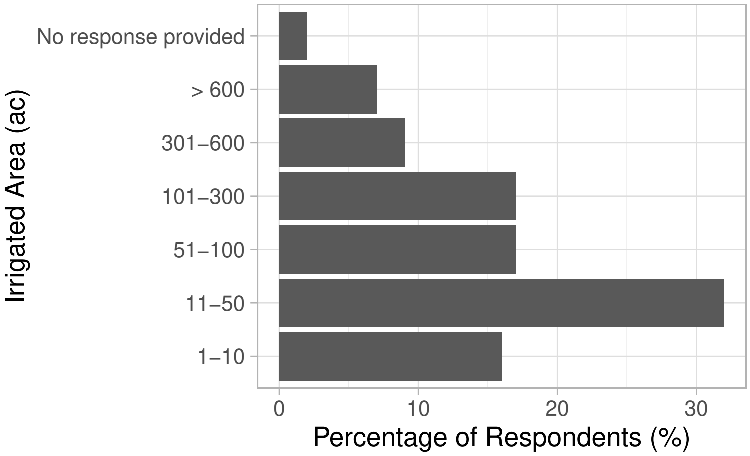


FIGURE 4.7. Total acreage under irrigation.

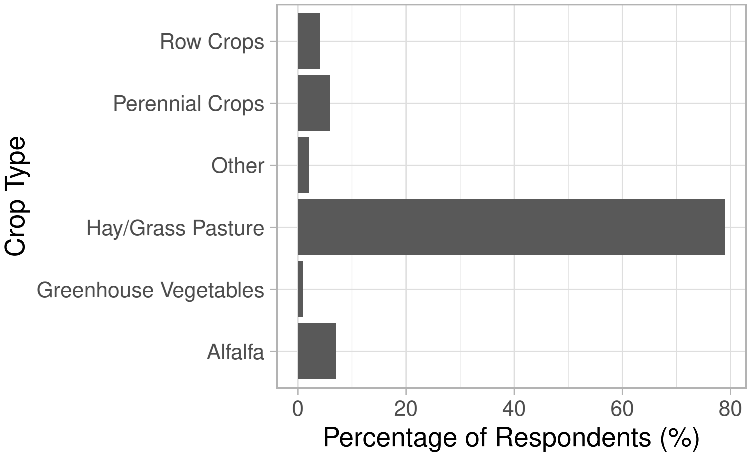


FIGURE 4.8. Dominant agricultural production activity utilizing irrigation water.

4.4.3 ATTITUDES

Respondent attitudes toward agricultural water conservation were assessed with a set of matrix table questions. Each matrix table was structured to elicit responses along a 5-point Likert scale. These questions were structured to serve as proxies for latent variables common to theoretical behavior models

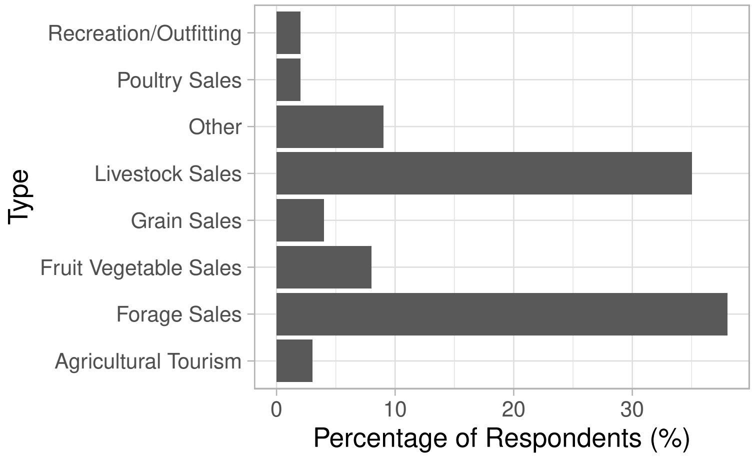


FIGURE 4.9. Respondent dominant revenue source.

[12, 13], including *awareness, responsibility, subjective norms, perceived behavioral control* and *personal norms*. Three linked questions (Awareness_1, Awareness_2, Awareness_3) probed respondents awareness of drought issues in the Colorado River Basin. Three linked questions (Responsibility_2, Responsibility_3, Responsibility_5) asked about respondents' feeling of responsibility to take personal action and help resolve drought-related issues. Three linked questions (SubNorms_1, SubNorms_2, SubNorms_3) explored the influence of friends, family, and community members on enterprise decision-making. Three linked questions (PBC_3, PBC_4, PBC_5) asked respondents' about their perceived ability to influence outcomes. A single question (PersNorms_1) directly queried respondents' feelings about temporary, voluntary, compensated water conservation programs.

4.4.4 DISCRETE CHOICE EXPERIMENT

In the DCE portion of the survey, each respondent was presented with twelve separate choice sets. Each choice set consisted of two water conservation alternatives and a status quo option. Each water conservation alternative was characterized by a unique set of policy attributes that reflected various risk/value propositions for agricultural water users. The individual attributes and their levels are described below:

- **Conservation Action** - The irrigation reduction activity that will be contracted and enacted for a single irrigation season. The included activities reflect common strategies implemented across Colorado's West Slope. **Levels**: "Full-Season Limited Irrigation", "Split-Season Curtailment", "Full-Season Curtailment"

- **Compensation Rate** - Payment for each acre of land placed under water conservation. The included compensation rates bracketed the range of payments for leased water observed in recent years in Colorado. **Levels**: “$150”, “$300”, “$600”, “$1200”, “$1600”
- **Conserved Acreage** - The portion of typically irrigated acreage allocated to water conservation program activities. The included irrigated land fractions accommodate farmer and rancher concerns about risks involved with committing entire operations to conservation in any given year. **Levels**: “25%”, “50%”, “75%”, “100%”
- **East Slope Match** - Whether any conserved consumptive water use would be matched in volume by curtailment of transmountain water diversions to Colorado’s Front Range. This attribute reflects sentiments expressed among West Slope Colorado water users for water conservation burden-sharing between rural communities west of the Continental Divide with urban communities on Colorado’s Front Range. **Levels**: “No”, “Yes”
- **Water Shepherding/Protection** - Whether any conserved consumptive use water will be shepherded downstream past all other water users and controlled by the Upper Basin states to reduce risks of a Compact Call on the Colorado River. This attribute was included to differentiate programs that generate “system water” that may be used by junior users from those that actively administer conserved consumptive use volumes as a basin-wide risk reduction strategy. **Levels**: “No”, “Yes”

The specific choice sets included in the DCE were determined using an experimental design that accounted for the total number of factors/levels present in the DCE and anticipated the number of likely survey participants. The experimental design was optimized using the D-efficiency, a standard approach used by others for the same purpose [14, 15, 16]. This optimization approach, implemented with the *idefix* library in R, is expected to constrain confidence ellipsoids around estimates for coefficients of a multinomial logit (MNL) model fit to the data generated by teh DCE [17].

The optimization approach began with generation of a full factorial design. All factors were coded as categorical variables. Constraints were imposed on the design to prohibit some impossible or highly unlikely combinations of factor levels. Specifically, sets that offered $150-$300 per acre for Full Season Curtailment were prohibited, along with sets that offered $1200-$1600 per acre for Full Season Limited Irrigation and Split Season Curtailment. Priors were established for model coefficients of the various factors/levels included in DCE. Priors for the various Compensation Rate levels and the “Yes” response to East Slope Match and Water Shepherding factors were defined as truncated normal distributions to conform to the expected directionality of the coefficients. Other coefficients were described with uninformative priors (mean of 0, s.d. of 1). The coordinate exchange algorithm (CEA) in *idefix* was used to sample from the prior distributions for each of the factors and their respective levels. The CEA was initiated with total of 25 random start designs, each containing 12 choice sets with two alternatives. The DB-error based on a MNL model was sequentially computed across 500 draws from the prior distributions for each of the start designs. The final, optimized designs were implemented as survey blocks.

4.4.5 SURVEY DISTRIBUTION

Surveys were initially encoded and distributed using the Qualtrics [18] survey platform. Qualtrics assigned a DCE choice set block to a respondent in a sequential manner where the first respondent was assigned to the first block, the second respondent was assigned to the second block, and so on. Survey links were sent to water/soil conservation districts, non-profit organizations, water management entities along with a request for redistribution among their respective memberships. Requests for survey participation were also made in person at conferences and meetings of entities like the Colorado River Water Conservation District. Participation by specific individuals was solicited via phone calls, emails, and in-person meetings. Finally, a paid marketing campaign was also conducted on the Facebook and Twitter social media platforms. The survey distribution effort sought to generate responses from > 400 individual water users residing in Colorado's West Slope region and characterizing different socioeconomic and demographic classes. Anemic responses to the web-based survey after 4 months prompted distribution of approximately 4,500 paper versions of the survey to addresses associated with farm and ranch properties on Colorado's West Slope (Appendix A). All paper surveys included the same DCE choice set block. At the conclusion of the survey distribution and response collection period, 573 high-quality responses were recorded. All identifying information (e.g., names, addresses, phone numbers, etc.) was removed from the final set of responses prior to publication.

4.4.6 SAMPLE REPRESENTATIVENESS CHECK

A cursory exploration of the demographic characteristics of the survey sample was performed. Where possible, demographic data characterizing survey participants was compared against similar data available from the 2022 U.S. Department of Agriculture (USDA) Census of Agriculture [19] Figure 4.10, Figure 4.11, Figure 4.12. The dominant irrigated crop proportions reported by survey respondents were compared to mapped acreages of various crop types on Colorado's West SlopeFigure 4.13 produced by Colorado Division of Water Resources (DWR) [20]. These qualitative comparisons helped assess the representativeness of the survey sample within the broader population of West Slope agricultural producers.

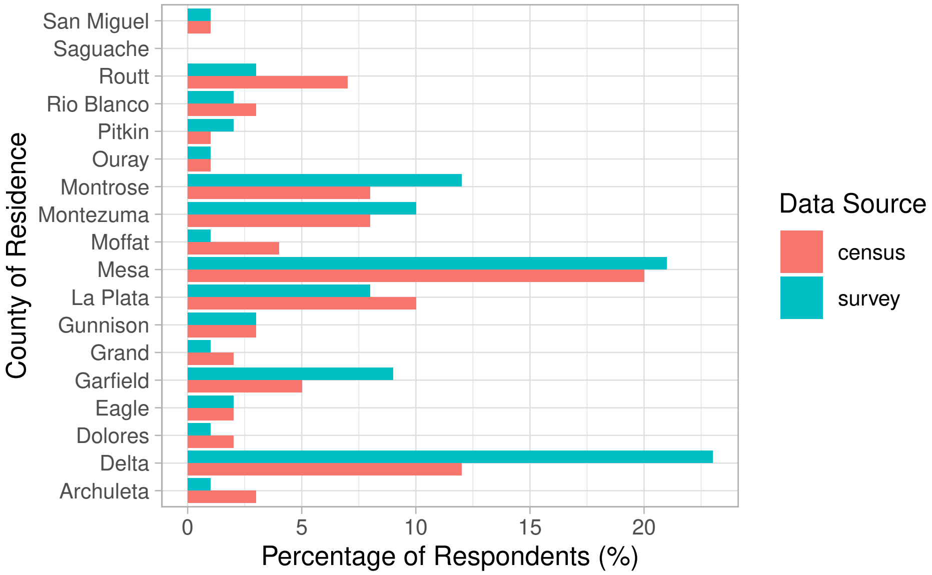


FIGURE 4.10. Comparison of survey respondent county of residence distribution to distributions reported in the 2022 USDA Agriculture Census for farms and ranches on Colorado's West Slope.

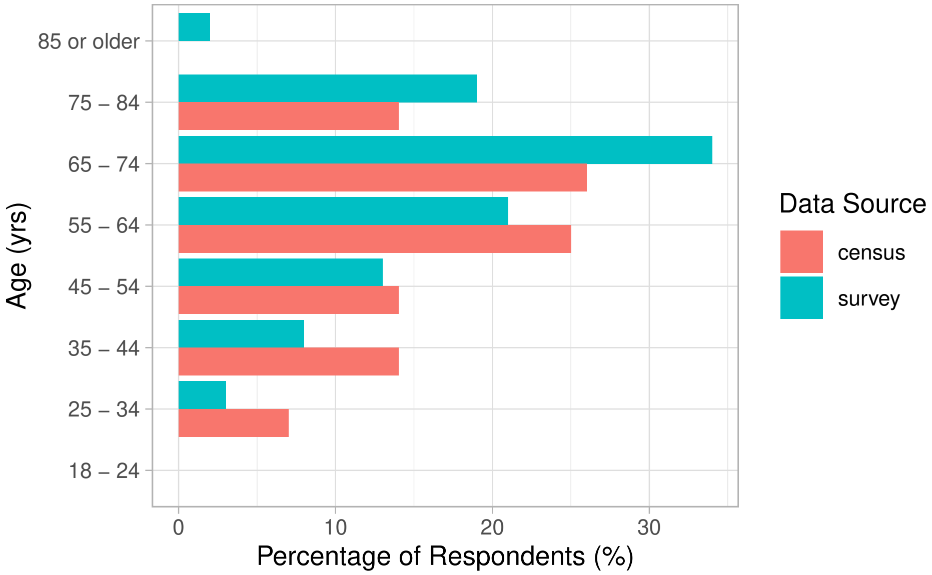
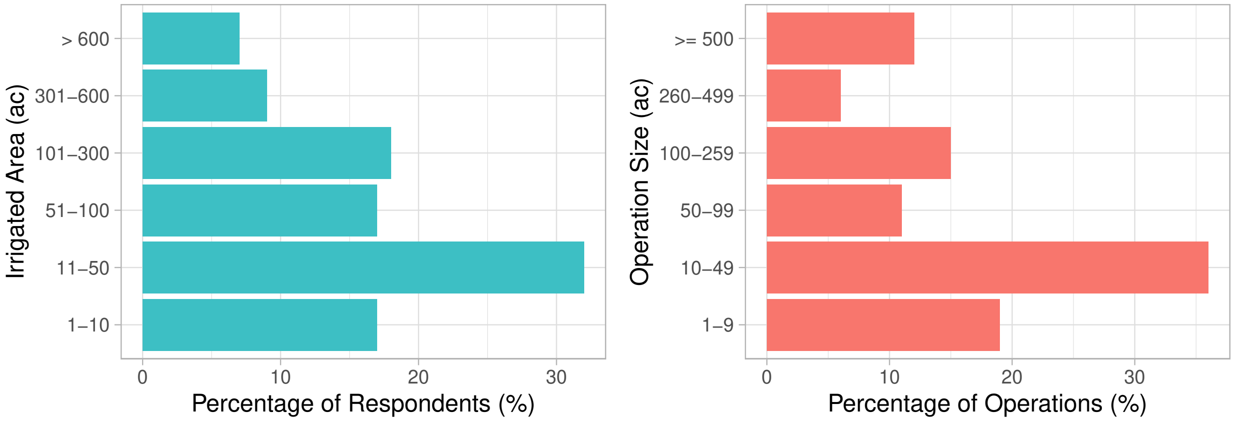
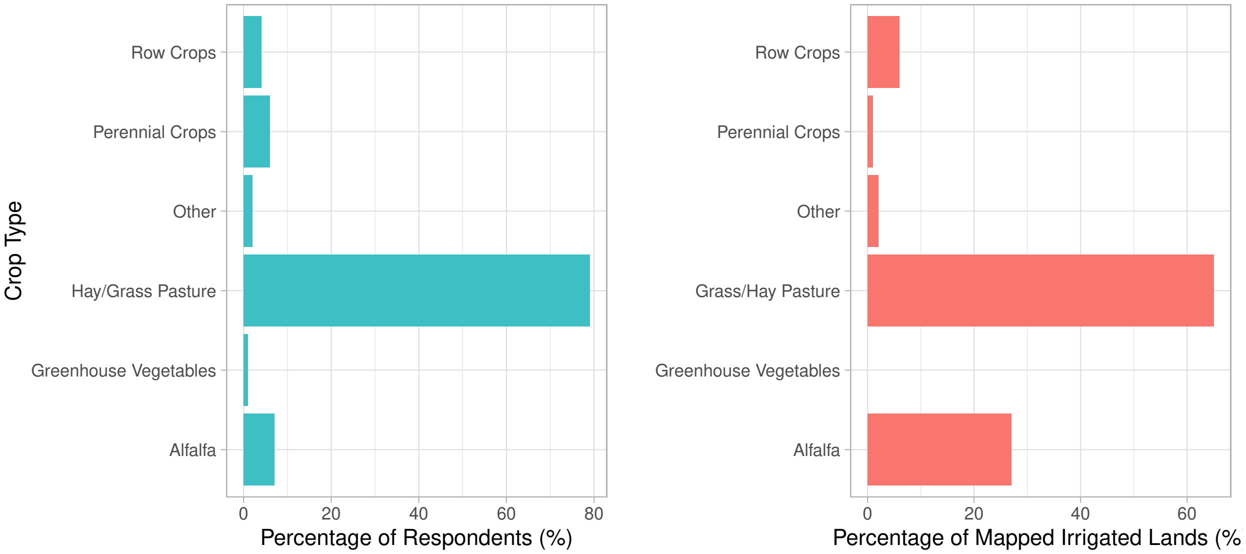


FIGURE 4.11. Comparison of survey respondent ages to ages reported in the 2022 USDA Agriculture Census for farms and ranches on Colorado's West Slope



(A) Survey Respondents (B) USDA Agriculture Census

FIGURE 4.12. Comparison of survey respondent reported irrigated acreage distribution (A) to distribution of agricultural operation acreages reported in the 2022 USDA Agriculture Census for farms and ranches on Colorado's West Slope (B). Results are separated into two figures due to differing response scales used by each survey source.



(A) Survey Respondents (B) Colorado DWR

FIGURE 4.13. Comparison of dominant crop types reported by survey respodents (A) to areal proportions of West Slope crop types mapped by Colorado DWR (B). Results are separated into two figures due to differing response scales used by each survey source.

Among the survey respondents, a disproportionate number came from Delta County when compared to the proportional distribution of county residence evident in the USDA Agricultural Census data. Garfield County is also somewhat over-represented in the survey responses and Routt County is somewhat under-represented. Distributions of respondent ages were similar between the survey data and the USDA

Agriculture Census data, however, the survey data appears to skew slightly older. The distribution of irrigated acreages reported in my survey were similar to the distribution of operation sizes reported in the USDA Census. The most common operation size in both fell between ~10-50 ac. Some differences were apparent between the distribution of irrigated crop types reported in my survey to the proportion of mapped irrigated acreages associated with those crop types produced by Colorado DWR. Notably, a greater areal proportion of alfalfa was evident in the DWR mapped acreages. This may suggest an under-representation of alfalfa producers in my data. However, my survey did not ask respondents to report crop types by area, only by operation. Conversely, it is not possible to discern distinct groupings of fields within the mapped acreages that would correspond to ownership or farm/ranch operational boundaries.

4.5 LIMITATIONS

Surveys were distributed solely to agricultural water users in Colorado's West Slope region. Responses may not be representative of water users in other portions of the UCRB. Participation in this survey was strictly voluntary and no effort was made to verify that respondents actually resided on Colorado's West Slope and used irrigation water to support an agricultural operations. It is possible that some responses contained in the survey are erroneous and otherwise not representative of the population of interest. As discussed above, data presented here may contain bias toward the perspectives and preferences among water users in Delta County and may somewhat under-represent alfalfa producers. Observed differences in the proportions of crop types may not indicate bias and may instead arise from fundamental differences in the perspective of the survey and Colorado DWR datasets. Survey results may also reflect a selection bias where agricultural users who elected to respond to the survey hold distinctly different perspectives, preferences, and attitudes than those who elected not to respond to the survey.

4.6 ETHICS STATEMENT

The Colorado State University Institutional Review Board (FWA0000647) determined data collection activities associated with the project are exempt under 45CFR46.104(d). Participation in the study was strictly voluntary. All study participants were informed of the expected use of the data and were made aware that their deidentified responses would be combined with similar responses from others and made publicly available. All study participants provided consent to the collection and use of their responses in this manner. All personal identifier information, including names, addresses, and phone numbers, was removed from the data included here prior to its publication.

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CHAPTER 5

ATTITUDES, ASYMMETRY, AND AVERSION: SENTIMENT AND CONTEXT-DEPENDENT RISK PERCEPTIONS SHAPE PREFERENCES FOR WATER CONSERVATION IN WESTERN COLORADO.

5.1 INTRODUCTION

The specter of a water management crisis on the Colorado River is looming larger with each passing month. Persistent drought in the Colorado River Basin over the last quarter century continues to strain existing water supplies and challenge the effective management of storage reservoirs and water delivery systems. Joint management of the two largest reservoirs on the Colorado River, Lake Powell and Lake Mead, is, perhaps, the most important and consequential consideration for ensuring that the Colorado River system continues to sustain growing populations and unique ecosystems as I move into a highly uncertain future. Reservoir operations policies, variable hydrology and growing demand can all conspire to enhance or diminish the reliability of the system with respect to interstate and international compacts and treaties. Conditions in the large reservoirs motivate the search for water management techniques that can help stave off catastrophic failure of regional water administration and supply systems, along with the local economies that rely on them.

Concerns over the stability of large storage reservoirs and the potential for non-compliance with water delivery obligations set forth in the Colorado Compact prompted a recent spate of water conservation projects in both the Lower Colorado River Basin (LCRB) and the Upper Colorado River Basin (UCRB). Water conservation in both basins is currently voluntary, temporary and compensated. Participating water users are compensated for periods of non-use, commensurate with the estimated value of water for a given use sector and the expected volumetric reduction in water use achieved by conservation. The agricultural sector comprises the largest water use activity by volume in both basins. The resulting dominance of water conservation on irrigated agricultural lands [1, 2, 3] is a natural consequence of the predominance of agricultural water use.

While the factors driving water conservation in both basins are shared, the specific contexts that frame conservation activities in each basin differ. Between 2023 and 2024, the LCRB implemented projects to conserve approximately 1.85e+9 m^3 of water, while the UCRB conserved approximately 1.16e+8 m^3 over the same period, an order of magnitude difference. Basin-scale conservation outcomes may be affected, in part, by differences in geography that drive variability in the amount of water savings that can be achieved on one field vs another. However, the rate of participation among water users in a sector is arguably a more critical control on conserved consumptive use (CCU) volumes. Research that enhances my understanding of the factors that drive greater water conservation savings in the LCRB than the UCRB may support strategic and effective policy and program development in the UCRB.

Participation in a water conservation program in any given year is likely mediated by individuals' attitudes, the characteristics of the natural environment that an agricultural producer interacts with, the size and type of social network that individual is embedded within, and farm-specific operational constraints or economic realities. Information context is also known to alter perceived utility and control, thereby shifting choices Sussman et al. [4]. Significantly smaller water volumes conserved in UCRB may speak to the politicization of water conservation, the tone of the messaging (or lack thereof) around water users' shared responsibility for conservation, the high percentage of perennial cropland in upper basin, the unique constraints posed by cow-calf operations, and other local sociopolitical and geographic constraints that are not as prevalent in the LCRB.

In the LCRB, agricultural water conservation that reduces down-canal demand for water translates directly to enhanced storage volumes in Lake Mead. This stored water is available for later use or contributes to stabilization of the Lake Powell-Lake Mead system. While behavioral controls on conservation in the LCRB is not a focus of this research, the relationship between water conservation and incremental risk reduction for non-voluntary curtailment of future water supply may engender a sense of agency and urgency unmatched in the UCRB. Much of the political and legal positioning over use of Colorado River water in the UCRB promotes a narrative that the unfolding water supply crisis in the Colorado River basin is an unavoidable outcome of persistent overuse in the LCRB and that resolving the crisis should then be shouldered by Lower Basin water users. While this may be a reasonable political position, the attendant messaging to constituencies may unintentionally depress water conservation adoption rates among water users in the UCRB. The current lack of administrative mechanisms to deliver conserved water to UCRB reservoirs for the purpose of risk reduction may also give water users the impression that conservation efforts are futile. These differences may help explain the large discrepancies between UCRB and LCRB water conservation yields in recent years.

Arriving at successful outcomes for water conservation efforts envisioned under Upper Colorado River Commission's 5-Point Plan [5] and similar policy documents is contingent upon voluntary action across heterogeneous groups of actors. The participation rates and CCU outcomes associated with System

Conservation Pilot Program projects in recent years do not reflect the level of participation required for meaningful water conservation outcomes in the UCRB Group [2]. The complexities vexing this water management issue are not wholly dissimilar from complexities that arise elsewhere in the natural resource management domain. Context matters. Research efforts that probe the interactions between the social-environmental-economic context and the decision-making process employed by individual water users may yield new insights and enhance the reliability of statistical models employed to predict water conservation program participation levels under a given policy or mix of policies.

Limited water conservation pilot programs were enacted in the the UCRB in recent years. However, widespread and long-term water conservation programs have yet to be implemented. As a result, quantitative characterizations of water conservation program participation rates in response to different policy characteristics, social networks, economic conditions, or environmental settings are not available. The limited information that does exist includes survey results and interviews evaluating water user opinion about water conservation programs [6, 7]. While providing some important insights into the perceived opportunities and challenges associated with scaling up agricultural water conservation efforts in the UCRB, the structure of the available information is insufficient for rigorous quantitative exploration of the relationships between demographic or sociopolitical characteristics of water users and preferences for specific policy or program attributes. This dearth of data constrains any effort to estimate the likelihood of user participation in proposed water conservation programs. Developing sound policy for basin-scale water conservation program in the absence of such information is challenging.

This work probes the decision-making frameworks that influence water conservation program participation among diverse groups of agricultural water users. The specific behavior of interest is an individual electing to participate in a water conservation program. The population of interest includes agricultural water users in the UCRB. Considerable attention in the UCRB is given to the mechanics of conservation project implementation and the optimal compensation rates for generating the greatest return on investment for those projects. Less attention is given to the complex behavioral dynamics that govern conservation project adoption rates. Addressing this shortcoming should help water managers and policymakers implement strategies that can more effectively “scale-up” the conservation pilot projects implemented in the UCRB in recent years. The work detailed here responds to two hypotheses:

- H1: Attitudes play a dominant role in shaping individual water users’ intention to participate in water conservation programs.
- H2: Among water users who intend to participate in water conservation programs, perceptions

of risk disproportionately affect decision-making.

These linked hypotheses frame a two-stage decision making process where I expect water users' attitudes govern their willingness to engage in conservation, forming a conceptual hurdle that must be overcome before a water user is willing to contemplate preferences for various conservation program attributes. I employ theories of human behavior and quantitative social survey tools from the social sciences to explore the interactive effects of sociodemographic factors, individuals' attitudes, and policy or program attributes on decision-making in the water conservation space.

5.2 THEORETICAL BACKGROUND

Recent research shows that the way water conservation choices are framed and the attributes associated wtih a given alternative action materially affect water conservation program uptake (e.g., see urban adoption context in Conrad et al. [8]). The social sciences literature provides a burgeoning number of theories and conceptual models that can help understand and predict conservation adoption. These theories and models attempt to discretize the waypoints along the decision pathways that humans utilize prior to selecting to engage in specific behaviors. In some cases, they provide a mathematical foundation for predicting the likelihood of a decision in a given context. The social sciences provide no universal model of behavior. Indeed, no unified theory of human behavior exists. Instead, various conceptual models are advanced to provide insights into human decision-making in specific settings. Several popular behavior theories that are likely relevant to water users' decision to participate in water conservation programs are discussed below.

The Theory of Planned Behavior (TPB) assumes that humans act as rational processors of information available to them. The theory suggests that all decisions are predicted best by intentions to behave in a certain way, that intentions are informed by attitudes and social norms, and that these attitudes and social norms are shaped by beliefs. The TPB exhibits a quasi-hierarchical structure whereby intentions are the closest antecedents to behavior [9]. Intentions, in turn, are a function of attitudes toward a behavior, injunctive (social) norms and perceived behavioral control. Each of these three variables is determined by behavioral beliefs.

Beliefs contemplate the consequences of a behavior and determine attitudes. Normative beliefs contemplate the expectations of social groups and determine social norms. Behavioral control beliefs reflect on the factors that facilitate or constrain performance of a behavior [9]. Ajzen [10, 11, 12] suggests that beliefs are the primary driver of all behaviors and that changes to belief should lead to behavior change. The TPB is challenged by the possible presence of cultural, gender, or socioeconomic background factors that confound the relationships present in the model. The socioeconomic, demographic, and environmental context germane to any given water user is expected to weigh heavily in the decision to participate in water conservation programs. Authors, including Trafimow and Finlay [13] and Sheeran, et al. [14] discuss the presence of persistent background factors that govern the strength of the relationships between social norms, attitudes, perceived behavioral controls and intentions. Despite these complications, the model continues to provide a useful predictive tool for decision-making in diverse situations.

The Norm Activation Model (NAM), originally proposed by Schwartz [15], provides a construct for predicting altruistic or environmentally friendly behavior. The NAM suggests that awareness of an issue or problem is antecedent to an individual's feeling of responsibility to act. Awareness is specific to knowledge of the consequences of acting or not acting. The strength and direction of the relationship between awareness and responsibility is mediated by social pressures or injunctive norms. The interaction of responsibility and perceived behavioral control then drive intention. Personal norms are the primary determinant of intention to act in a certain altruistic manner. Aspects of the NAM are relevant to decisions about voluntary participation in water conservation programs. The act of program participation, in this context, is not expected to be motivated purely by individual gains. Instead, individuals may participate in water conservation programs—at least in part—out of a shared sense of responsibility to act in order to reduce risks faced by the collective.

The concept of bounded rationality was developed in response to the rational choice theory models like TPB and posits that individuals often do not engage in fully rational decision-making because they are limited by time, imperfect information, or the cognitive state/ability of the decision-maker. Prospect Theory (PT) is a popular model of behavior that grew out of the bounded rationality school of economic thought [16, 17]. PT posits that internalized value functions inform asymmetrical perceptions of gains and losses and that these perceptions play a role in individuals' decision making. The underpinning of PT is that individuals weigh perceived losses in utility more heavily than perceived gains of a similar magnitude. PT is particularly relevant in situations where individuals make decisions effected by an elevated degree of risk and/or uncertainty. Water conservation program participation is an inherently risky behavior affected by several types of uncertainty. Participants face the risk of potential negative lag effects on crop yields of unknown magnitude. Uncertainty about drought conditions or changes in the crop commodity marketplace that manifest after an individual commits to a conservation program leads to some degree of risk that the participant will realize a larger loss than originally expected.

None of the above models of behavior appear singularly well-suited to the decision-making process that individuals are expected to engage in when contemplating water conservation program participation. Numerous examples exist in the literature where investigators integrate multiple theories of behavior to create a conceptual model more salient to the primary question(s) of interest [18, 19, 20]. The conceptual model proposed here integrates aspects of the TPB, NAM, and PT. The model attempts to simultaneously accommodate the influence of awareness of an issue (Awareness), a personal sense of responsibility to act (Responsibility), the social pressures that may enhance or depress individual attitudes toward conservation (Social Norms), an individual's sense of agency in a decision space (Perceived Behavioral Control), and the risk valuation process that occurs when an individual is presented with a set of alternatives, each carrying some uncertain potential for gains (Perceived Reward) or losses (Perceived Risk). The socioeconomic, demographic and environmental context within which a behavior is situated are all expected to affect the concepts represented in the model.

5.3 Focus Geography and Primary Data Sources

The primary geography of interest to this study was the UCRB. However, the primary data used in the analyses were collected exclusively in the West Slope region of Colorado. The West Slope region includes the counties west of the Continental Divide that contribute runoff to the Colorado River Basin (Figure 5.2). The primary dataset used in the analyses discussed below was generated through development and distribution of a quantitative social survey to agricultural water users.

5.3.1 Survey Design

The relevant decision-making variables that influence water conservation program participation among diverse groups of agricultural water users was explored through a voluntary survey of agricultural producers located on Colorado's West Slope. The integrated behavior model (Figure 5.1) served as a guiding framework for the focus and organization of questions included in the survey. Further insights were garnered through aggregation of existing reports and workshop proceedings [21, 22, 23, 24, 25], one-on-one interviews with agricultural water users, and consultation with professionals in the water management sector who currently or previously managed or implemented agricultural water conservation

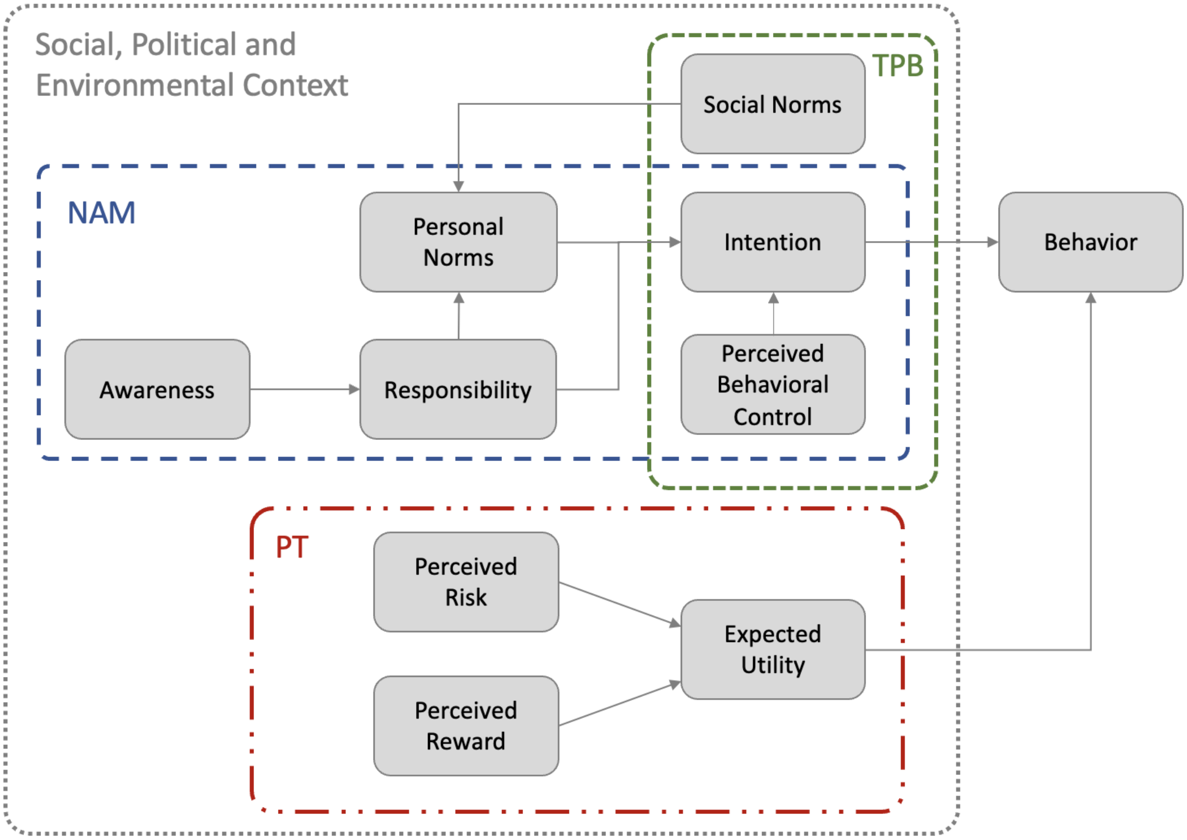

FIGURE 5.1. Suggested conceptual model for relating attitudes and risk valuations to water conservation program participation among agricultural water users in the Upper Colorado River Basin. The conceptual model integrates concepts promoted by the Theory of Planned Behavior (TPB), the Norm Activation Model (NAM), and Prospect Theory (PT).

programs.

The final survey questionnaire (Appendix A) consisted of two primary parts. The first part of the survey included questions that characterized the socioeconomic and demographic context relevant to each respondent (e.g., age, gender, political affiliation, annual income, etc.). This section also solicited responses to questions meant to serve as proxies for the latent variables of attitude contained in the integrated behavior model. Respondent attitudes toward agricultural water conservation were assessed with a set of matrix table questions. Each matrix table was structured to elicit responses along a 5-point Likert scale. One set of grouped questions was used to characterize a respondent's *awareness* of water supply and management challenges on the Colorado River. Another question set probed a respondent's sense of *responsibility* to act in the face of those challenges. The influence of social networks in farm and ranch operational decision-making (i.e. *social norms*) were explored through an additional question set. A

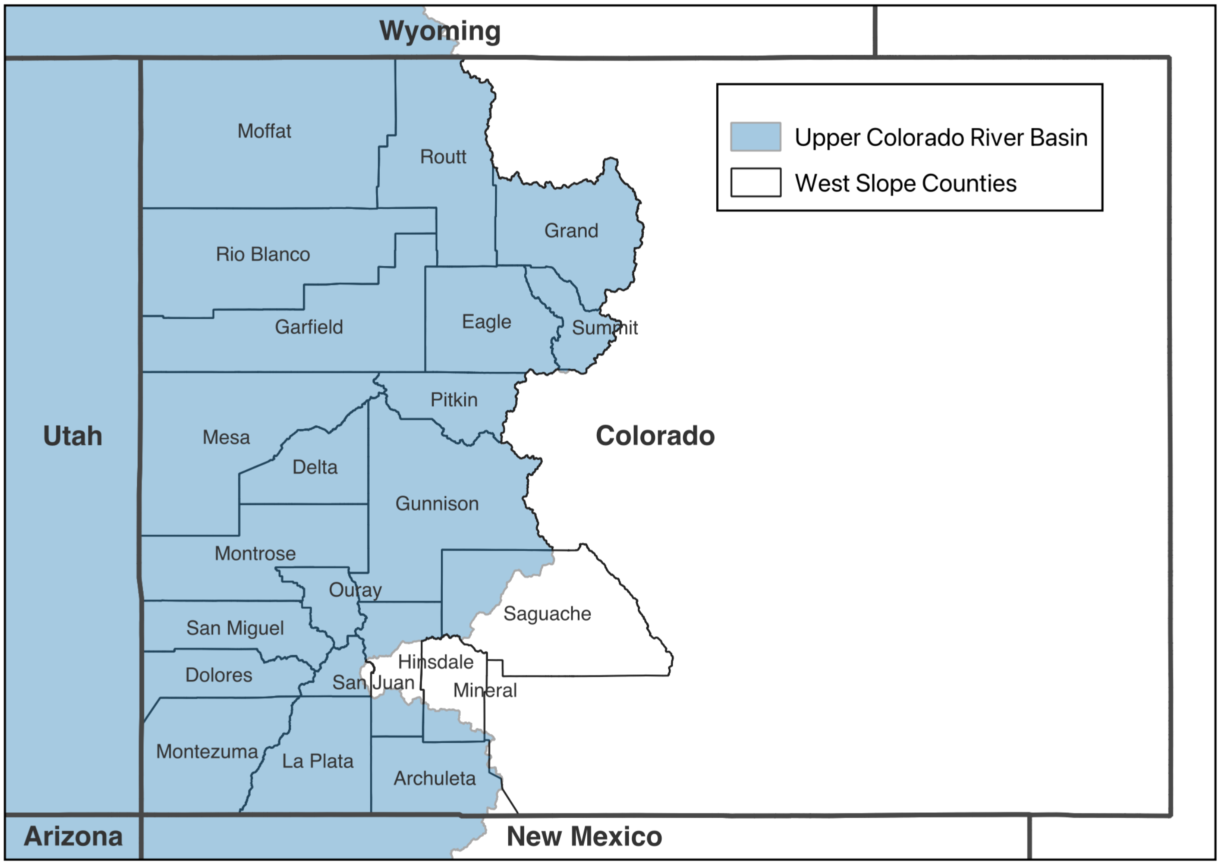

FIGURE 5.2. Colorado's West Slope region includes the counties that fall within the Upper Colorado River Basin.

final question set explored each respondent's sense of agency (i.e. *perceived behavioral control*) related to water conservation implementation and outcomes. Each respondent's general attitude (i.e. *personal norms*) toward water conservation programs as a tool for addressing water supply and management challenges in the UCRB was explored with a single question.

Questions related to attitude were followed by a Discrete Choice Experiment (DCE). DCEs are quantitative social survey devices that collect respondents' stated preferences for features of competing goods, policies, or programs. These tools are finding increasing use in the field of natural resource management and environmental valuation [26, 27, 28, 29, 30]. Within a DCE, multiple choice sets are posed to each respondent as hypothetical scenarios where the respondent must choose one option among two or more alternatives, where each alternative is defined by a unique set of attributes.

The specific choice sets included in the DCE were determined using an experimental design that accounted for the total number of factors/levels present in the DCE and anticipated the number of likely survey participants. The experimental design was optimized using the D-efficiency, a standard approach used by others for the same purpose [31, 32, 33]. Each respondent was presented with 12 distinct choice sets. Within each choice set, respondents were asked to indicate their preference for one of two water conservation alternatives or a status quo option (Figure 5.3). Each alternative was characterized by a unique set of water conservation program/policy attributes (Table 5.1) that represent different risk/value propositions.

	Option 1	Option 2	Neither of these
Conservation Action	Full Season Curtailment (Apr 1 - Oct 31)	Full Season Curtailment (Apr 1 - Oct 31)	Maintain normal irrigation practices
Compensation Per Participating Acre	$1600	$1600	
Irrigated Acreage Under Conservation	50%	25%	
East Slope Match	Yes	No	
Water Shepherding/Protection	Yes	No	
	○	○	○

FIGURE 5.3. Example choice set from the DCE portion of the survey.

TABLE 5.1. Water conservation program attributes and levels included in the discrete choice experiment

Attribute (Levels)	**Description**
Conservation Action (Full-Season Limited Irrigation, Split-Season Curtailment, Full-Season Curtailment)	The irrigation reduction activity that will be contracted and enacted for a single irrigation season. The included activities reflect common strategies implemented across Colorado's West Slope.
Compensation Rate ($150, $300, $600, $1200, $1600)	Payment for each acre (1 ac = 0.40 ha) of land placed under water conservation. The included compensation rates bracketed the range of payments for leased water observed in recent years in Colorado. Note the use of imperial units for land area. All compensation values are represented in USD.

Attribute (Levels)	**Description**
Conserved Acreage (25%, 50%, 75%, 100%)	The portion of typically irrigated acreage allocated to water conservation program activities. The included irrigated land fractions accommodate farmer and rancher concerns about risks involved with committing entire operations to conservation in any given year.
East Slope Match (No, Yes)	Whether any conserved consumptive water use would be matched in volume by curtailment of transmountain water diversions to Colorado's Front Range. This attribute reflects sentiments expressed among West Slope Colorado water users for water conservation burden-sharing between rural communities west of the Continental Divide with urban communities on Colorado's Front Range.
Water Shepherding/ Protection (No, Yes)	Whether any conserved consumptive use water will be shepherded downstream past all other water users and controlled by the Upper Basin states to reduce risks of a Compact Call on the Colorado River. This attribute was included to differentiate programs that generate "system water" that may be used by junior users from those that actively administer conserved consumptive use volumes as a basin-wide risk reduction strategy.

5.3.2 SURVEY DISTRIBUTION

Surveys were distributed digitally using the Qualtrics (*Qualtrics* [34]) survey platform. Requests for digital survey participation were made at workshops, meetings of regional governmental entities, and regular meetings of soil and water conservation districts. Approximately 4,500 paper versions of the survey were mailed to addresses associated with farm and ranch properties on Colorado's West Slope. The survey distribution effort sought to generate responses from > 400 individual water users residing in different basins and characterizing different socioeconomic and demographic classes. Survey distribution began in May of 2023. The survey period closed in February of 2024.

5.4 METHODS

The survey data collected in Colorado's West Slope region was used to construct a probabilistic model of water conservation adoption behavior. My conceptual behavior model was applied to the data through development and implementation a two-stage hurdle model. The selected approach used attitude data from the survey to predict intention to participate in a water conservation program. This portion of the model formed the hurdle. A secondary effort fit a Bayesian hierarchical model to the DCE results as a tool for evaluating the role of various conservation program attributes in motivating conservation program participation. The effort to develop and integrate the two models is described below.

5.4.1 COMPOSING LATENT VARIABLES

The components of attitude included in the integrated behavior model are latent variables that cannot be measured directly through survey questionnaires. For example, an individual's awareness of a specific issue may be difficult to quantify in great detail, even if it can be explored qualitatively through open ended questions or semi-quantitatively through questions related to the concept or topic at hand. Despite this fundamental challenge, latent variables are used widely in the social sciences [35, 36, 37]. Numerous constructs exist for assigning values to latent variables and assessing their relative affects [38, 39]. In this analysis, latent variables for *Awareness*, *Responsibility*, *Social Norms*, *Personal Norms*, and *Perceived Behavioral Control* were composed by averaging Likert values (on a 1-5 scale) for each respondent across the relevant grouped survey questions. The averaged scores were then translated back into categorical variables by binning average values onto a five point scale.

The latent variable *Intention* could not be effectually evaluated in the same manner as the other latent measures of attitude. Instead, *Intention* was assessed as a binary variable (High/Low) where survey respondents who elected the status quo option for every choice set included in the DCE were assessed to *Intention* = *High* (i.e. a general willingness to participate in water conservation). The universal election of the status quo option was a distinctive behavior exhibited by ~ 45% of DCE participants and was assessed as *Intention* = *Low*. I assume that the persistent adoption of the status quo option indicated an aversion to water conservation rather than a specific unfavorable reaction to each choice set included in the DCE.

5.4.2 VALIDATING THE BEHAVIOR MODEL

A water user's willingness to participate in water conservation in response to a unique collection of attitudes and demographic characteristics was evaluated through application of a Bayesian Belief Network (BBN). BBNs are acyclic graphs that define probabilistic relationships between pairs of variables. The links between variable pairs are structured as conditional probability tables that define conditional dependencies between the categorical levels of connected variables [40]. The probability of a child node taking on a specific state is a function of the state(s) of its parent node(s) (Equation 5.1).

$$P(X_i = x_i \mid U_1 = u_1, U_2 = u_2, \ldots, U_k = u_k) \tag{5.1}$$

Where:

- x_i is the i^{th} state of variable X,
- $U_1, U_2, \ldots, U_k$ are parent variables to variable X, and
- $u_{1a}, u_{1b}, \ldots, u_{kc}$ are the states of the parent variables.

BBNs are used with some regularity to develop expert systems in the field of natural resource management [41, 42]. A principal advantage of BBNs is that they can be developed using a mix of quantitative data, social survey results, and expert judgement. They are also readily adaptable to new information as it comes available and, critically for my dataset, can be fit to incomplete data. The use of a BBN to confirm the validity of the conceptual behavior model structure was preferred over more traditional Structural Equation Modeling (SEM) approaches due to a relatively high number of incomplete survey responses. In order to make use of the full, incomplete dataset, use of an SEM would have required imputation of missing values. Avoiding the uncertainty associated with the imputation step would have required the removal of a large number of survey responses. The BBN, alternatively, was able to construct conditional probability tables in the presence of missing values, without the need for imputation.

The BBN fit was constructed and fit to the survey data using the *bnlearn* library in R [43]. The core structure of the BBN was not learned from the data but fixed via a white list to reflect the hypothesis about the nature of belief systems that motivate agricultural water users in the UCRB to participate in water conservation programs (Figure 5.4). The unidirectional linkages between the latent variables in the BBN followed the general structure of linkages present in the integrated behavior model. For example, the *Awareness* latent variable was fixed as a parent to the *Responsibility* latent variable. In this way, the network structure was used to determine the joint probabilities between *Responsibility* and *Awareness*.

Relationships between other latent variables followed suit. The relationship between the latent variables and other demographic information present in the survey was learned from the data. Sociodemographic and farm variables were be included in the BBN as antecedent predictors of the latent variables. The final network was fit using a Bayesian posterior estimator with a uniform prior. Model performance was assessed using k-fold cross validation (k = 10).

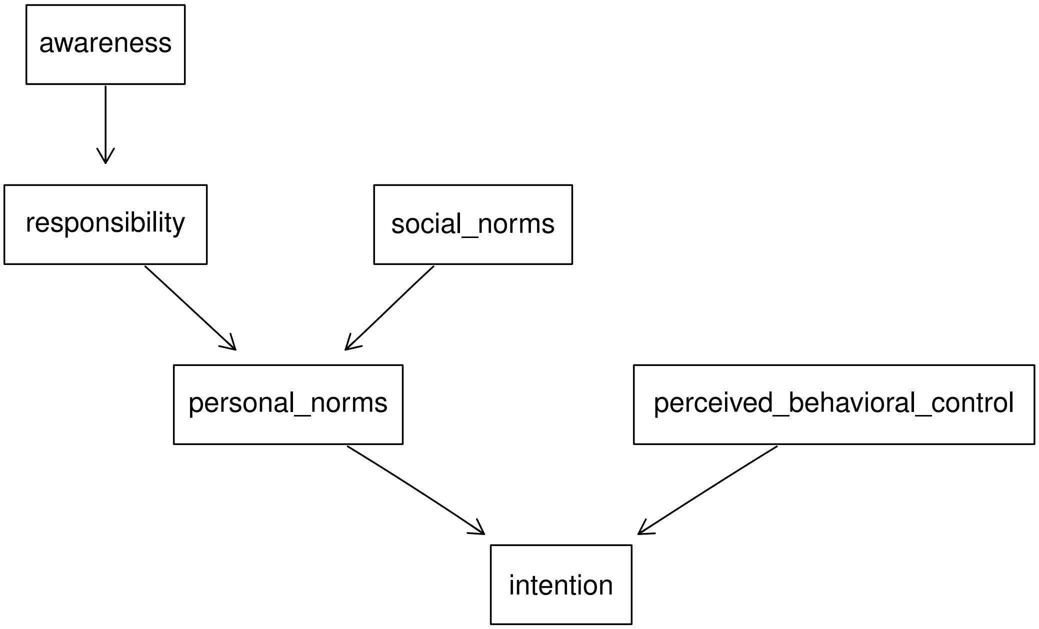

FIGURE 5.4. Directed acyclic graph structure used to train the Bayesian Belief Network model. Boxes indicate individual nodes and arrows indicate the linkages between nodes formed by conditional probability tables.

5.4.3 MODELING CHOICE PREFERENCES

The BBN was constructed to help understand the influence of attitudes on the intention to participate in a water conservation program. Ultimately, the goal was to link information provided by the BBN with a choice model that assessed stated preferences for specific water conservation policy or program attributes. Conceptually, I sought a model that could evaluate the probability of respondent j opting into a conservation program defined by the attribute set of alternative i (Equation 5.2).

$$P(\text{Opt-In}_{ij}) = P(\text{Intention}_j = \text{True}) \times P(\text{Choice}_i \mid \text{Intention}_j = \text{True}) \tag{5.2}$$

Where:

- $P(\text{Intention}_j = \text{High})$ is the hurdle that assesses the probability that respondent *j* belongs to the group with high intention, and
- $P(\text{Choice}_i \mid \text{Intention}_j = \text{High})$ is the choice model that assesses probability of selecting alternative *i*, given that respondent *j* belongs to the high intention group.

A sequential regression model was selected for this task. The first stage (the "Intention Stage") assessed the likelihood of a respondent belonging to the *Intention* = *High* class. The first stage in the model functioned as a conceptual hurdle, predicting *Intention* as a function of latent attitude variables. I used the coded the variable *Intention* to differentiate respondents who selected the status quo option for each choice (*Intention* = *Low*) from those who selected a conservation alternative at least once (*Intention* = *High*). This was the same perspective on the data applied in the BBN model.

The second stage of the sequential regression model (the "Choice Stage") evaluated the likelihood of selecting a conservation program, given a set of attribute levels Table 6.1. The Choice Stage was structured as a hierarchical model that included both main effects and random effects for individual respondents. A hierarchical structure was well suited to DCE data, where choices were nested within choice sets, which were, in turn, nested under individual respondents. In this way, heterogeneity in respondent-level regression slopes was directly incorporated into model predictions. The likelihood of respondent *j* selecting a conservation program represented by alternative *i* was modeled as a sequential Bernoulli process (Equation 5.3).

Part 1: The Intention Stage

$$\text{Intention}_j \sim \text{Bernoulli}(\theta_j)$$

$$\text{logit}(\theta_j) = \gamma_0 + \gamma_1 \cdot \text{PBC}_j + \gamma_2 \cdot \text{PN}_j$$

Part 2: The Choice Stage

$$\text{OptIn}_{ij} \sim \text{Bernoulli}(p_{ij})$$

$$\text{logit}(p_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \underbrace{\begin{array}{l} \beta_0 \\ + \beta_1 \cdot \text{Intention}_j \\ + \beta_2 \cdot \text{ConservationPractice}_{ij} \\ + \beta_3 \cdot \text{EastSlopeMatch}_{ij} \\ + \beta_4 \cdot \text{WaterShepherding}_{ij} \\ + f(\text{CompensationRate}_{ij}, \text{CommittedFraction}_{ij}) \end{array}}_{\text{Fixed Effects}} + \underbrace{\begin{array}{l} u_{0,j} \\ + u_{1,j} \cdot \text{CompensationRate}_{ij} \\ + u_{2,j} \cdot \text{CommittedFraction}_{ij} \\ + u_{3,j} \cdot \text{ConservationPractice}_{ij} \\ + u_{4,j} \cdot \text{EastSlopeMatch}_{ij} \\ + u_{5,j} \cdot \text{WaterShepherding}_{ij} \end{array}}_{\text{Random Effects}} \tag{5.3}$$

Distribution of Random Effects

$$\begin{pmatrix} u_{0,j} \\ u_{1,j} \\ \vdots \\ u_{5,j} \end{pmatrix} \sim \text{MVNormal}(\mathbf{0}, \Sigma)$$

Where, for the Intention Stage:

- Intention_j is modeled as a binary outcome for respondent *j*,
- θ_j is the probability that respondent *j* clears the Intention “hurdle”, and
- $\gamma_{1,2}$ are respondent-specific regression coefficients.

Where, for the Choice Stage:

- Choice_{ij} is modeled as a binary outcome where p_{ij} is the probability that respondent *j* selects alternative i,

- μ_{ij} is the linear predictor for alternative i on the logit scale,
- α_j is a respondent-specific intercept,
- β_k are population-level regression coefficients,
- u_{kj} are respondent-specific regression coefficients representing a deviation from the population average, and
- $f(\cdot)$ is a Gaussian Process that models the shape of the relationship between the continuous variables.

Where, for the priors:

- $u_{0,j}, u_{1j}...u_{5j}$ are respondent-specific parameters drawn from a multivariate normal distribution.

I used the *brms* library in R to fit the model to the data. The two numerical predictors, *Compensation Rate* and *Conserved Fraction* were scaled using a z-score normalization prior to fitting the model. The model was assessed over 11,664 observations from the respondents who participated in the DCE. Model performance was assessed using k-fold cross validation (k = 10). Data from a single respondent was prohibited from spanning multiple folds.

5.4.4 DEMOGRAPHIC PROFILING

The fitted sequential model was used to create demographic profiles for groups of respondents that seemed to exhibit similar choice behaviors. The respondent-level random effect coefficients for all respondents defined by *Intention* = *High* were extracted from the Choice Stage. These random effects represented the departure from the population mean of each respondent's preference for the conservation program attributes included in the DCE. A Gaussian finite mixture model was applied to the random effects data using the *mclust* library in R. The optimal number of clusters for segmentation (n=5) was determined manually through examination of elbow and density plots. The sociodemographic and farm or ranch characteristics associated with the respondents in each cluster were statistically summarized. Qualitative descriptions of each cluster were developed based on the summarized data.

5.5 RESULTS AND DISCUSSION

The survey data contained responses from 573 respondents. Respondents represented agricultural water users in counties across Colorado's West Slope Region (Figure 5.5). Many respondents only provided responses to demographic and attitude related questions. 438 survey respondents participated in the DCE. Of these, only 254 selected a choice other than the status quo option at least one time. A cursory exploration of the demographic characteristics of the survey sample was performed. Where possible, demographic data characterizing survey participants was compared against similar data available from the 2022 U.S. Department of Agriculture Census [44]. This qualitative comparison generally confirmed the representativeness of the survey sample within the broader population of West Slope agricultural producers, despite some minor deviations.

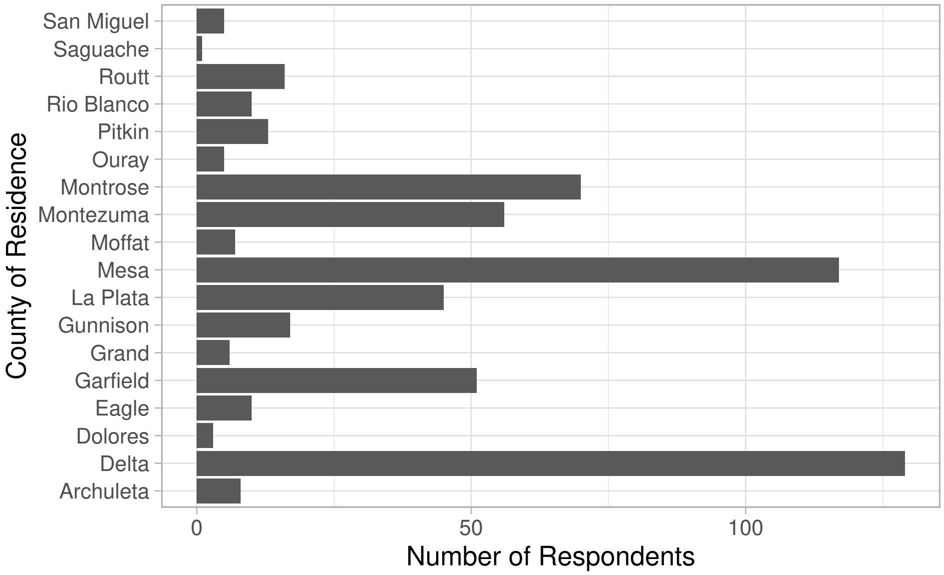

FIGURE 5.5. Survey respondent county of residence on Colorado's West Slope.

The majority of survey respondents were male, white, and over the age of 55. Most operated farms or ranches less than 40 hectares in size, relied on agricultural production for less than 25% of their income, and earned an adjusted gross income less then 150,000 USD per year. A majority of respondents reported water use for the purpose of irrigating grass pasture, a characteristic reflective of the dominant agricultural land use patterns on Colorado's West Slope.

5.5.1 ATTITUDES DRIVE INTENTION

Fitting the BBN to the data revealed several linkages between latent variables of attitude and sociodemographic and farm or ranch characteristics (Table 5.2). Political affiliation (*is_liberal*) was identified as a predictor of awareness. Age was identified as a predictor of responsibility. Farm or ranch size (*hectares*) was identified as a predictor of Perceived Behavioral Control. Model performance was assessed through *k*-fold cross validation. The validation test showed that the model could predict *Intention* on unobserved data with ~74% accuracy. The model incurred Type II errors in approximately 11% of cases, and Type I errors for approximately 15% of cases (Table 5.3, Figure 5.6).

TABLE 5.2. Demographic variables included in the BBN.

Variable	Description	Levels
is_liberal	Binary variable indicating Democratic party affiliation.	True, False
age	Categorical variable indicating the age of the respondent at the time of survey administration.	18-24, 25-34, 35-44, 45-54, 55-64, 65-74, 75-84, 85 or older
hectares	Categorical variable indicating farm or ranch size.	1-4, 4-20, 21-40, 41-120, 121-240, >240

TABLE 5.3. Cross validation results for the final BBN model structure.

Statistic	Value
Accuracy Estimate	0.7378
Accuracy 95% CI	(0.6936, 0.7787)
No Information Rate (NIR)	0.5963
p-value [Accuracy > NIR]	5.333e-10
Kappa	0.4457
Mcnemar's Test *p*-value	0.0904
Sensitivity	0.8171
Specificity	0.6207
Positive Predicted Value	0.7609
Negative Predicted Value	0.6968
Prevalence	0.5963
Detection Rate	0.4872
Detection Prevalence	0.6404

Statistic	Value
Balanced Accuracy	0.7189

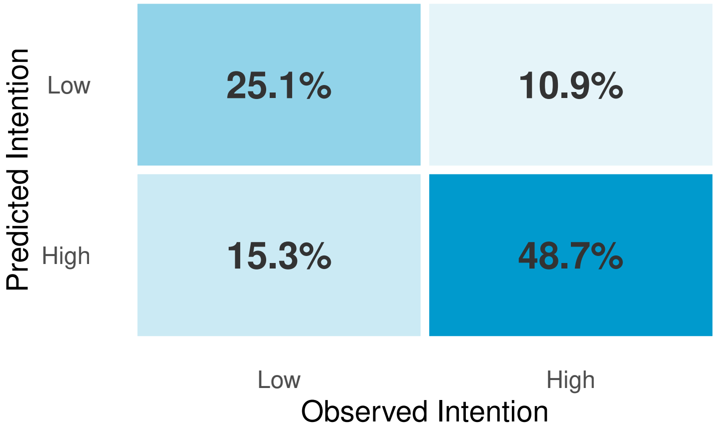

FIGURE 5.6. Confusion matrix of cross validation test results for the final BBN structure.

The validity of the BBN model structure was evaluated by testing the strength of the individual links. The conditional independence of each link was assessed by applying a χ^2 test to the conditional probability tables for adjoining nodes (Table 5.4). The vast majority of the links in the model exhibited strong conditional dependence (p-value < 0.01), between variables and their respective states. The relationship between farm or ranch size (*hectares*) and perceived behavioral control (*pbc*) and the separate relationship between the influence social networks (*social_norms*) and personal beliefs about conservation (*personal_norms*) were still significant (p-value < 0.03), but not as strong as other links in the network. The relationship between respondent age (*age*) and a sense of responsibility to act (*responsibility*) was the weakest link in the model (p-value < 0.1). Links between the latent variables and other demographic characteristics available in the survey data with p-values greater than 0.1 were excluded from the final BBN structure.

TABLE 5.4. Results from a χ^2 test of significance on the conditional probability tables present in the BBN.

From Node	To Node	p-value
hectares	pbc	0.02

From Node	To Node	p-value
is_liberal	awareness	< 0.01
awareness	responsibility	< 0.01
age	responsibility	0.09
responsibility	personal_norms	< 0.01
social_norms	personal_norms	0.03
personal_norms	intention	< 0.01
pbc	intention	< 0.01

The results of χ^2 test of independence provided confirmatory evidence for the conceptual behavior model in the data, in alignment with my first hypothesis. The BBN also provided a unique perspective on the ways that attitudes may be predicted by a minimal set of observable demographic characteristics and farm or ranch attributes.

Through the course of this analysis, I expected to identify a larger number of demographic or farm and ranch characteristics exerting some influence on the latent variables of attitude included in the integrated behavior model. The limited set of such relationships expressed in the final BBN may reflect the limitations of the survey dataset or may reflect a flaw in the methodology used to combine responses from multiple survey questions and characterize latent variables as ordered categorical values. Opportunity exists for future work to further explore alternative latent variable constructions and BBN structures.

5.5.2 INTENTION AND ATTRIBUTES DRIVE CHOICE

The sequential regression model was used to assess the probability of choosing to participate in a water conservation program, given a unique set of conservation program attributes. Visual inspection of the posterior prediction distributions showed the model was well calibrated to the data. Cross-validation on the fitted model indicated an out-of-sample prediction accuracy of 89.2% (Figure 5.7). The model exhibited robust performance predicting whether an individual would select to participate in a conservation program.

Computation of the Marginal R^2 (fixed effects only) and Conditional R^2 (fixed + random effects) confirmed the critical role individual preference plays in the water conservation decision-making process (Table 5.5). Attitudinal characteristics were only able to describe 21% of the variance in respondent intention to participate in conservation. The conservation program attributes (fixed effects) included in the Choice Stage were able to explain 43% of the variance in choice behavior. Individual preferences (random effects) accounted for an additional 20% of the observed choice variance.

TABLE 5.5. Marginal and conditional R^2 test results for each stage in the final hierarchical model.

Test	Intention Stage	Choice Stage
Marginal R^2	0.21	0.43
Conditional R^2	-	0.63

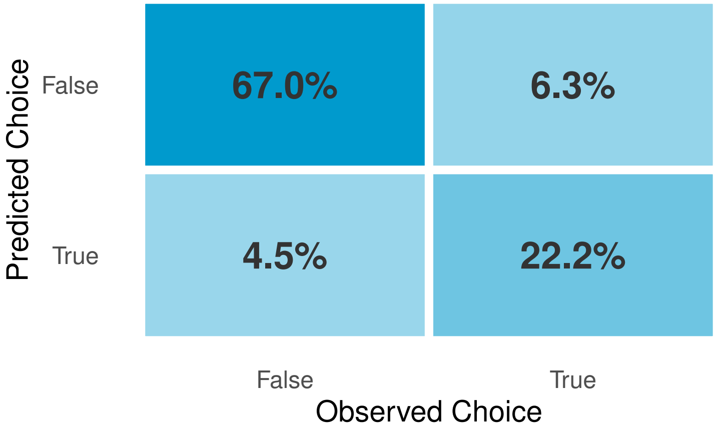

FIGURE 5.7. Confusion matrix of cross validation test results for the fitted choice model.

Intention exerts an enormous influence on choice behavior predicted by the Choice Stage. Clearing this conceptual hurdle makes a water user much more likely to identify preferences for water conservation. Evidence provided by both the BBN and the Intention Stage of the sequential regression model suggest that attitudes are strongly correlated with *Intention* (Table 5.6). The 95% credible interval (CI) for each coefficient were determined by sampling the the coefficient's posterior distribution and computing the 2.5$^{\text{th}}$ percentile and 97.5$^{\text{th}}$ percentile of the ordered values.

Respondents with *Personal Norms* indicative of modest or strong support for conservation increased the likelihood for *Intention* = *High*. A modest or strong sense of agency had a similar positive effect on *Intention*, but the effect size was much smaller. Conversely, a limited sense of agency was associated with a strong negative effect on *Intention*. The negative effect sizes for personal norms opposed to conservation were smaller than those with low scores for PBC.

TABLE 5.6. Intention Stage regression coefficient estimates and 95% credible intervals. Rhat for all coefficients < 1.01

Regression Coefficient	Estimate	Lower 95% CI	Upper 95% CI
Intercept	-0.16	-0.26	-0.06
PBC: Strong Sense of Agency	0.34	0.11	0.58
PBC: Modest Sense of Agency	0.51	0.38	0.64
PBC: Somewhat Limited Sense of Agency	-0.67	-0.77	-0.58
PBC: Very Limited Sense of Agency	-1.47	-1.61	-1.34
Personal Norms: Strong Support for Conservation	1.48	1.34	1.62
Personal Norms: Modest Support for Conservation	1.08	0.98	1.19
Personal Norms: Modest Aversion To Conservation	-0.08	-0.24	0.08
Personal Norms: Strong Aversion To Conservation	-0.57	-0.72	-0.43

An examination of the other main effects of the Choice Stage helped isolate and quantify the influence of different water conservation program attributes and their respective levels (Table 5.7). For the Choice Stage, I calculated a ~60% baseline probability of conservation program selection among respondents where *Intention* = *High*, holding all other attributes at their mean or reference level. The effect of each attribute level in the Choice Stage was compared against this baseline.

Inclusion of the *East Slope Match* exhibited the largest positive effect size, increasing the probability of selection by ~9% (log-odds = 0.41). The *East Slope Match* attribute likely appealed to West Slope water users' desire for equitable burden sharing with users of Colorado River transmountain diversion water. The effect size of *Water Shepherding* (log-odds = 0.19) was smaller than *East Slope Match*. Nonetheless, inclusion of that attribute increased the probability of selection by 4%. The *Water Shepherding* attribute likely appealed to individuals seeking more than just financial compensation from conservation. Ensuring that participation in water conservation contributes to meaningful risk reduction for water users in the UCRB requires careful administrative shepherding of conserved water downstream past other users. The positive influence of both *Water Shepherding* and *East Slope Match* suggest that conservation policies or programs that include those attributes will be much more effective at motivating participation than policies or programs that do not.

The effects of the various *Conservation Practices* were mixed. The *Full Season Limited Irrigation* level was represented by the baseline condition. The *Split Season Curtailment* level was statistically indistinguishable from *Full Season Limited Irrigation. Full Season Curtailment,* however, drove a statistically significant ~9% decrease in the probability of selection. This outcome may indicate risk aversion behavior where a commitment to a full season of irrigation withdrawal is perceived as a higher risk proposition than the other two *Conservation Practice* strategies.

TABLE 5.7. Choice Stage regression coefficient estimates and 95% credible intervals. Rhat for all coefficients < 1.01

Regression Coefficient	Estimate	Lower 95% CI	Upper 95% CI
Intercept	-9.24	-10.53	-8.10
Intention	9.64	8.56	10.86
Split Season Curtailment	-0.07	-0.27	0.13
Full Season Curtailment	-0.38	-0.61	-0.15
East Slope Match	0.41	0.25	0.56
Water Shepherding	0.19	0.07	0.34
Gaussian Process Marginal SD	0.42	0.23	0.81
Gaussian Process Length Scale	0.24	0.09	0.60
Intercept SD (Random Effect on Choice)	2.24	1.95	2.56

The effect of *Compensation Rate* and *Committed Area* were examined through evaluation of the shape and standard deviation (SD) terms on the Gaussian Process and through visualization of the conditional effects of the two variables. The SD term (log-odds = 0.42) indicated that the 2-dimensional surface created by the Gaussian Process exhibited modest changes in magnitude across its domain. The relatively short length scale (0.24) indicates that the magnitude variability indicated by the SD term manifests across relatively short distances in the scaled Gaussian Process space, which has a range of ~3.0 for both *Compensation Rate* and *Committed Area*. Visualization of the indifference map for *Compensation Rate* and *Committed Area* highlights the complexity of the process domain space (Figure 5.8). Perhaps unsurprisingly, the highest choice probabilities occur where *Compensation Rate* is high (>1200 USD) and *Committed Area* is low (<50%). Choice probabilities drop by ~20% for low *Compensation Rate* (<600 USD) and high *Committed Area* (>50%), holding all other attributes constant. The shape of the surface suggests that respondents may have relied on asymmetrical risk vs. reward calculations when identifying preferential conservation program attributes.

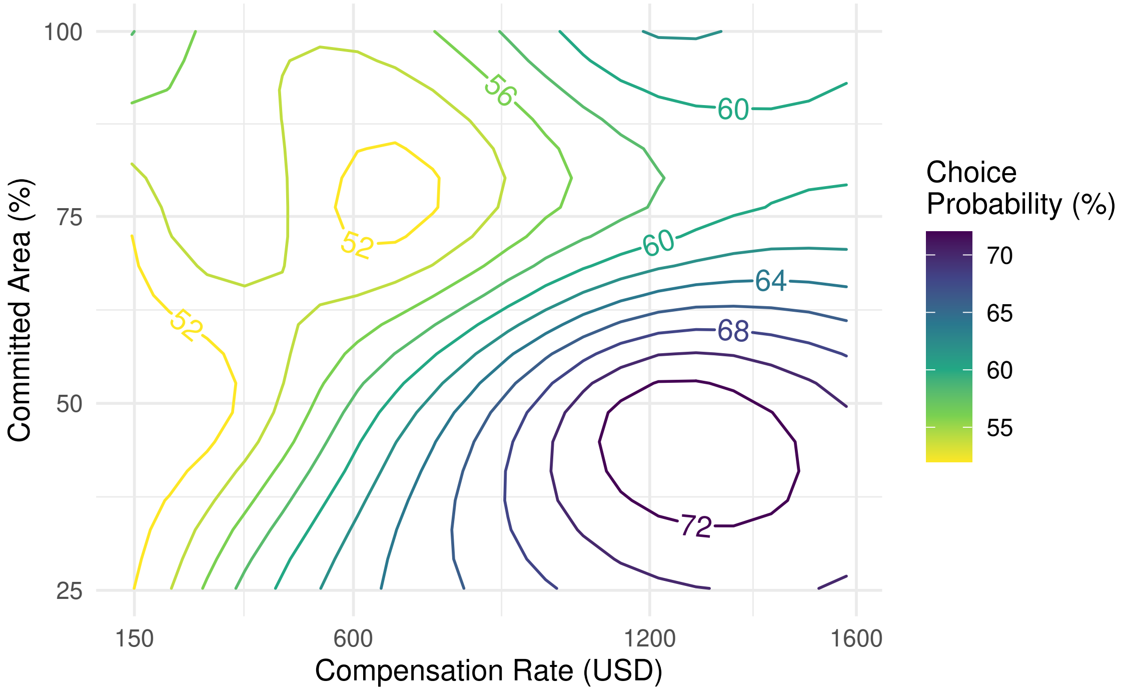

FIGURE 5.8. Choice probability indifference map for respondents with *Intention* = *High* reflecting the interaction of *Compensation Rate* and *Committed Area* in a Gaussian Process domain.

The large relative explanatory power of the random effects portion of the Choice Stage suggests that conservation program choice behavior is highly individualized. For example, some respondents may be more price sensitive than others. This price sensitivity may reflect different income levels or farm or ranch operational constraints. Other respondents may be more generally inclined toward conservation due to political leanings or the influence of social pressures. This finding confirms my expectation that individuals' attitudes and personal circumstances strongly influence choice and that understanding drivers of attitude may be key to understanding choice behavior. While the Choice Stage was able to systematically explain 63% of the variance in the data, 37% remained unexplained. This large unexplained variance reflects the inherently stochastic nature of water conservation program participation choice.

5.5.3 EVIDENCE OF ASYMMETRICAL PREFERENCES AND AVERSIONS

This effort sought to understand the decision pathways employed by agricultural water users when contemplating participation in water conservation programs. I expected that respondents employed elements of Prospect Theory when evaluating the utility of a set of conservation program attributes. Prospect Theory is built on observations of human behavior. The theory identifies difference in the way decision makers respond to realized or potential gains and losses. The concept of loss aversion posits that losses are felt more intensely than equivalent gains. The complimentary concept of risk aversion suggests that decision-makers weight potential gains differently, depending on the perceived risk for loss [45, 46]. The fundamental concepts of Prospect Theory are expressed as an s-shaped utility curve that contrasts the marginal utility curve theorized by Expected Utility Theory [47]. The shape of the curve conveys that, when faced with the prospect of two decisions that net the same relative gain, individuals will discount the utility of the option with the higher perceived risk.

Agricultural outcomes under the water conservation strategies contemplated in the DCE are largely unknown or highly uncertain to producers on Colorado's West Slope. This uncertaintly reflects the limited direct or indirect experience that most agricultural water users in the region have with conservation. The effect of risk aversion is expected in the water conservation decision making space where individual water users are likely to perceive greater risk for reduced income or crop yield as a result of participating in a water conservation program (e.g., due to a difference between the expected and realized CCU), even if that risk is essentially equivalent to the risk for yield reduction or reduced income wrought by drought or disease under normal operations. Prior implementation of DCEs with agricultural producers indicate similar policy trade-off behavior and risk sensitivity under drought conditions Conrad et al. [48].

I expected that the fear of loss under conservation would drive respondents to disproportionately select the status quo option. In this way, I expected risk aversion to drive the status quo bias regularly noted by researchers implementing DCEs in the natural resource conservation space Barreiro-Hurle et al. [49]. Among respondents who selected something other than the status quo alternative, I expected this utility valuation process to hinge, primarily, on *Compensation Rate*, an indicator of potential gain (or utility), and *Committed Area*, an indicator of potential risk.

Plotting choice probability as a function of *Compensation Rate* and assessing the relationship at different levels for *Committed Area* allowed us to explore the influence of risk aversion in stated preferences for water conservation program attributes (Figure 5.9). Each curve in the plotted space indicated diminishing marginal utility at the upper end of the *Compensation Rate* range. Respondents showed a general insensitivity to increasing *Compensation Rate* above ~1200 USD. This finding suggested that conservation programs may not produce meaningful improvements in participation rates by increasing compensation rates above ~1200 USD. *Committed Area* was assumed to represent a risk proposition, where committing a greater acreage to irrigation curtailment was likely associated with a greater perceived risk for undesirable outcomes. At fixed *Compensation Rate* levels greater than ~400 USD, choice probability generally decreased as *Committed Area* increased–respondents' stated preference for a given *Compensation Rate* decreased as perceived risk increased. At the highest levels of *Committed Area* (i.e. the highest perceived risk), respondents were relatively insensitive to price. The effect of reward was shown to be conditioned on the perceived level of risk, providing strong support for the influence of risk aversion in water conservation decision-making.

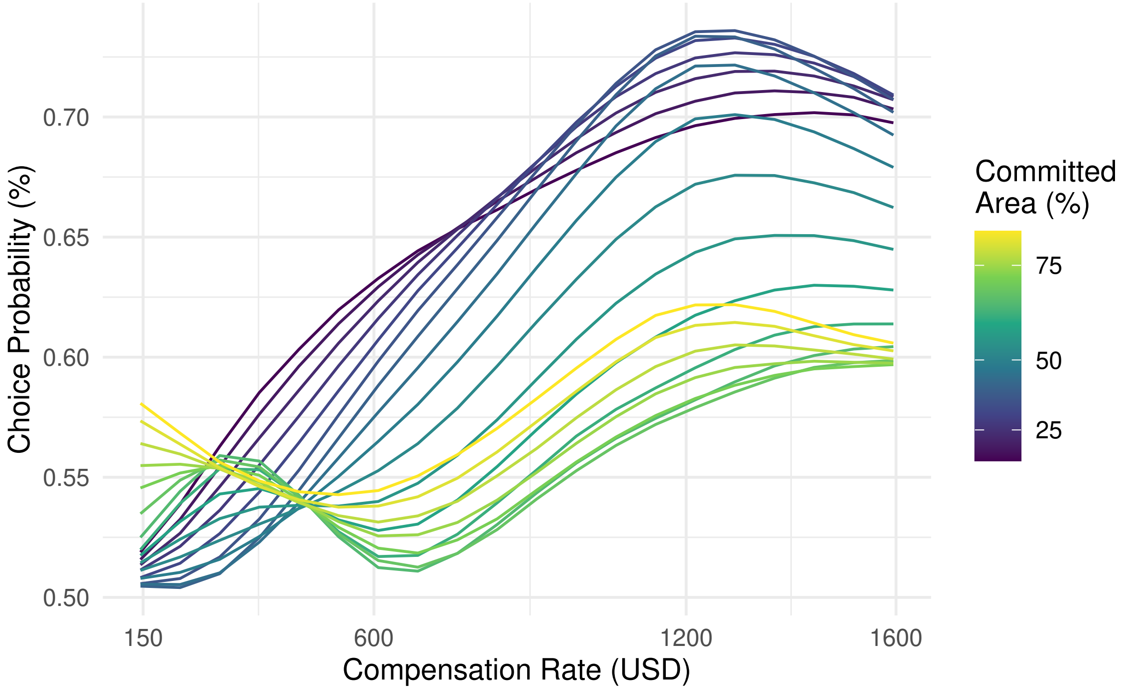

FIGURE 5.9. Extracts from the Gaussian Process domain for respondents with *Intention* = *High* illustrating the impact of *Compensation Rate* (i.e. expected gain) on choice probability for different levels of *Committed Acreage* (i.e. percieved risk).

Respondent-level indifference maps of *Compensation Rate* and *Committed Area*, like the one provided here for the modeled main effects (Figure 5.8), may provide important reference information for water managers and policymakers. The point on the map of maximum choice probability represents the optimal balance between expected reward and perceived risk. Indifference maps can be created for each respondent and the point of maximum choice probability can be identified. The position of the maxima for each respondent can be aggregated and visualized as joint probability distributions. These distributions can be used to subdivide or cluster respondents into behavioral archetypes. Characterization of the demographic characteristics of each archetype might then help identify water users who are more or less likely to participate in a conservation program characterized by a given *Compensation Rate* and *Committed Area*. While such an analysis was beyond the scope of this study, an alternative approach was used to subdivide respondents into behavioral groups.

5.5.4 Behavioral Archetypes

The attitudinal controls on intention to participate in water conservation revealed by the BBN and the stated preferences for various water conservation attributes revealed through analysis of the DCE contribute to a general understanding of the human behaviors most proximal to the decision to opt-in to a water conservation program. While useful in their own right, these analyses are of limited utility in a decision making or policy domain. This is particularly evident, given the seemingly outsized influence latent (unobserved) variables exert on the decision-making process. Making the insights derived here more relevant in a policy or management context required an exploration of the relationships between latent variables, stated preferences, and the sociodemographic groups that tend to behave in one way or another. Characterization of behavioral archetypes within the survey sample proceeded along two parallel pathways. The first focused on results from the BBN. The second focused on results from the choice modeling effort. Both are described in the sections below.

5.5.4.1 Archetypes of Intention

The structure of BBN and the learned set of linkages to a limited set of sociodemographic characteristics permitted exploration of relationships between those characteristics, latent measures of attitude, and intention to participate in water conservation. Water user age and political affiliation strongly predicted an awareness of the water supply and management challenges on the Colorado River (Figure 5.10) and a sense of responsibility to act in the face of those challenges (Figure 5.11). Respondents who indicated a preference for Democratic political candidates demonstrated a greater awareness of the water management and supply challenges facing the Colorado River system. This may have reflected differences in preferred media sources that break across political lines and the typical content available in those media sources. Outcomes for the *Responsibility* latent variable were strongly influenced by the level of *Awareness* where an elevated sense of awareness corresponded to an elevated sense of responsibility.

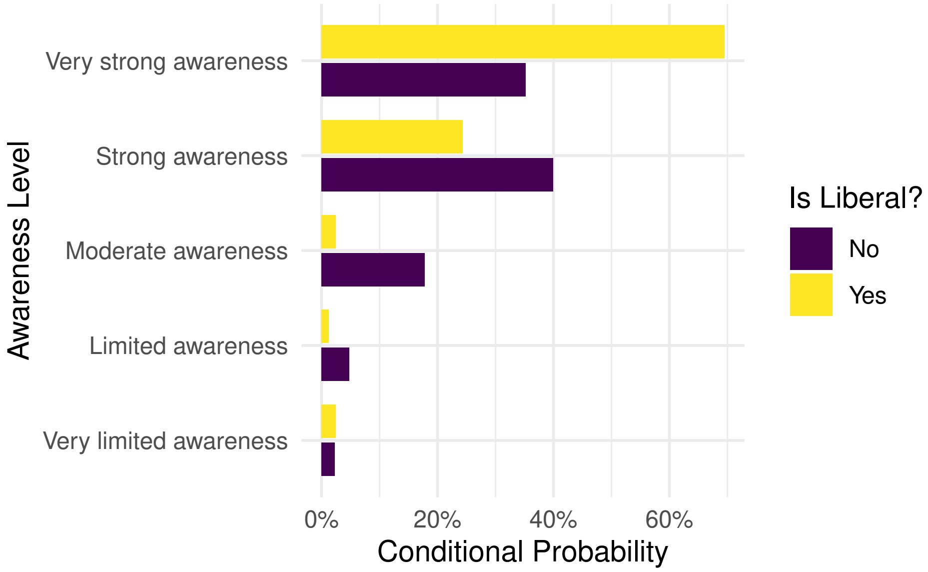

FIGURE 5.10. Conditional probability table outputs from the BBN displaying latent variable levels of awareness conditioned on political affilitation.

The relationship between irrigated acreage and the *PBC* latent variable was highly non-linear. The conditional probability table indicated a weak trend toward an increasing sense of agency for respondents with larger irrigated areas (Figure 5.12). This finding may reflect the enhanced degree of management flexibility imparted by large farm or ranch sizes where a change in irrigation management on some portion of the irrigated area is less consequential that it is for smaller operators.

Intention was conditioned on the latent variables for *PBC* and *Personal Norms* in the final BBN model. Review of the conditional probability tables that defined those relationships indicated some clear patterns (Table 5.8, Table 5.9, Figure 5.13). *Personal Norms* generally exerted a larger influence on *Intention* than *Personal Norms* above the *Neutral* level. Near the *Neutral* level for *Personal Norms*, *PBC* appeared to exert the dominant effect. Bi-modal behavior was evident at the highest levels of *PBC* where an individual characterized as having a strong sense of agency could either have a strong aversion toward or strong support of conservation. Individuals with a strong sense of agency may be more decisive in their views. Alternatively, the structure of the questions in the set responding to the *PBC* latent variable may have

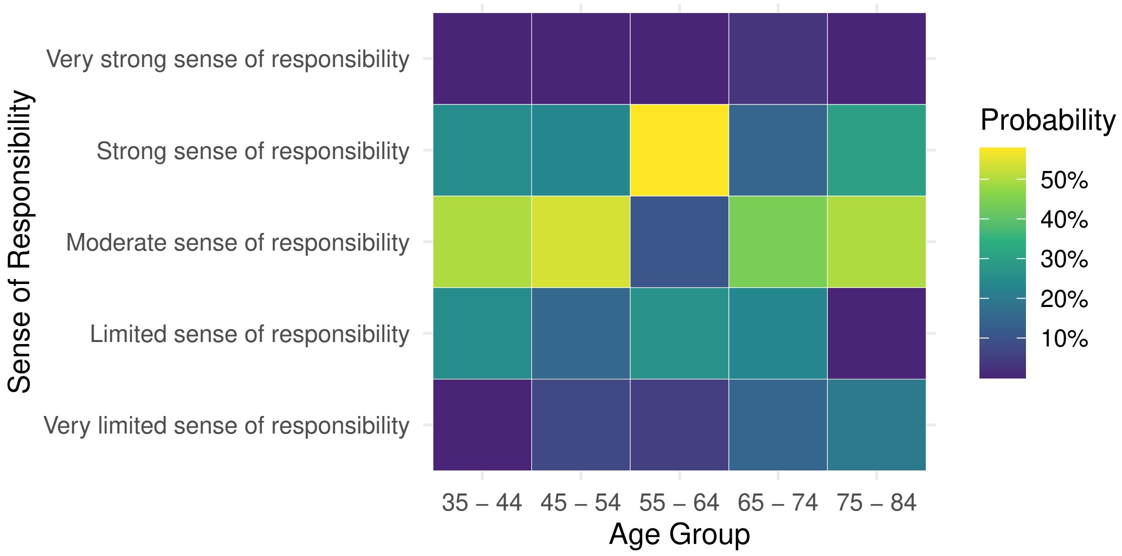

FIGURE 5.11. Conditional probability table outputs from the BBN displaying latent variable levels of responsibility conditioned on respondent age and a fixed level for the latent variable for awareness (i.e. “Moderate awareness”).

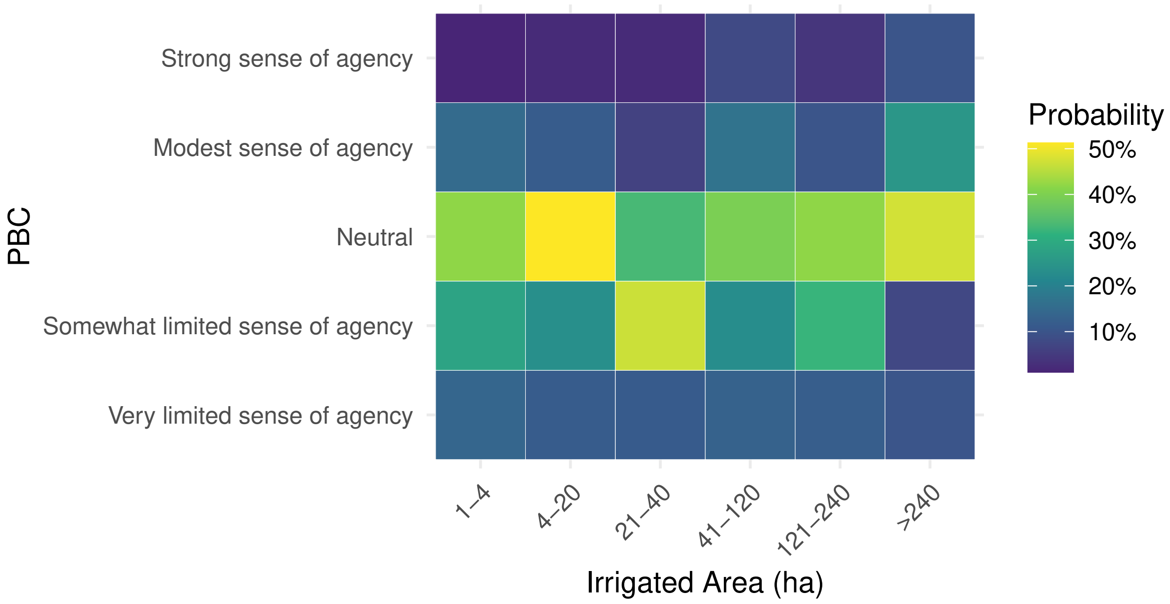

FIGURE 5.12. Conditional probability table outputs from the BBN displaying latent variable levels of preceived behavioral control conditioned on irrigated area.

been structured in a way that caused confusion and led respondents to answer on one side of the scale when they intended to answer on the opposite side of the scale.

TABLE 5.8. Attitude characteristics of respondents segmented by Intention.

	Respondent Segment	
Characteristic	**High** N = 257[1]	**Low** N = 173[1]
Personal Norms		
Strong aversion to conservation	17 (6.7%)	43 (25%)
Modest aversion to conservation	14 (5.5%)	18 (10%)
Neutral	40 (16%)	52 (30%)
Modest support for conservation	121 (47%)	47 (27%)
Strong support for conservation	63 (25%)	12 (7.0%)
Awareness		
Very limited awareness	8 (3.1%)	4 (2.3%)
Limited awareness	9 (3.5%)	9 (5.2%)
Moderate awareness	37 (14%)	36 (21%)
Strong awareness	91 (35%)	63 (36%)
Very strong awareness	112 (44%)	61 (35%)
Responsibility		
Very limited sense of responsibility	7 (2.7%)	14 (8.1%)
Limited sense of responsibility	34 (13%)	36 (21%)
Moderate sense of responsibility	71 (28%)	49 (28%)
Strong sense of responsibility	103 (40%)	59 (34%)
Very strong sense of responsibility	42 (16%)	15 (8.7%)
Social Norms		
Very limited responsivness to social network	11 (4.3%)	17 (9.9%)
Limited responsivness to social network	28 (11%)	33 (19%)
Moderate responsivness to social network	101 (40%)	72 (42%)
Strong responsivness to social network	110 (43%)	44 (26%)
Very strong responsivness to social network	4 (1.6%)	5 (2.9%)
PBC		
Very limited sense of agency	16 (6.3%)	44 (26%)
Somewhat limited sense of agency	58 (23%)	66 (38%)
Neutral	114 (45%)	42 (24%)
Modest sense of agency	52 (20%)	16 (9.3%)
Strong sense of agency	16 (6.3%)	4 (2.3%)

[1] n (%)

5.5.4.2 ARCHETYPES OF CHOICE

The random effect coefficients fit by the Choice Stage of the sequential regression model were used to identify dominant behavioral archetypes among the sub-population of respondents characterized by *Intention = High*. Respondents characterized by *Intention = Low* were not included in the characterization of behavioral archetypes for two primary reasons. First, those respondents did not participate in the DCE and, therefore, did not contribute to the random effects for the Choice Stage. Second, the BBN and the Intention Stage of the sequential regression model confirmed that attitudes were the primary driver of

TABLE 5.9. Sociodemographic characteristics of respondents segmented by Intention.

Characteristic	Respondent Segment	
	High N = 257[1]	**Low** N = 173[1]
Is Liberal	57 (24%)	16 (11%)
Age		
25 - 34	6 (2.5%)	3 (1.9%)
35 - 44	23 (9.5%)	8 (5.2%)
45 - 54	36 (15%)	20 (13%)
55 - 64	57 (24%)	29 (19%)
65 - 74	82 (34%)	55 (36%)
75 - 84	35 (14%)	35 (23%)
85 or older	3 (1.2%)	4 (2.6%)
Hectares		
1-4	36 (14%)	26 (15%)
4-20	87 (35%)	50 (29%)
21-40	37 (15%)	37 (22%)
41-120	46 (18%)	32 (19%)
121-240	23 (9.2%)	18 (10%)
>240	22 (8.8%)	9 (5.2%)

[1] n (%)

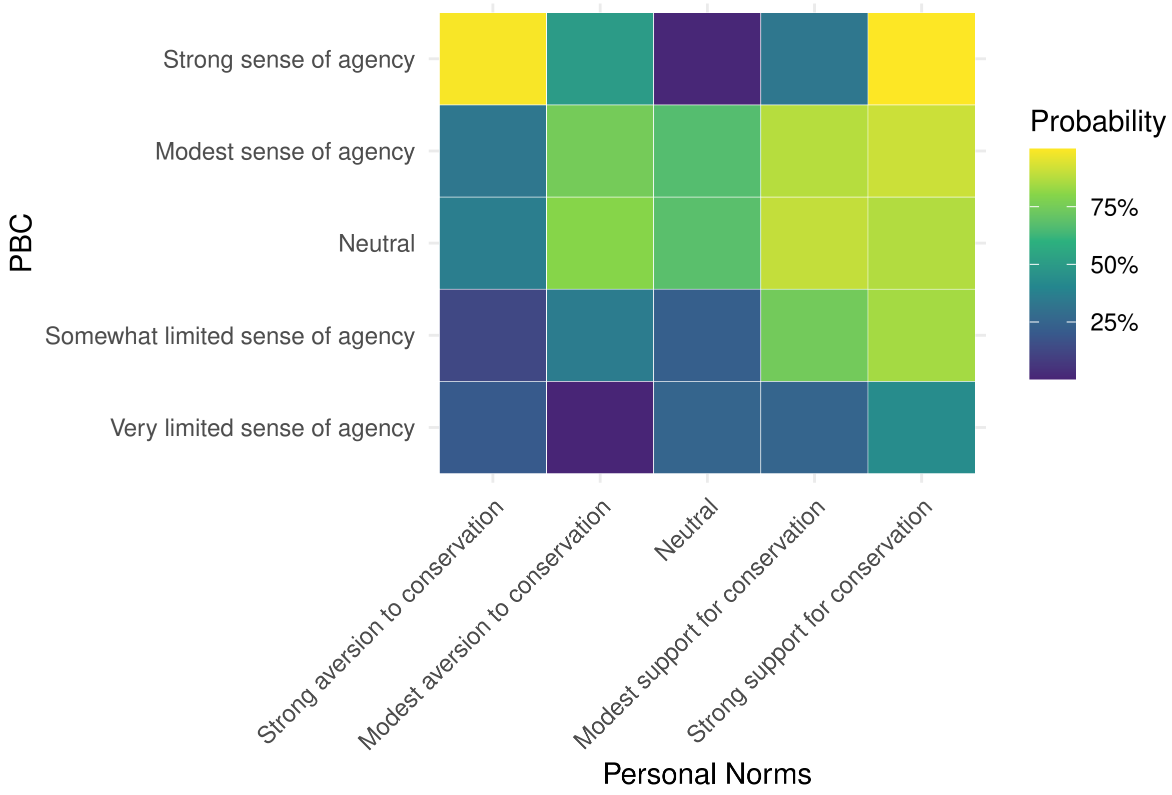

FIGURE 5.13. Conditional probability table outputs from the BBN displaying the probability of the latent variable for Intention being true. Probabilities are conditioned on PBC and Personal Norms.

Intention. The insights provided in the segmentation effort were, thus, limited to the sub-population of water users willing to consider participating in agricultural water conservation. Five distinct segments (Figure 5.14) were identified within the respondent-level random effects from the Choice Stage of the sequential regression model.

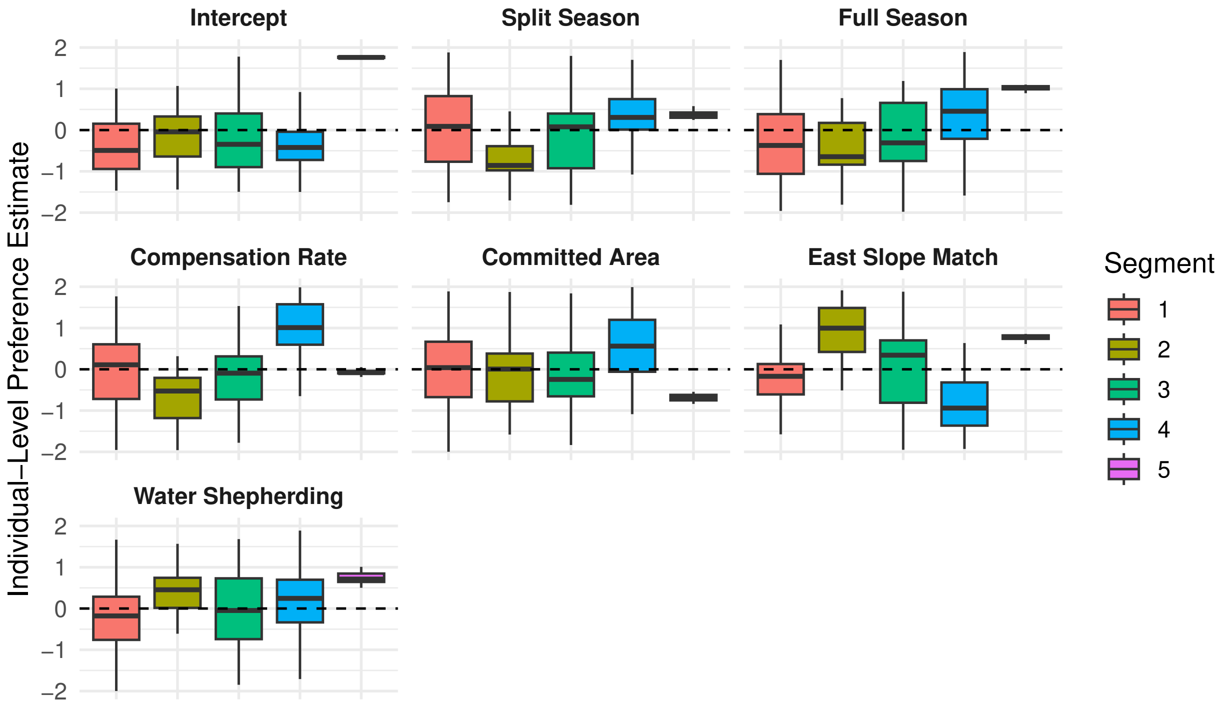

FIGURE 5.14. Boxplots of scaled choice model random effects for each of the respondent segments.

The first segment of water users (Segment 1) was characterized by a general aversion to conservation program participation. Respondents in this segment exhibited a low general willingness (negative intercept) to choose a conservation alternative over the status quo alternative. They were strongly opposed to *Full Season Curtailment* and demonstrated little sensitivity to financial incentives or other conservation program attributes (Figure 5.14), suggesting that an aversion to risk may have dominated this segment's decision making. This segment tended to be older than other segments (Table 5.10). Most operations represented in this class utilized irrigation water to support grass pasture and generated most farm income from livestock sales (Table 5.11). The class contained the highest proportion of farms and ranches in the 4-40 ha size category. A majority of respondents in this segment also received most of their water from a shared ditch. The profile of this group may indicate actively managed farms and ranches that contribute meaningfully to relatively low annual incomes. Economic vulnerabilities and the operational constraints imposed by year-round livestock operations likely contributed to this segment's apparent risk aversion. This was the largest segment, comprising 33% of all respondents.

The second segment (Segment 2) seemed highly motivated by attributes that reflected the equity and effectiveness of water conservation programs. Respondents in this segment exhibited a preference for inclusion of *East Slope Match* and *Water Shepherding* in the conservation program attributes and appeared less sensitive to *Compensation Rate* than other segments. This segment was comprised of the highest proportion of respondents who derived less than 10% of their income from farm and ranch operations. A majority of farm operations in this segment were of modest size (1-20 ha) and used water to irrigate grass pasture. These operations were not, generally, oriented toward livestock sales. The profile of this segment suggested a high proportion of hobby ranchers, retirees, or individuals who use their agricultural lands opportunistically but do not fully depend on them for regular income. This segment represented only 13% of the full set of respondents.

The third segment (Segment 3) exhibited characteristics that were typical of the average preferences expressed by the regression model main effects. This group was characterized by a modest aversion to *Full Season Curtailment* and a modest preference for an *East Slope Match*. This segment tended to be older than others. The largest fraction of respondents in the segment, although not a majority, affiliated with the Republican political party. This segment included the largest relative proportion of operations generating income primarily through livestock sales and the largest fraction of users getting less than 25% of their water from a shared ditch. The close alignment between this group's preferences and the model's main effects suggest this segment may best reflect the preferences of a typical water user in Colorado's West Slope region. 21% of respondents were represented by this segment.

TABLE 5.10. Demographic profiles of respondents segmented by random effects from the Choice Stage of the sequential regression model.

	Respondent Segment				
Characteristic	**1** N = 84[1]	**2** N = 34[1]	**3** N = 53[1]	**4** N = 48[1]	**5** N = 35[1]
Age					
25 - 34	0 (0%)	1 (3.0%)	2 (3.9%)	2 (4.5%)	1 (3.0%)
35 - 44	10 (12%)	4 (12%)	3 (5.9%)	4 (9.1%)	2 (6.1%)
45 - 54	8 (9.9%)	6 (18%)	6 (12%)	12 (27%)	4 (12%)
55 - 64	26 (32%)	5 (15%)	9 (18%)	10 (23%)	7 (21%)
65 - 74	23 (28%)	12 (36%)	26 (51%)	10 (23%)	11 (33%)
75 - 84	14 (17%)	4 (12%)	4 (7.8%)	5 (11%)	8 (24%)
85 or older	0 (0%)	1 (3.0%)	1 (2.0%)	1 (2.3%)	0 (0%)
Farm Income					
< 10%	36 (43%)	23 (70%)	22 (42%)	12 (26%)	16 (46%)
10-25%	22 (26%)	3 (9.1%)	12 (23%)	14 (30%)	10 (29%)
25-50%	9 (11%)	3 (9.1%)	6 (12%)	5 (11%)	5 (14%)
50-75%	4 (4.8%)	0 (0%)	2 (3.8%)	7 (15%)	4 (11%)
> 75%	13 (15%)	4 (12%)	10 (19%)	9 (19%)	0 (0%)
Total Income					
less than $75,000	27 (32%)	15 (50%)	21 (43%)	11 (23%)	10 (29%)
$75,001 - $150,000	35 (42%)	10 (33%)	19 (39%)	21 (45%)	14 (40%)
$150,001 - $250,000	11 (13%)	0 (0%)	5 (10%)	11 (23%)	5 (14%)
$250,001 - $500,000	8 (9.5%)	3 (10%)	2 (4.1%)	1 (2.1%)	5 (14%)
$500,001 - $900,000	2 (2.4%)	1 (3.3%)	1 (2.0%)	1 (2.1%)	1 (2.9%)
greater than $900,001	1 (1.2%)	1 (3.3%)	1 (2.0%)	2 (4.3%)	0 (0%)
Party Affilitation					
Democrat	20 (25%)	8 (28%)	10 (22%)	9 (20%)	10 (30%)
Republican	30 (38%)	8 (28%)	19 (41%)	20 (44%)	8 (24%)
Independent	22 (28%)	11 (38%)	12 (26%)	13 (29%)	14 (42%)
Other	7 (8.9%)	2 (6.9%)	5 (11%)	3 (6.7%)	1 (3.0%)
Ethnicity					
White	74 (91%)	31 (97%)	43 (88%)	41 (89%)	33 (100%)
Hispanic/Latino	1 (1.2%)	0 (0%)	0 (0%)	3 (6.5%)	0 (0%)
Other	6 (7.4%)	1 (3.1%)	5 (10%)	1 (2.2%)	0 (0%)
Native Hawaiian or Pacific Islander	0 (0%)	0 (0%)	0 (0%)	1 (2.2%)	0 (0%)
American Indian	0 (0%)	0 (0%)	1 (2.0%)	0 (0%)	0 (0%)

[1] n (%)

TABLE 5.11. Farm and ranch characteristics of respondents segmented by random effects from the Choice Stage of the sequential regression model.

	Respondent Segment				
Characteristic	**1** N = 84[1]	**2** N = 34[1]	**3** N = 53[1]	**4** N = 48[1]	**5** N = 35[1]
Shared Ditch					
< 25%	10 (12%)	3 (9.1%)	11 (21%)	4 (8.3%)	5 (14%)
25-50%	8 (9.5%)	1 (3.0%)	3 (5.7%)	8 (17%)	1 (2.9%)
51-75%	3 (3.6%)	0 (0%)	0 (0%)	4 (8.3%)	2 (5.7%)
> 75%	63 (75%)	29 (88%)	39 (74%)	32 (67%)	27 (77%)
Crop Type					
Alfalfa	7 (8.3%)	0 (0%)	7 (13%)	3 (6.3%)	2 (5.7%)
Greenhouse Vegetables	1 (1.2%)	1 (2.9%)	0 (0%)	0 (0%)	0 (0%)
Hay/Grass Pasture	68 (81%)	30 (88%)	40 (75%)	39 (81%)	29 (83%)
Other	1 (1.2%)	0 (0%)	1 (1.9%)	0 (0%)	0 (0%)
Perennial Crops	4 (4.8%)	1 (2.9%)	3 (5.7%)	2 (4.2%)	2 (5.7%)
Row Crops	3 (3.6%)	2 (5.9%)	2 (3.8%)	4 (8.3%)	2 (5.7%)
Farm Revenue Source					
Agricultural Tourism	2 (2.4%)	3 (9.1%)	1 (1.9%)	1 (2.1%)	2 (5.7%)
Forage Sales	34 (41%)	18 (55%)	16 (30%)	22 (46%)	16 (46%)
Fruit Vegetable Sales	4 (4.9%)	4 (12%)	4 (7.5%)	3 (6.3%)	1 (2.9%)
Grain Sales	4 (4.9%)	0 (0%)	2 (3.8%)	4 (8.3%)	3 (8.6%)
Livestock Sales	29 (35%)	5 (15%)	21 (40%)	15 (31%)	9 (26%)
Other	8 (9.8%)	1 (3.0%)	5 (9.4%)	2 (4.2%)	3 (8.6%)
Poultry Sales	0 (0%)	1 (3.0%)	3 (5.7%)	1 (2.1%)	0 (0%)
Recreation/Outfitting	1 (1.2%)	1 (3.0%)	1 (1.9%)	0 (0%)	1 (2.9%)
Hectares					
1-4	8 (9.9%)	9 (27%)	8 (16%)	7 (15%)	4 (11%)
4-20	29 (36%)	13 (39%)	17 (33%)	12 (25%)	14 (40%)
21-40	18 (22%)	3 (9.1%)	8 (16%)	5 (10%)	3 (8.6%)
41-120	10 (12%)	6 (18%)	8 (16%)	13 (27%)	8 (23%)
121-240	9 (11%)	1 (3.0%)	5 (9.8%)	4 (8.3%)	4 (11%)
>240	7 (8.6%)	1 (3.0%)	5 (9.8%)	7 (15%)	2 (5.7%)

[1] n (%)

The fourth segment (Segment 4) exhibited a particularly high sensitivity to *Compensation Rate* and a relatively low adversity to risk. This group appeared most tolerant to the *Full Season Curtailment* alternative and to conservation programs that required large *Committed Area*. This group appeared somewhat opposed to the inclusion of an *East Slope Match* and insensitive to *Water Shepherding*. These behaviors suggest that profit maximization may have motivated this segment's decision making. This segment included a relatively large proportion of larger farms and ranches (>21 ha). Most were engaged in irrigation of grass pasture. 31% of operations were focused on livestock sales. The respondents comprising this segment tended to be younger than the other segments and contained a relatively large proportion of respondents that derived more than 50% their income from agricultural activities. Agricultural properties in this group skewed toward larger sizes. The profile of this segment suggests respondents are engaged in large profit-oriented commercial agricultural enterprises. This segment comprised 19% of respondents.

The fifth segment (Segment 5) exhibited distinct behaviors with relatively little variance. This group demonstrated the highest likelihood of selecting a conservation alternative. Respondents in this group seemed somewhat insensitive to *Compensation Rate* and instead appeared more focused on conservation effectiveness and equity, demonstrating a clear preference for *Full Season Curtailment*, *East Slope Match*, and *Water Shepherding*. Their aversion for high *Committed Area* may have reflected a preference for pragmatic, easy to implement water conservation programs with clear connection to a perceived goal. This group skewed toward higher income earners. It also contained the highest proportion of respondents over the age of 75 and the highest proportion of respondents that affiliated the Democratic or Independent political parties. Segment 5 made up 14% of respondents.

The majority of respondents were represented in Segments 1, 3, and 4. Water conservation policies or programs designed to appeal broadly across the population should appeal to these segments. Conversely, Segments 2 and 5 represented smaller niche groups of water users. Engaging these groups may necessitate targeted outreach tailored to their unique proclivities. For example, a program designed to maximize equity between East Slope and West Slope users of Colorado River Water may resonate with Segment 2. However, if the goal of a program is to generate maximum participation rates, it may be more beneficial to focus on minimizing perceptions of risk through offerings of flexible contract arrangements that don't necessitate full season irrigation curtailment on a majority of irrigated land.

5.6 DATA LIMITATIONS

The survey data used as the basis for the analyses performed here were assumed representative of the perspectives of water users in Colorado's West Slope region and, more broadly, in the UCRB. Surveys were only distributed to agricultural water users on Colorado's West Slope. Cursory checks of the collected survey data against similar agricultural survey data from U.S. Department of Agriculture provided confidence in the representativeness of the survey sample. However, survey participation was strictly voluntary and unsupervised and contained many elements that could not be effectively validated against other data sources. It is possible that some portions of responses did not reflect preferences or attitudes held by the majority of water users in the area of interest. Furthermore, the tendency among many respondents to leave portions of the survey blank or completely disregard the DCE may have biased my results. The self-selected sub-population that elected to participate in the DCE may have represented a set of preferences that was distinct among the broader set of survey respondents. Finally, the stated preferences measured by the DCE may diverge from revealed preferences among water users in real-world water conservation scenarios. Future work to collect stated and revealed preference data across the UCRB can supplement and, perhaps, help validate the results presented here.

5.7 ETHICS STATEMENT

The Colorado State University Institutional Review Board (FWA0000647) determined data collection activities associated with the project are exempt under 45CFR46.104(d). Participation in the study was strictly voluntary. All study participants were informed of the expected use of the data and were made aware that their deidentified responses would be combined with similar responses from others and made publicly available. All study participants provided consent to the collection and use of their responses in this manner. All personal identifier information, including names, addresses, and phone numbers, was removed from the data included here prior to its publication.

5.8 CONCLUSION

This effort sought to explore the role of attitudes in motivating water conservation decision-making among agricultural water users in the UCRB. Surveyed sociodemographic information and a DCE were used to validate a conceptual behavior model that integrated several major theories of behavior from the social sciences. My results illustrate the importance of attitudes in mediating decision making. I also demonstrate population-level preferences for various conservation program attributes and the importance of considering individual-level random effects on these preferences. These results are highly relevant to policymakers in the UCRB promoting agricultural water conservation as a tool for addressing water supply and management challenges in the Colorado River Basin.

Generating meaningful CCU volumes through implementation of conservation projects will require broad and sustained participation among diverse groups of agricultural water users. The most significant leverage point driving participation outcomes appears to be rooted in attitudes toward conservation. Attitudes toward conservation represent a conceptual hurdle that must be overcome before a water user is willing to engage in an evaluation of conservation program alternatives. A sense of responsibility to act and a strong sense of agency were deemed prerequisite to favorable behavior patterns towards water conservation alternatives. Among water users who express a willingness to participate in conservation, my results indicated clear preferences for some conservation program attributes over others. Notably, water users exhibited a distinctive pattern of risk aversion where risks associated with increasing areas of land committed to conservation diminished the perceived utility of compensation at any given rate. This tendency toward risk aversion suggests that policymakers and water managers must seek an optimal balance between 1) programs designed to motivate participation by lowering perceived risk and maximizing perceived equity, and 2) programs that maximize the CCU volumes by requiring long periods of sustained irrigation curtailment on large land areas.

Finally, I provide a set of behavior archetypes that can support policymakers as they endeavor to develop conservation programs that have broad appeal. These archetypes can also support the development of targeted outreach campaigns to a subpopulation of water users. While my findings are limited by the fact that they are derived from stated preferences and not revealed preferences, I believe they can support the design and testing of future water conservation pilot programs in the UCRB.

This research demonstrates that successfully engaging agricultural water users in conservation requires more than simply identifying the optimal price point for contracted water. Diverse individual attitudes and sociodemographic circumstances can play a significant role in decision-making. Understanding the nuances driving water user behaviors can help ensure that future water conservation programs and policies are effective, equitable, and scalable. Future work should endeavor to link the human-behavioral modeling presented here with models that predict water conservation outcomes given a set of environmental controls. Linking stated choice information with physically based water models has proven effective for informing policy design in other settings Conrad and Yates [28] and would likely provide the same benefit here.

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PART III

System Integration

CHAPTER 6

FORECASTING THE IMPACT OF AGRICULTURAL WATER CONSERVATION POLICIES

6.1 SUMMARY

Colorado is committed to pursuing water conservation as a strategy for addressing water supply and management challenges broadly across the state and, specifically, in the Colorado River Basin. However, the state lacks policy frameworks or established management programs for strategically implementing conservation projects over the long-term. Policymakers and water managers can benefit from enhanced understanding of the water conservation decisions that different groups of water users are likely to make when presented with different perceived risks, environmental circumstances, or policy attributes. Those same policymakers and water managers can benefit from a nuanced understanding of the ways that geography moderates or accentuates the ability of different water conservation practices to deliver reductions in consumptive water use.

I present a simulation modeling approach that can support the evaluation of different policies, water conservation practices, and environmental conditions on water conservation program effectiveness. My model integrates work products from a pair of recent research projects in a stochastic simulation framework that projects water user participation in conservation programs and field-specific consumptive water use reductions associated with participation. My simulations reveal emergent behaviors among social groups faced with different conservation policies and time-variant environmental conditions. This analysis helps evaluate and target water conservation programs for deployment in different geographies or among different user groups. Alternatively, my simulations can help tailor the characteristics of a single water conservation program or policy to respond broadly to the greatest number of water users. Simulation results can inform ongoing conversations about whether large-scale water conservation programs are achievable, worthy, and advisable strategies for securing Colorado's water future.

6.2 THE CHALLENGE

Colorado water users face ever mounting challenges. Growing populations and persistent drought place increasing demands on a system that is producing less water than in past decades. At the same time, the specter of a water management crisis in Lake Powell and Lake Mead is looming larger with each passing month. Recent research suggests that a future of dwindling Colorado River supplies [1, 2, 3, 4, 5, 6] and fiercer competition for what remains is likely [7, 8, 9].

The unfolding water supply and management situation in the greater Colorado River system highlights the need for continued development of innovative strategies to support diverse water needs. While many of the ongoing discussion about the challenges on the Colorado River—the joint operations of Lake Powell and Lake Mead, current use relative to allocations of water between the states in the Upper and Lower Colorado River Basin, and water delivery obligations specified in the Colorado Compact—deal in issues that feel far removed from the daily activities of residents in the State of Colorado, the fate of the Colorado River implicates all residents and constituencies.

Colorado's economies, on both sides of the Continental Divide, thrive on Colorado River water. The largest sector for use of Colorado River water in the state, by volume, is West Slope agriculture. Farms and ranches are ubiquitous features across western mountain valleys and desert shrub lands, where they remain a dominant economic force and a cherished heritage in many communities. Diversions of Colorado River water to the Front Range through an extensive network of transmountain diversions constitute the state's second largest use of Colorado River water. Water that flows under the mountains, east of the Continental Divide, supports growing populations and vast commercial and industrial activities in metropolitan areas. Thus, the risk for changes in the supply and allocation of Colorado River water carry far reaching implications. This risk exposure continues to motivate robust policy debates on both sides of the Continental Divide and at all levels of government.

Goals and objectives laid out in various state level and regional planning documents reflect the water supply and management challenges facing the State of Colorado. Among them, compensated water conservation programs and policies are gaining traction as a viable means for reducing risks among water users and equitably distributing a shrinking supply [10]. In 2022, the Upper Colorado River Commission identified Demand Management (i.e. temporary, voluntary, and compensated water conservation) as one of five strategies the UCRB would employ to address water supply challenges in the Colorado River Basin [11]. In 2023, the Colorado Water Plan (CWP) identified agricultural water conservation as a critical tool for stretching water supplies and meeting future needs. The Upper Basin Demand Management Economic Study in Western Colorado [12] evaluated the potential impacts of "Moderate" and "Aggressive" water conservation programs—hypothetical programs differentiated by presumed levels of basin-wide annual consumptive water reductions. In a related effort, the Colorado River Risk Study [2] characterized the impact of different consumptive water use reduction targets on the risk of passing certain storage and water delivery thresholds at Lake Powell.

While calls for water conservation are increasing—accompanied by assessments of potential secondary impacts—no cohesive plan exists for strategic and sustained implementation of conservation projects at scale. A limited number of pilot studies endeavored to implement and test outcomes of water conservation efforts among agricultural producers in the UCRB. The System Conservation Pilot Program (SCPP) piloted water conservation projects from 2015-2018 and again in 2023-2024. Modest participation rates among agricultural producers [13, 14, 15] and annual conserved volumes that both paled relative to average annual uses of Colorado River water in the Upper Basin [16] and were lower than expected suggest that critical open questions remain regarding 1) the attitudes and risk assessment frameworks that drive decision-making among diverse groups of water users, and 2) the the environmental factors that moderate conservation-induced conserved consumptive use (CCU) of water across diverse geographies.

6.3 SOURCES OF UNCERTAINTY IN CONSERVATION OUTCOMES

Significant uncertainty exists in the "scaling-up" of water conservation pilot projects to the level where conservation outcomes can meaningfully contribute to the fulfillment of long-term water supply and management goals in the State of Colorado and more broadly across the UCRB. My research into the interactions between attitudes and conservation policy characteristics suggests that high levels of sustained annual participation in water conservation programs are not guaranteed (see Chapter 5). Separate work investigating environmental controls on water savings at the field scale indicates that conservation practices yield highly variable CCU across different elevations, soil types and cropping patterns (see Chapter 3). Incorporation of these insights into policy and decision making frameworks can support efforts to develop water conservation programs and policies that produce meaningful and sustained reductions in consumptive use at the basin scale.

6.3.1 NOT ALL FIELDS ARE CREATED EQUAL

Understanding the social conditions, policy characteristics and environmental circumstances that conspire to enhance or constrain conservation effectiveness is critical for those tasked with planning for Colorado's water use and management in the years to come. Analysis of remotely sensed evapotranspiration data from fields that participated in water conservation programs in recent years provides a unique view into the uncertain outcomes associated with various conservation practices on Colorado's West

Slope (Figure 6.1). Full season irrigation curtailment (Full Season) generated the largest average seasonal water savings, but differences in environmental characteristics between fields drove wide variability in outcomes. Irrigation curtailment during the early and mid-summer, followed by resumption of irrigation in the fall (Split Season Early), yielded slightly less savings than full season irrigation curtailment, on average. This strategy was characterized by a similar degree of uncertainty in outcomes due to between-field environmental differences. Curtailing irrigation for the second half of the irrigation season (Split Season Late) produced the smallest CCU volumes. The variance in outcomes was relatively low for this strategy. Modeling work presented in Chapter 3 assessed the relationships between conservation practices and environmental factors and identified significant effects from crop types, soil characteristics, seasonal weather patterns, irrigation strategies, and elevation.

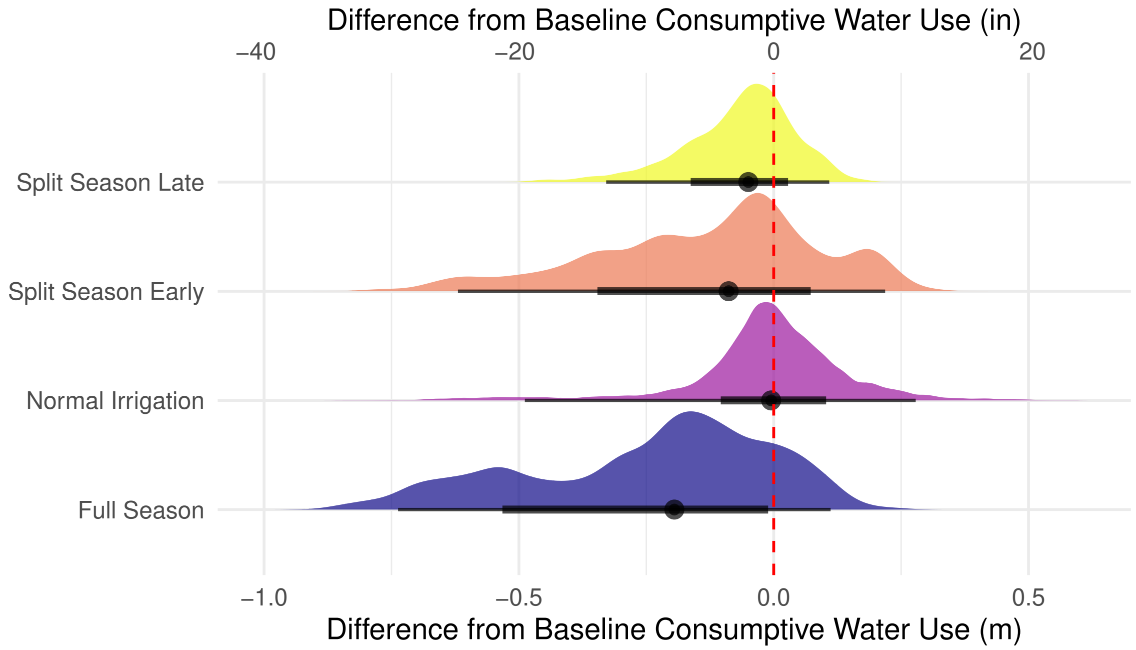

FIGURE 6.1. Plot-scale changes in consumptive water use associated with various water conservation practices, compared to patterns of baseline consumptive water use during non-conservation years.

The presence of grass pasture generally diminished CCU outcomes. The perennial nature of grass pasture (and many alfalfa fields) means that some water consumption occurs in years when conservation is enacted. Model results suggested that full season irrigation curtailment on grass-pasture was the most promising strategy for consistently reducing consumptive water use. CCU outcomes were greatly diminished under other conservation strategies. An evaluation of elevation effects demonstrated that conservation at higher elevations regularly generated less CCU than similar conservation measures implemented at lower elevations. High-elevation grass pasture is common across Colorado's West Slope. Future water conservation programs will inevitably involve participation by farmers and ranchers who own or manage grass pasture in these elevation bands. Larger areas of high-elevation irrigated grass pasture will be required to generate the same CCU outcomes as conservation projects implemented on other crop types at lower elevations. Achieving equivalent conservation outcomes in a high elevation (2100 m, 6900 ft) grass pasture may require up to five times the land area as a low elevation (1600 m, 5250 ft) field cultivating corn or other annual crops, all other conditions being equal. The environmental limitations on CCU generated on mid- to high-elevation grass pasture and the predominance of that agricultural pattern on Colorado's West Slope significantly constrains policy options for generating significant volumes of CCU in any given year. Instead, sustained implementation of conservation programs over many years is likely necessary to accumulate limited annual water savings to levels commensurate with the volumetric target envisioned in the 2019 Drought Contingency Plan *Agreement Concerning Colorado River Drought Contingency Management and Operations.* [17] or the "Aggressive" target outlined in the Colorado River Risk Study Consulting et al. [2].

6.3.2 CLEAR PREFERENCES FOR POLICY ATTRIBUTES

Generating meaningful CCU volumes through implementation of conservation projects requires more than understanding the environmental factors that moderate project outcomes. Successful, basin-scale conservation programs must also inspire broad and sustained participation among diverse groups of agricultural water users. Analysis of quantitative social survey results reflecting attitudes and preferences among West Slope agricultural water users in Chapter 5 provided an opportunity to identify the policy attributes most likely to boost participation. Modeling work assessed stated preferences for a suite of plausible conservation policy attributes (Table 6.1).

TABLE 6.1. Assessed water conservation program attributes and levels

Attribute (Levels)	**Description**
Conservation Action (Full-Season Limited Irrigation, Split-Season Curtailment, Full-Season Curtailment)	The irrigation reduction activity that will be contracted and enacted for a single irrigation season. The included activities reflect common strategies implemented across Colorado's West Slope.
Compensation Rate ($150, $300, $600, $1200, $1600)	Payment for each acre (1 ac = 0.40 ha) of land placed under water conservation. The included compensation rates bracketed the range of payments for leased water observed in recent years in Colorado. Note the use of imperial units for land area. All compensation values are represented in USD.
Conserved Acreage (25%, 50%, 75%, 100%)	The portion of typically irrigated acreage allocated to water conservation program activities. The included irrigated land fractions accommodate farmer and rancher concerns about risks involved with committing entire operations to conservation in any given year.
East Slope Match (No, Yes)	Whether any conserved consumptive water use would be matched in volume by curtailment of transmountain water diversions to Colorado's Front Range. This attribute reflects sentiments expressed among West Slope Colorado water users for water conservation burden-sharing between rural communities west of the Continental Divide with urban communities on Colorado's Front Range.
Water Shepherding/ Protection (No, Yes)	Whether any conserved consumptive use water will be shepherded downstream past all other water users and controlled by the Upper Basin states to reduce risks of a Compact Call on the Colorado River. This attribute was included to differentiate programs that generate "system water" that may be used by junior users from those that actively administer conserved consumptive use volumes as a basin-wide risk reduction strategy.

Model results demonstrated that the effect of monetary compensation (*Compensation Rate*) was dependent on the perceived level of risk to the water user incurred by conservation. This finding assumed that the area of irrigated land committed to conservation (*Committed Area*) served as a proxy for perceived risk exposure. This finding suggests that risk aversion significantly influences water conservation decision-making among West Slope agricultural producers. The probability of hypothetical program participation was maximized at a *Compensation Rate* near $1200 and a *Committed Area* near 25%. The tendency towards risk aversion was also reflected in the finding that full season irrigation curtailment was less preferable than other conservation practices. Full season curtailment is likely perceived as a higher risk option where other strategies allow a greater degree of hedging against uncertain conservation outcomes.

Inclusion of an *East Slope Match* produced a large positive effect on hypothetical program participation. The *East Slope Match* attribute likely appealed to West Slope water users' desire for equitable burden sharing with users of Colorado River water in Front Range communities. The positive effect of *Water Shepherding* was smaller than *East Slope Match* but did provide a modest increase the probability of participation. The *Water Shepherding* attribute likely appealed to individuals seeking more than just financial compensation from conservation. These users indicated a preference for programs that ensured that conserved water was not just used by downstream junior users. The positive influence of both *Water Shepherding* and *East Slope Match* suggest that conservation policies or programs that include those attributes will be much more effective at motivating participation than policies or programs that do not.

6.3.3 ATTITUDES OUTWEIGH POLICY DETAILS

The most significant leverage point driving participation outcomes appears to be rooted in attitudes toward conservation. Strong relationships were identified between a water user's individual proclivity toward conservation participation, a sense of responsibility to act in the face of basin-scale water management challenges, and a perceived sense of agency. Collectively, these attitudes toward conservation represent a conceptual hurdle that must be overcome before a water user is willing to engage in a conservation program. Approximately 42% of surveyed water users demonstrated attitudes indicative of low participation likelihoods. The relatively high fraction of water users with low participation likelihoods created a dwarfing effect on the calculated effects of conservation program attributes (Figure 6.2). The most effective strategies for increasing participation rates, therefore, may be public outreach and messaging campaigns or programs aimed at altering attitudes toward conservation. A limited set of observable demographic characteristics were found to be related to attitudes, providing a means for anticipating water users' participation likelihoods in different settings.

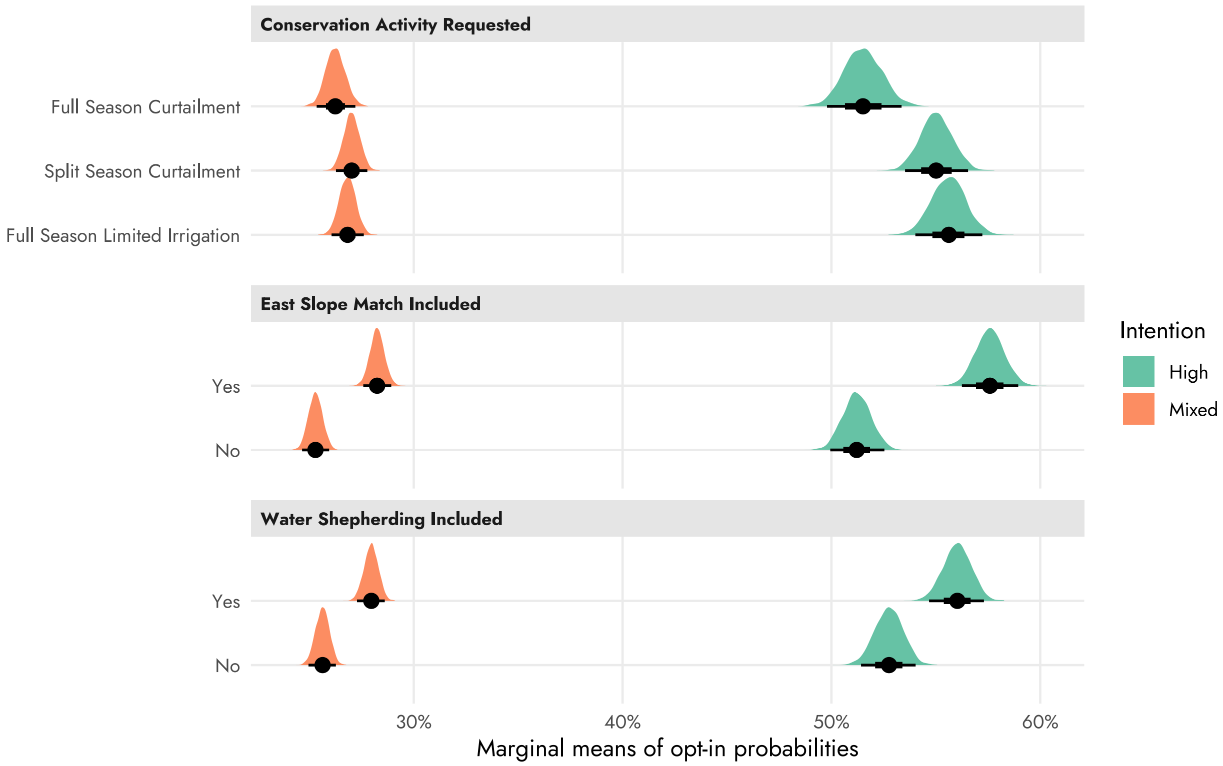

FIGURE 6.2. Marginal means of participation (i.e. opt-in) probabilities predicted for survey respondents on the West Slope. The differences between levels (e.g., Yes/No) within a given attribute (e.g. East Slope Match Included) indicate the expected change in participation probability resulting from inclusion of a given level. The leftward shift in participation probabilities between The High Intention group and the Mixed Intention group demonstrate the dwarfing effect of attitudes on attribute preferences and overall participation probabilities.

6.4 A NEW TOOL FOR DATA DRIVEN POLICY SUPPORT

Here, I present a new simulation tool that can support critical ongoing conversations about which large-scale water conservation program concepts are worthy and advisable strategies for securing Colorado's water future. This tool integrates social and hydrological signals for policy design in a manner similar to decision-support approaches used in other utility management contexts [18, 19]. Here, my goal is to link the social and environmental characteristics that limit or promote the effectiveness of water conservation programs in Colorado's West Slope region.

Complex social and environmental interactions can be difficult to capture via simple analyses. They can be even harder to incorporate into policy frameworks. I explicitly link information about field-scale CCU outcomes (see Chapter 3) with insights about the preferences of individual water users (see Chapter 5) to provide an integrated model of water conservation effectiveness under deep uncertainty (Figure 6.3).

The sections below discuss results from a virtual policy laboratory for testing conservation program strategies before they are implemented in the real world.

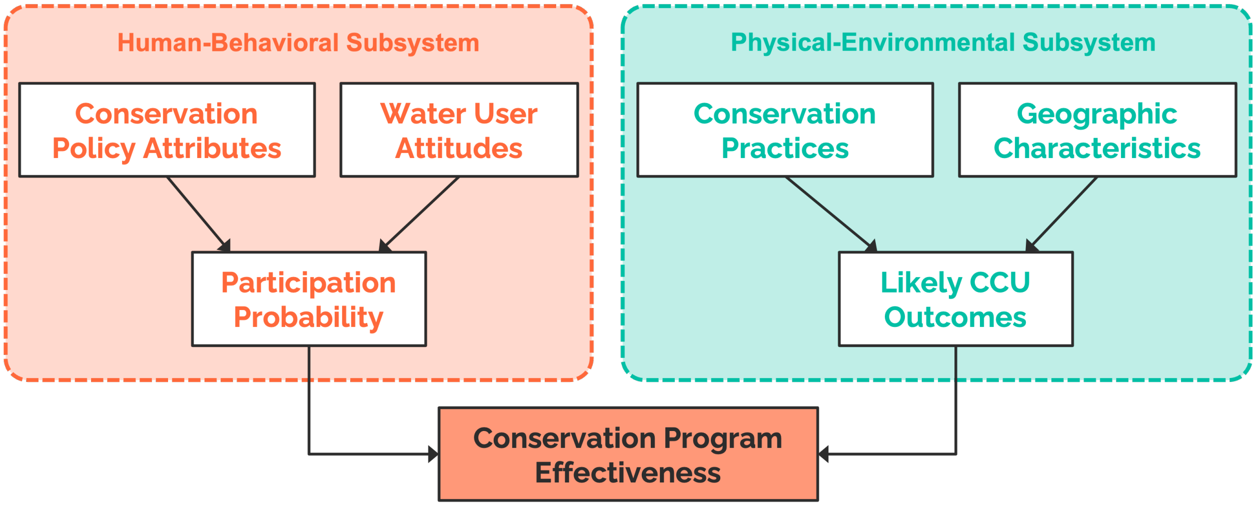

FIGURE 6.3. Conceptual flowchart indicating the subsystem data sources and information pipelines that were integrated into the simulation tool presented here.

The virtual policy laboratory detailed here employs a hybrid agent based model (ABM) to predict conservation program participation rates and CCU for individual fields on Colorado's West Slope (Appendix B). Model simulations explore the time-variant adoption rates and CCU outcomes associated with a small set of alternative conservation policies (Table 6.2). Individual policies are structured to reflect the breadth of preferences assessed among agricultural water users.

- Policy A represents a maximum adoption strategy where each attribute is matched to the attribute levels that drive the highest participation probabilities. This is a low risk, high reward policy for waters. Conversely, the high compensation rate, coupled with low obligations for commitments of irrigated land to conservation (i.e. the Conserved Fraction) and high uncertainty associated with the split season conservation strategy make this policy a high risk, low reward alternative for the state. Policy A was expected to generate relatively small amounts of water from each participant for a high cost.
- Policy B reflects compensation rates and program attributes observed during recent rounds of SCPP. The requirements committed land area intend to fall in a 'middle ground' between Policy A and Policy C. No provisions for an East Slope Match or Water Shepherding are included.
- Policy C is structured as a maximum efficiency strategy. The selected conservation practice, compensation rate and conserved area make this a low risk policy for the state with an expected

high CCU return on each dollar invested. Conversely, the attributes included with this policy are expected to drive relatively low participation rates.

- Policy D matches Policy B in every attribute. However, the Policy D simulation includes a shift in attitudes among the population of water users toward more favorable view of conservation. This policy intends to reflect the potential outcomes associated with implementation of outreach or public messaging campaigns about the importance or collective benefits of conservation.
- Policy E makes use of the same compensation rate, conserved area, and attitude shift as Policy D. However, this policy adds East Slope Match and Water Shepherding provisions. This policy is presumed to be most strongly aligned with the preferences of West Slope water users and decision makers.

TABLE 6.2. Conservation policies evaluated with the simulation model

Policy	Conservation Practice	Compensation ($/acre)	Conserved Fraction	East Slope Match	Water Shepherding	Attitudes
A	Split Season (Early)	$1,200	25%	Yes	Yes	Baseline
B	Split Season (Early)	$600	50%	No	No	Baseline
C	Full Season	$300	100%	No	No	Baseline
D	Split Season (Early)	$600	50%	No	No	Improved
E	Full Season	$600	50%	Yes	Yes	Improved

All simulations carried out with the model enforce two critical rules for water user participation. Any given water user simulated by the ABM is only allowed to participate in conservation for two consecutive years. Additionally, water users are allowed to participate in conservation for a maximum of 4-of-10 years. These rules reflect preferences for water conservation on Colorado's West Slope put forward by the Colorado River Water Conservation District [20].

The assessed policies and simulation results presented here are not intended as an exhaustive exploration of the policy space. Rather, the results discussed below are intended only to demonstrate the types of information and insights that may be generated through application of the ABM. Note that the simulation model relies on fundamental assumptions regarding the number of farmers and ranchers in the water conservation market in any given year and the impact of social networks on diffusion of water conservation adoption among social networks. Readers interested in understanding the ABM model structure and associated assumptions are directed to Appendix B.

6.4.1 SIMULATED ADOPTION RATES

Simulation results indicate the impact of hypothetical policies on annual water conservation program adoption rates (Figure 6.4). Unsurprisingly, Policy A generated high adoption rates due to its favorable compensation rate and low land area commitment. Policies B and C shared similar adoption rates in early years but Policy B's greater incentive generated slightly higher adoption rates by the end of the 30 year simulation. Improvements in water users' attitudes toward conservation under Policy D produced a noticeable boost in adoption rates, relative to Policy B. This result demonstrates the potential effectiveness of public outreach campaigns for driving increased conservation program adoption. Modifying Policy D to include provisions for East Slope Match and Water Shepherding drastically improved adoption rates, making Policy E the most popular among the assessed policy alternatives.

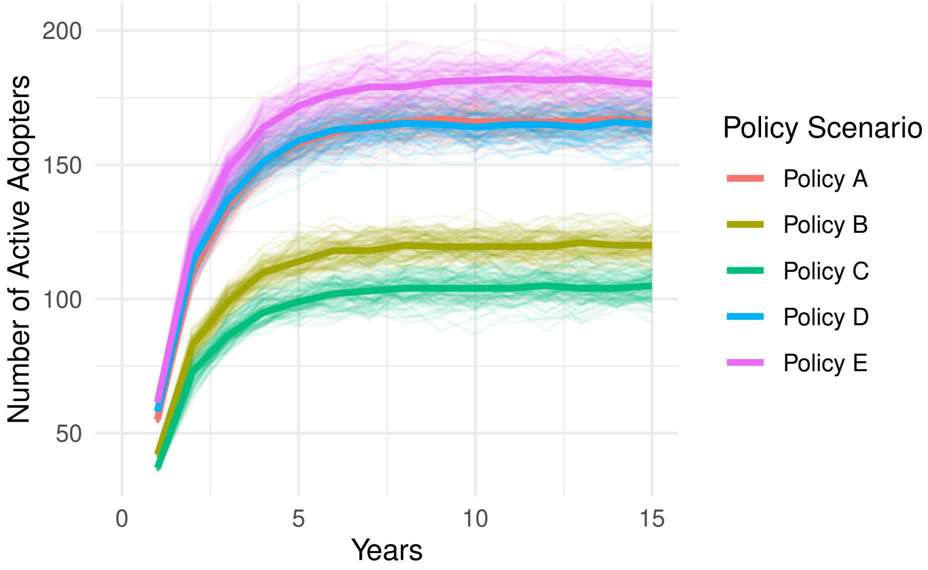

FIGURE 6.4. Simulated water conservation program adoption rates under different policy regimes. Thick lines indicate the median simulated condition. Thin lines indicate results from individual Monte Carlo simulation runs.

6.4.2 SIMULATED CONSUMPTIVE USE SAVINGS

The simulation of participation rates represents only one part of the water conservation policy puzzle. Increased adoption rates are only beneficial where they lead to measurable improvements in CCU outcomes. Simulation of annual volumes of conserved water generated under different conservation policies provided some unexpected results (Figure 6.5). While Policy A was able to generate the greatest participation, it failed to produce commensurately high CCU volumes. The low simulated annual CCU rates were driven by relatively small land areas placed under conservation on any given farm or ranch and the inherent uncertainty in CCU outcomes associated with split season irrigation, particularly on grass pasture. It is important to note here that Policy A includes a provision for a 1:1 match of water conserved on the West Slope with reductions of transmountain diversions. This provision has the effect of doubling the CCU volumes in each year of the simulation period. Despite having a slightly less favorable compensation terms and lower overall adoption rates, Policy B delivered more conserved water than Policy A over the simulation period. This difference was driven primarily by the increased fraction of irrigated land area obligated to conservation in any given year. Policy C, despite very low adoption rates, was capable of producing much more water than either Policy A or Policy B. The difference between the outcomes was driven by the requirement for full season irrigation curtailment on 100% of irrigated ground. The boost in CCU driven by these policy attributes was sufficient to overcome low adoption rates. The supplementation of Policy B with efforts to shift water users' attitudes toward conservation led to modest increases in CCU outcomes under Policy D. This policy produced the higher median CCU volumes than Policy B, but was associated with greater uncertainty. The high adoption rates associated with Policy E drove CCU outcomes commensurate with Policy C, despite the former only requiring commitment of 50% of irrigated land to conservation. Supplementation of the West Slope CCU volumes with water matched by transmountain diversions to the East Slope made Policy E the most effective at generating conserved water.

6.4.3 SIMULATED PROGRAM COSTS

Understanding the long-term viability of any basin-scale conservation program requires some recognition of the budgets that will be required to support project implementation. Model outputs included the total cost of conservation on each farm or ranch across the simulation period (Figure 6.6). Annual costs were based on the compensation rate included in the policy, pro-rated by the amount of irrigated

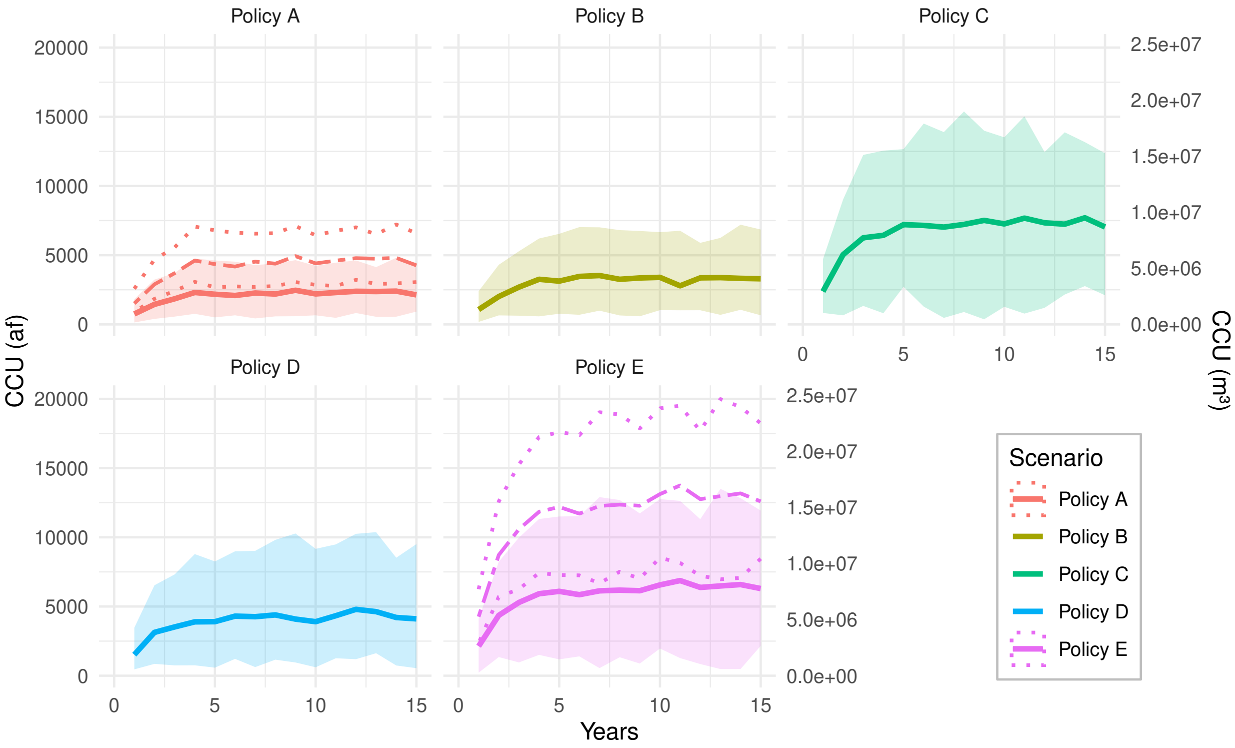

FIGURE 6.5. Simulated annual CCU volumes generated by different policy regimes. Median values are indicated by the solid lines. 95% prediction envelops are indicated by the solid colored area. The provision for a 1:1 match of conserved water with reductions in transmountain diversions to the East Slope has the effect of doubling the CCU volumes in each year for Policy A and Policy E. Median CCU volumes that include the East Slope Match are indicated by dashed lines. The prediction envelope bounds are indicated by the dotted lines.

land dedicated to conservation in that year. Even though Policy A only required that participants dedicate 25% of their irrigated land to conservation, the high incentive rate drove long-term costs associated with this policy higher than many of the other policies. The combination of low overall CCU volumes and high costs suggest that Policy A is a minimally effective policy. Policies B and C shared similar long-term cost projections. The higher CCU outcomes associated with Policy C, combined with the slightly lower long-term costs make it the more cost-effective option. Increased participation rates associated with Policy D, relative to Policy B, make it more expensive to implement over the long term. However, this policy was responsible for larger CCU volumes. Some additional analysis of trade-offs is required to assess whether Policy C or Policy D is more cost effective. Policy E drove the highest annual costs. The high overall rate of CCU generation associated with this policy make it among the most cost effective option, despite the high total annual costs.

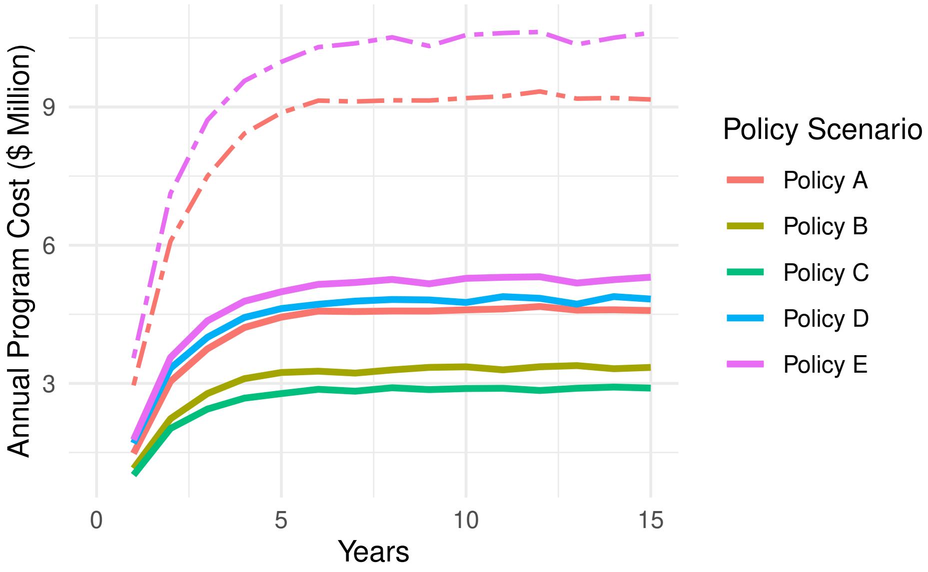

FIGURE 6.6. Simulated costs for CCU generated by different policy regimes. The provision for a 1:1 match of conserved water with reductions in transmountain diversions to the East Slope has the effect of doubling the CCU volumes in each year for Policy A and Policy E. The computation of costs that reflect the East Slope Match provision assume that compensated reductions in transmountain diversions result in a doubling of overall program costs. Cumulative costs that include the East Slope Match for Policy A and Policy E are indicated by dashed lines.

6.4.4 POLICY OPTIMIZATION

Simulation results demonstrate clear trade-offs between and among the assessed policies (Table 6.3). While a policy designed for maximum water user participation (Policy A) was shown to be expensive and inefficient, the most cost-effective policy (Policy C) struggled with low participation rates and reflected a suite of conservation policy attributes noted by others as unpalatable to West Slope water users [[20, 21]]. The collective interpretation of simulation results presented here, along with the body of research used to develop the virtual policy laboratory, suggest a pathway for policy optimization that achieves the benefits of high adoption rates, while still producing meaningful CCU volumes.

Meaningful increases in conservation program participation rates may be achieved through public outreach and messaging campaigns that aim to change agricultural producers' attitudes towards water conservation. New administrative tools or locally developed operational supports for farmers and ranchers to be implemented during conservation periods may contribute to an enhanced sense of agency among water users that translates to increased rates of participation. The impact of shifting attitudes on adoption rates is demonstrated by Policy D (relative to Policy B) and Policy E (relative to Policy D).

The unrealized CCU associated with policies that obligate lower fractions of irrigated land area to conservation can be made up through increased adoption rates and inclusion of an East Slope Match provision. This is demonstrated by comparing median CCU volumes generated under Policy E to those generated under Policy C. The East Slope Match provision provides a double benefit of increasing participation likelihoods and generating larger annual CCU volumes. Neither do forgone transmountain water diversions to the East Slope suffer from the same CCU uncertainties as conservation activities on farms and ranches. A single acre-foot of forgone transmountain diversion translates exactly to a one acre-foot CCU volume.

The impact of administrative water shepherding of conserved water past junior water rights holders was not assessed directly by the ABM presented here. However, the expected benefit of this provision is similar to the East Slope Match—enhanced participation rates and greater certainty in generated CCU volumes. Future modeling work should explicitly incorporate the impact of administrative water shepherding.

TABLE 6.3. Median values for Monte Carlo simulation results produced for each of the assessed policies. [a]Reflects an assumption that conservation on the West Slope will be matched on a 1:1 basis by forgone transmountaind diversions to the East Slope. [b]Reflects an assumption that compensation for forgone transmountain water diversions to the East Slope will result in a doubling of overall program costs.

Policy	Median Adoption Rate (participants/year)	Median Generated CCU (acre-feet/year)	Median Annual Cost (Million USD)	Median Cost-Effectiveness (USD/acre-foot)
A	166	2277 (4554[a])	4.6 (9.2[b])	2019
B	120	3269	3.3	1017
C	104	7232	2.9	397
D	165	4319	4.8	1096
E	181	6245 (12490[a])	5.3 (10.6[b])	818

6.5 KEY FINDINGS AND RECOMMENDATIONS

The question of how to best connect policy makers with data and evidence that supports development of effective and scalable policies plagues many domains. Water planning in Colorado is not exempt from this condition. The State of Colorado relies on programmatic structures that dictate regular updates to strategic planning documents at the state, basin, and local scale (e.g., the Colorado Water Plan and Basin Implementation Plan review and update process), the maintenance of decision support tools (e.g., CDSS), and engagement with formal stakeholder groups (e.g., Roundtables) to make important connections between evidence and policy. Opportunities for innovation that better connect data and evidence with policy exist at all levels of the water planning process.

Linking social survey results, social network simulation modeling, and field-scale hydrological models brings cutting edge academic research to bear on strategic water planning efforts in Colorado. The work presented here directly supports the goals and objectives of the CWP and the CBRT BIP by providing critical information on the effectiveness, scalability, and long-term costs of water conservation programs. Notably, my modeling approach illustrates how adoption rates of large-scale water conservation programs may be influenced by social networks, attitudes, and individual preferences. This work also illuminates the ways that conservation practices interact with geography to control consumptive water use reductions at the field-scale.

The policy evaluation provided in this document serves only as an indication of the opportunities provided by the presented simulation tool. The results presented here reflect deep unceratinty in policy outcomes and are not intended to predict specific participation rate or CCU outcomes associated with any given policy. Instead, the utility of this virtual policy laboratory comes from its ability to perform relative evaluations of competing policy approaches. The critical insights that can be generated through application of this modeling approach to new policy questions can help decision-makers craft conservation policies that are equitable, efficient, and help meet water conservation goals under a range of climate and development futures. Key findings and recommendations for future model utilization or extension include the following:

- No policies evaluated were able to generate annual CCU volumes equivalent to the conservation volumes used as the basis for the most aggressive hypothetical programs in The Upper Basin Demand Management Economic Study in Western Colorado [12] or the Colorado River Risk Study [2]. This may be a function of the assumptions and constraints used in the ABM. However, the order of magnitude difference between what the tested policies were capable of generating and the CCU volumes commensurate with the least aggressive hypothetical programs proposed in the documents noted above suggests that meeting aggressive annual conservation targets may be infeasible. The severity of the water supply and management crisis on the Colorado River seems to increase with every passing year. Expected impacts from climate change are likely to accelerate and deepen the current crisis. The long lag-time required to generate modest annual CCU volumes suggests that sustained water conservation policies need to be established well in advance of crisis-level conditions in order to be effective. Each year of delay decreases the likelihood that the scale of conservation project outcomes can match the scale of the crisis.

- Geography presents a critical control on conservation outcomes. The presence of perennial grass pasture and high elevations both work to reduce CCU. The dominance of mid- and high-elevation grass pasture on Colorado's West Slope presents policymakers with a clear management challenge. The simulation model can be used to identify optimal conservation strategies that maximize CCU while minimizing uncertainty. Alternatively, the model can be used to explore targeted policies that seek different practices in different geographies as a means for maximizing program effectiveness.
- Attitudes moderate participation likelihood. Findings suggest that shifting attitudes may drive greater increases in participation than increasing compensation rates, etc. A diminished sense of responsibility to act in the face of current water supply and management challenges is associated with a lower likelihood of conservation program participation. Currently, there is no shared understanding of the need for collective action to stabilize conditions in the Colorado river basin. In fact, many of the announcements and proclamations from state officials and water managers in the UCRB suggest that the management challenges to Lake Powell and Lake Mead are a problem for the LCRB to solve. At the same time, the Upper Basin states continue to pilot conservation projects through SCPP. So long as policymakers and water managers reinforce the message that downstream Colorado River issues are not the problem of Colorado's water community, the sense of responsibility to act will remain low. Alternative messaging may help shift attitudes and raise the likelihood of conservation program participation among many West Slope agricultural water users.
- A limited sense of agency and influence on basin-scale outcomes is also associated with low conservation program participation likelihoods. Administrative, institutional, or farm and ranch operational constraints appear to drive perceptions of limited control. Many agricultural producers on Colorado's West Slope use water to support cow-calf operations. The requirement for consistent livestock forage in every year of operation means these users are uniquely constrained when contemplating participation in conservation programs. If conservation reduces forage yields on a participating ranch, that lost forage needs to be offset with forage purchased

elsewhere. Targeted, flexible policies that can reduce perceived barriers to entry for cow-calf operators may help boost participation among this subpopulation.

- The supplementary impact of the East Slope Match attribute on CCU outcomes greatly magnifies adoption rates and policy effectiveness. Notably, reductions in transmountain diversions are not affected by the same uncertainties in CCU outcomes as conservation practices on agricultural fields. As a result, policies that include the East Slope Match requirement will receive a three-fold beneficial impact: broader conservation program participation, a substantial increase in annual CCU volumes, and a long-term reduction in the uncertainty associated with the total CCU delivered by the policy.
- Future applications of the model should contemplate the role of transit losses and basin-scale CCU calculations in the absence of administrative water shepherding. Both effects are expected to reduced CCU and failure to explicitly or implicitly account for them may produce unrealistic characterizations of all policies, especially those that do not include the Water Shepherding attribute. Achieving this goal may be accomplished using coarse approximations within the current modeling framework. However explicit characterization of the impacts of transit losses or water administration will require a full network representation of the ABM, complete with hydrological routing capabilities and logic from a water rights allocation and accounting model like StateMod.

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CHAPTER 7

CONCLUSION

Policymakers and water managers need new strategies for responding to the water management challenges in the Colorado River Basin. Recent planning documents propose voluntary, temporary and compensated water conservation programs targeting agricultural water users as a critical tool for addressing water supply issues. Water conservation projects piloted in recent years were successful at generating much larger reductions in water use in the Lower Colorado River Basin than in the Upper Colorado River Basin. Open questions remain regarding the disparities in participation rates between the two basins. For voluntary agricultural water conservation to produce meaningful benefits to basin-scale water management, broad and sustained participation among agricultural water users is needed. Conservation practices that produce measurable conservation gains at the field scale are also necessary. Conservation strategies contemplated in recent planning documents and pilot projects guarantee neither. In fact, the parallel aims of enhancing participation rates and maximizing conservation gains exist in a state of tension. Implementing strategies that maximize one objective are likely to come at the cost of diminishing the other. This dissertation explores that point of tension.

The distillation and quantification of the tensions that exist between the opportunities and constraints to agricultural water conservation on Colorado's West Slope and, more broadly across the Upper Colorado River Basin should support water managers and policymakers who require insights into the scalability and potential impact of proposed programs and policies. Specifically, this work characterizes the dependency of consumptive use water reductions on geographic context and demonstrates of the way that attitudes and risk aversion shape moderate conservation program participation.

My research demonstrates the application of Systems Engineering philosophies and heuristics to the water resource management policy domain. This dissertation provides a novel, empirically grounded investigation into the physical-environmental and human-behavioral controls on water conservation program effectiveness. The structure of my program of research generally conformed to the Systems Engineering evolutionary sequential model (the "Vee model")(Figure 7.1).

- Chapter 1 presents background information, the general problem statement, and a conceptual diagram of the system boundaries and interacting subsystems that directly inform the architecture of my research program.

- Investigation of the physical-environmental (Chapters 2-3) and human-behavioral subsystems (Chapters 4-5) represent implementation sub-loops. Each sub-loop presents a detailed research design consisting of hypotheses and conceptual models. Detailed research designs are implemented through baseline data collection and construction of predictive models. These models are subsequently verified against the relevant hypotheses and conceptual models.
- The outputs from the implementation sub-loops are integrated in Chapter 6 to create a virtual laboratory for testing water conservation policy effectiveness.
- The validation of the policy optimization findings from the integrated system cannot be demonstrated here. Instead, validation must follow future implementation of pilot projects that test specific policy prescriptions.
- Ongoing operation and maintenance will require a long-term commitment to implementation of policies or pilot projects, evaluation of outcomes against the goals of water conservation in the UCRB, and reformulation of approaches to generate more effective, equitable, and acceptable policies.

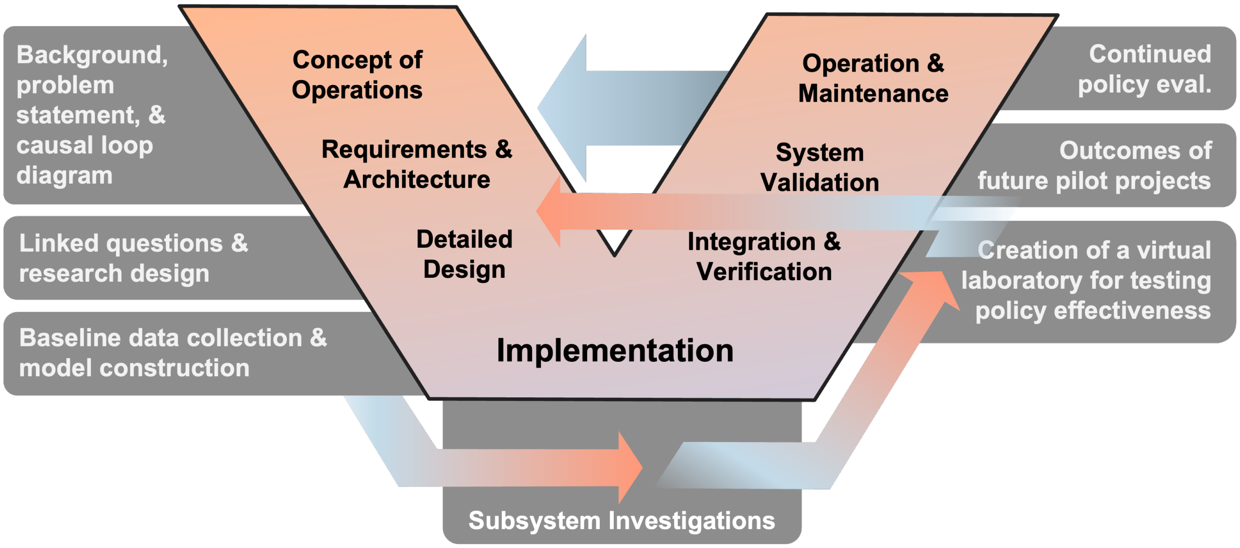


FIGURE 7.1. The planning and execution of research activities presented in this dissertation followed the general structure of the Vee model. Text in the gray call-outs indicate the alignment of my research activities and expected follow-up actions with the components of the Vee model.

The relevance of this work to current water management issues, coupled with the unique data collection and analysis methodologies documented here, make this research contribution both timely and significant. The data products and models generated by this research are formatted and conveyed to support future updates as new information becomes available. Research results may also contribute to the development of strategic, data-driven water conservation policies. My hope is that the value derived from this work is long-lived and that the methods and results presented in this dissertation are adapted by others to respond to changing attitudes, policies, economic and environmental realities.

APPENDIX A

PAPER SURVEY INSTRUMENT

Water Conservation Survey

Please enter the ZIP code of the agricultural property you own or manage on Colorado's West Slope: ________________________

What county on Colorado's West Slope do you live in? ________________________

How many acres of irrigated land do you own and/or manage on Colorado's West Slope? Please do not include grazing leases on federal land in your answer. ____________________acres

What percentage of the land that you farm/ranch is leased from another private landowner? (Do not include grazing land leased from the federal government) ______________________%

Please estimate the percentage of your total annual water use allocated to the following agricultural activities on the property you own or manage. Your answers should sum to 100.

_______ Hay or grass pasture
_______ Alfalfa
_______ Row crops (field corn, grains, beans, peas, etc.)
_______ Greenhouse vegetables
_______ Perennial crops (tree nursery, fruit orchard, vineyard)
_______ Other

Please estimate the percentage of on-farm revenue generated annually by each of the following activities on the farm/ranch that you own or manage. Your answers should sum to 100.

_______ Livestock sales
_______ Forage sales
_______ Grain sales
_______ Fruit/vegetable sales
_______ Poultry sales
_______ Agricultural tourism (Guest/Dude Ranch, etc.)
_______ Recreation (guided hunting, fishing, etc.)
_______ Other

Do you use irrigation water to produce feed for livestock on the farm/ranch that you own or manage? ○ Yes ○ No

Excluding forage produced on federal lease land, approximately what percentage of your annual supply of livestock feed is typically obtained from an outside source?

Circle One:
0 10 20 30 40 50 60 70 80 90 100%

What percentage of the forage sales from your farm/ranch in any given year are covered by multi-year contracts?

Circle One:
0 10 20 30 40 50 60 70 80 90 100%

Do you know how many of your water rights have a pre-1922 seniority? ○ Yes ○ No

If so, approximately what percentage of the water rights (by flow rate or volume) for the land you own and/or manage have a pre-1922 seniority?

Circle One:
0 10 20 30 40 50 60 70 80 90 100%

To what extent do you disagree or agree with the following statements about water challenges facing Colorado?	Strongly disagree	Somewhat disagree	Neither agree nor disagree / not sure	Somewhat agree	Strongly agree
Unless something changes, Colorado and neighboring states are headed toward a water supply crisis	○	○	○	○	○
Extended drought and growing demand for water are straining water supplies in the Colorado River Basin	○	○	○	○	○
Recent drought conditions represent the "new normal" in the Colorado River Basin	○	○	○	○	○

How often do administrative calls from senior water rights in your basin or watershed lead to the following:	Frequently	Occasionally	Infrequently	Never
Curtailment of 25% of your water supply	○	○	○	○
Curtailment of 50% of your water supply	○	○	○	○
Curtailment of 75% of your water supply	○	○	○	○
Curtailment of 100% of your water supply	○	○	○	○

For which months during the year types indicated do you feel are you able to apply sufficient irrigation water to the land you own and/or manage?

	Apr	May	Jun	Jul	Aug	Sep	Oct
Dry year	○	○	○	○	○	○	○
Typical year	○	○	○	○	○	○	○
Wet year	○	○	○	○	○	○	○

Approximately what percentage of your water comes from a shared ditch or similar arrangement where multiple users receive water as shares from a single supply?

Circle One:

0 10 20 30 40 50 60 70 80 90 100%

Approximately what percentage of your total annual water supply is from reservoir storage?

Circle One:

0 10 20 30 40 50 60 70 80 90 100%

Have you ever participated in a program where you received financial compensation to reduce agricultural water use on your farm or ranch?

○ Yes ○ No

	Extremely negative	Somewhat negative	Neither positive nor negative	Somewhat positive	Extremely positive
If so, please rate that experience.	○	○	○	○	○

What category best describes your household's annual Adjusted Gross Income (AGI)?

- ○ less than $75,000
- ○ $75,001 - $150,000
- ○ $150,001 - $250,000
- ○ $250,001 - $500,000
- ○ $500,001 - $900,000
- ○ greater than $900,001

What percentage your household's annual Adjusted Gross Income (AGI) is derived from agricultural production (e.g. crop/forage sales, livestock production, etc.) on the farm/ranch property that you own or manage?

- ○ < 10%
- ○ 10-25%
- ○ 25-50%
- ○ 50-75%
- ○ >75%

To what extent do you disagree or agree with the following statements?	Strongly disagree	Somewhat disagree	Neither agree nor disagree / not sure	Somewhat agree	Strongly agree
I feel compelled to participate in coordinated efforts to address water supply shortages in the Colorado	○	○	○	○	○
Water users in Colorado have a role to play in ensuring that Lake Powell does not drop to critical levels	○	○	○	○	○
All water users, including me, have a role to play in ensuring that Colorado's water needs are met now, and in the future	○	○	○	○	○

How much should each of the following water user groups in Colorado collectively reduce water consumption in order to address water supply challenges in the Colorado River Basin?

Agricultural (%)	0	10	20	30	40	50	60	70	80	90	100
Municipal (%)	0	10	20	30	40	50	60	70	80	90	100
Industrial (%)	0	10	20	30	40	50	60	70	80	90	100

Do you have the authority to choose whether or not to enter into an agreement for compensated water conservation practices on the farm/ranch that you own or manage?

○ Yes, I have the authority to make that sort of decision.
○ I have some authority but would need reach an agreement with other individuals before a final decision was made.
○ No, I do not have the authority to make that sort of decision.

The next portion of the survey will ask you to select a preferred option among two competing hypothetical water conservation program options. Each option is defined by different attributes. The relevant attributes are as follows:

Conservation Action - The irrigation reduction activity that will be contracted and enacted for a single irrigation season

Compensation - Payment for each acre of land placed under water conservation

Conserved Acreage - The portion of your typically irrigated acreage allocated to water conservation program activities

East Slope Match - Whether any conserved consumptive use will be matched in volume by curtailment of transmountain water diversions to the Front Range

Water Shepherding/Protection - Whether any conserved consumptive use water will be shepherded downstream past all other water users and controlled by the Upper Basin states to reduce risks of a Compact Call on the Colorado River

All options assume that your water right will be at NO risk of diminishment or abandonment if/when you choose to participate in conservation. If neither of the proposed options is acceptable, you may indicate that you would prefer to maintain your normal irrigation practices.

This is a critical portion of the survey where you can help communicate the aspects of a future water conservation policy or program that you find more or less preferable. Please review each option carefully and provide thoughtful responses.

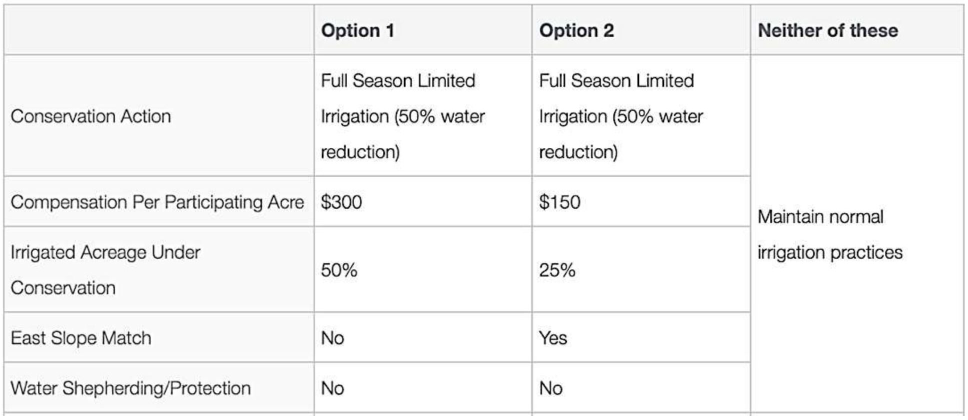
For each of the following 12 choice sets, select a preferred option among two competing hypothetical water conservation program options. Each option is defined by different attributes.

Choice set 1 of 12:

Option 1 ○

Option 2 ○

Neither ○



	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Limited Irrigation (50% water reduction)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$300	$150	
Irrigated Acreage Under Conservation	50%	25%	
East Slope Match	No	Yes	
Water Shepherding/Protection	No	No	

Choice set 2 of 12:

Option 1 ○

Option 2 ○

Neither ○

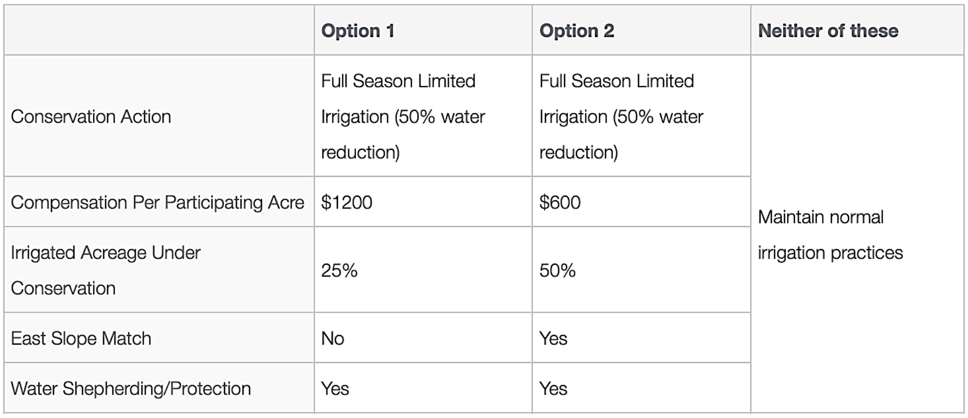
	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Curtailment (Apr 1 - Oct 31 dry-up)	Split Season Curtailment (July 1 - Oct 31 dry-up)	Maintain normal irrigation practices
Compensation Per Participating Acre	$300	$600	
Irrigated Acreage Under Conservation	50%	50%	
East Slope Match	Yes	No	
Water Shepherding/Protection	No	Yes	

Choice set 3 of 12:

Option 1 ○

Option 2 ○

Neither ○



	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Limited Irrigation (50% water reduction)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$1200	$600	
Irrigated Acreage Under Conservation	25%	50%	
East Slope Match	No	Yes	
Water Shepherding/Protection	Yes	Yes	

Choice set 4 of 12:

Option 1 ○

Option 2 ○

Neither ○

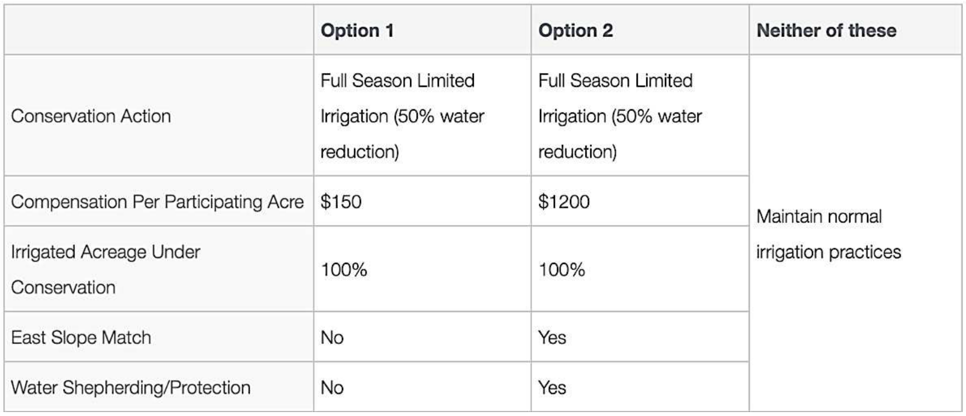
	Option 1	**Option 2**	**Neither of these**
Conservation Action	Split Season Curtailment (July 1 - Oct 31 dry-up)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$150	$600	
Irrigated Acreage Under Conservation	75%	25%	
East Slope Match	Yes	No	
Water Shepherding/Protection	No	No	

Choice set 5 of 12:

Option 1 ○

Option 2 ○

Neither ○



	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Limited Irrigation (50% water reduction)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$150	$1200	
Irrigated Acreage Under Conservation	100%	100%	
East Slope Match	No	Yes	
Water Shepherding/Protection	No	Yes	

Choice set 6 of 12:

Option 1 ○

Option 2 ○

Neither ○

	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Curtailment (Apr 1 - Oct 31 dry-up)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$600	$300	
Irrigated Acreage Under Conservation	75%	50%	
East Slope Match	No	Yes	
Water Shepherding/Protection	Yes	No	

Choice set 7 of 12:

Option 1 ○

Option 2 ○

Neither ○

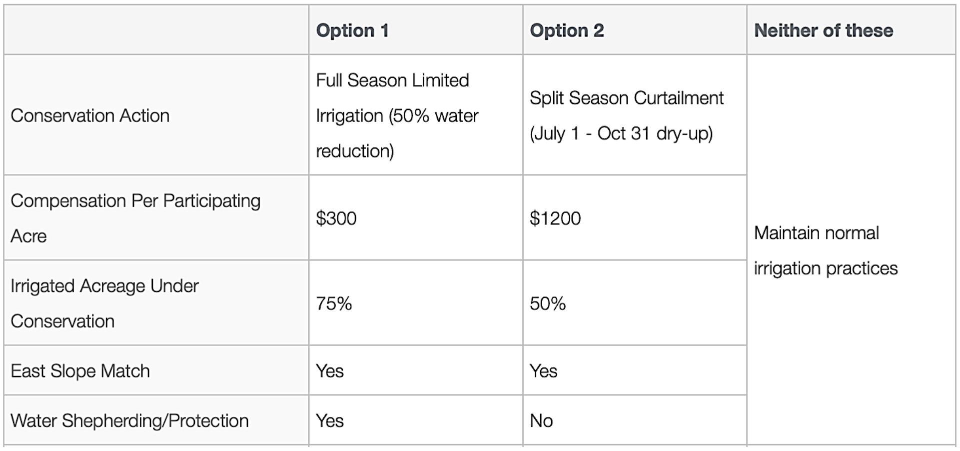
	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Curtailment (Apr 1 - Oct 31 dry-up)	Split Season Curtailment (July 1 - Oct 31 dry-up)	Maintain normal irrigation practices
Compensation Per Participating Acre	$150	$1600	
Irrigated Acreage Under Conservation	100%	100%	
East Slope Match	No	Yes	
Water Shepherding/Protection	Yes	No	

Choice set 8 of 12:

Option 1 ○

Option 2 ○

Neither ○



	Option 1	**Option 2**	**Neither of these**
Conservation Action	Full Season Limited Irrigation (50% water reduction)	Split Season Curtailment (July 1 - Oct 31 dry-up)	Maintain normal irrigation practices
Compensation Per Participating Acre	$300	$1200	
Irrigated Acreage Under Conservation	75%	50%	
East Slope Match	Yes	Yes	
Water Shepherding/Protection	Yes	No	

Choice set 9 of 12:

Option 1 ○

Option 2 ○

Neither ○

	Option 1	**Option 2**	**Neither of these**
Conservation Action	Split Season Curtailment (July 1 - Oct 31 dry-up)	Split Season Curtailment (July 1 - Oct 31 dry-up)	Maintain normal irrigation practices
Compensation Per Participating Acre	$150	$600	
Irrigated Acreage Under Conservation	100%	75%	
East Slope Match	No	No	
Water Shepherding/Protection	Yes	No	

Choice set 10 of 12:

Option 1 ○

Option 2 ○

Neither ○

	Option 1	Option 2	Neither of these
Conservation Action	Split Season Curtailment (July 1 - Oct 31 dry-up)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$300	$1200	
Irrigated Acreage Under Conservation	25%	75%	
East Slope Match	No	No	
Water Shepherding/Protection	Yes	No	

Choice set 11 of 12:

Option 1 ○

Option 2 ○

Neither ○

	Option 1	Option 2	Neither of these
Conservation Action	Full Season Limited Irrigation (50% water reduction)	Full Season Limited Irrigation (50% water reduction)	Maintain normal irrigation practices
Compensation Per Participating Acre	$600	$150	
Irrigated Acreage Under Conservation	100%	50%	
East Slope Match	Yes	Yes	
Water Shepherding/Protection	No	Yes	

Choice set 12 of 12:

Option 1 ○

Option 2 ○

Neither ○

	Option 1	Option 2	Neither of these
Conservation Action	Split Season Curtailment (July 1 - Oct 31 dry-up)	Full Season Curtailment (Apr 1 - Oct 31 dry-up)	Maintain normal irrigation practices
Compensation Per Participating Acre	$300	$1600	
Irrigated Acreage Under Conservation	75%	50%	
East Slope Match	No	Yes	
Water Shepherding/Protection	No	Yes	

How certain do you feel that the responses you provided in the previous section are reflective of choices you may make in the real world if presented with similar options?

○ Very certain
○ Somewhat certain
○ Not Very Certain

How would the following long-range summer weather forecasts affect your decision to participate in a water conservation program?

	Much less inclined	Somewhat less inclined	No effect	Somewhat more inclined	Much more inclined
Forecast is for severe drought:	○	○	○	○	○
Forecast is for dryer than average conditions:	○	○	○	○	○
Forecast is for wetter than average conditions:	○	○	○	○	○

How would a multi-year contract for conservation activities affect your decision to participate in a program?

	Much less inclined	Somewhat less inclined	No effect	Somewhat more inclined	Much more inclined
3-year contract	○	○	○	○	○
5-year contract	○	○	○	○	○

To what extent do you disagree or agree with the following statements about your perceived ability to influence outcomes?	Strongly disagree	Somewhat disagree	Neither agree nor disagree / not sure	Somewhat agree	Strongly agree
I don't use enough water for conservation on my farm or ranch to produce a meaningful amount of water	○	○	○	○	○
Water conservation on my farm/ranch would not be worth it because the water would just be used by someone else downstream	○	○	○	○	○
I don't have the flexibility in my farming/ranching operation to forgo or reduce water use in any year, even if I wanted to.	○	○	○	○	○

Please rank the following in order of importance to you (1= most important, 3 = least important) when seeking input about the operations or management of your farm/ranch.

______ Input from friends and neighbors
______ Input from family
______ Input from agricultural professionals (NRCS staff, CSU Extension, farm equipment/implement dealers)

To what extent do you disagree or agree with the following statements about the role of your social network in your decision-making?	Strongly disagree	Somewhat disagree	Neither agree nor disagree / not sure	Somewhat agree	Strongly agree
I value the perspective and opinions of friends, relatives, or neighbors when making decisions about my farming or ranching enterprise	○	○	○	○	○
I have changed operations to make my farm or ranch more efficient or profitable in the past as a direct result of suggestions from or observations of the activities of friends or neighbors	○	○	○	○	○
If my friends, relatives and/or neighbors participated in a voluntary, temporary, and compensated water conservation program, I would be more open to doing the same	○	○	○	○	○

To what extent do you disagree or agree with the following statement about water conservation programs?	Strongly disagree	Somewhat disagree	Neither agree nor disagree / not sure	Somewhat agree	Strongly agree
Voluntary programs that compensate users for temporarily reducing water use are an important tool for securing Colorado's water future	○	○	○	○	○

Please select your gender: ○ Male ○ Female

Please indicate your age: ______

Please select your ethnicity:

- ○White
- ○Hispanic/Latino
- ○American Indian
- ○Black/African American
- ○Asian
- ○Native Hawaiian or Pacific Islander
- ○Other

What political party candidates do you typically vote for:

- ○ Republican
- ○ Democrat
- ○ Independent
- ○ Other

APPENDIX B

GOVERNING EQUATIONS FOR THE HYBRID AGENT BASED MODEL

B.1 GOVERNING EQUATIONS FOR THE HYBRID AGENT BASED MODEL

This document provides details about a simulation approach that employs a hybrid agent based model (ABM) to predict water conservation program participation rates and conserved consumptive use (CCU) outcomes for individual fields on Colorado's West Slope. The model integrates predictions from a pair of Bayesian hierarchical models: the Choice Model and the CCU Model. Agent behavior is modeled as a aggregate mean-field effect. Agent decisions are represented as probabilistic choices from the Choice Model. Interactions between agents are not modeled explicitly. Instead, the influence of social networks is simulated using the Bass model of diffusion. The Bass model captures general trends among groups in a network where a higher number of conservation participants leads to increasing levels of conservation adoption. The primarly components of the model are described in the sections below.

B.2 CONCEPTUALIZATION OF AGENTS

A synthetic population of agents is formed by bootstrapping unique respondents and their preferences for water conservation policy attributes from a survey of water users. Sampled respondents were assigned to fields represented in the Colorado Decision Support System (CDSS) Irrigated Lands database. Only mapped fields in the CDSS greater than 40 acres (16 ha) in size were used in the model to reflect recent SCPP restrictions on participating farms and ranches. The soil and elevation characteristics of each field were acquired through spatial joins of field centroids to digital elevation datasets and mapped soil characteristics from the U.S. Department of Agriculture. This approach resulted in a population of 4755 agents that provide a realistic representation of the attitudes, preferences, and field-scale environmental characteristics influence conservation on Colorado's West Slope.

B.3 CHOICE MODEL STRUCTURE

$$\text{OptIn}_{ij} \sim \text{Bernoulli}(p_{ij})$$

$$\text{logit}(p_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \underbrace{\begin{matrix} \beta_0 \\ + \beta_1 \cdot \text{Intention}_j \\ + \beta_2 \cdot \text{CompensationRate}_i \\ + \dots \\ + \beta_k \cdot (\text{Intention}_j \times \text{CompensationRate}_i) \\ + \dots \\ + f_{\text{Intention}_j}(\text{CompensationRate}_i, \text{ConservedFraction}_i) \end{matrix}}_{\text{Fixed Effects}} + \underbrace{\begin{matrix} u_{0,j} \\ + u_{1,j} \cdot \text{ConservationPractice}_i \\ + u_{2,j} \cdot \text{CompensationRate}_i \\ + \dots \end{matrix}}_{\text{Random Effects}}$$

$$\mathbf{u}_j = \begin{pmatrix} u_{0,j} \\ u_{1,j} \\ \vdots \end{pmatrix} \sim \text{MVNormal}(\mathbf{0}, \Sigma)$$

Where:

- OptIn_{ij} is modeled as a binary outcome for respondent j,
- p_{ij} is the probability that respondent j chooses to opt in to water conservation alternative i.
- η_{ij} is the linear predictor for alternative i on the logit scale,
- β_0 is the global intercept,

- $\beta_1, \ldots, \beta_k$ are the fixed-effect coefficients for the main effects and interactions,
- $f_{\text{Intention}_j}(\ldots)$ is a Gaussian Process, estimated separately for each level of intention,
- $ u_{0,j} $, is the random intercept for respondent j, representing their baseline preference for conservation,
- $u_{1,j}, u_{2,j}, \ldots$ are the random slopes for respondent j, representing a unique sensitivity to different policy attributes, and
- Σ is the covariance matrix for the random effects.

B.4 CCU MODEL STRUCTURE

$$\begin{aligned}
y_{ijm} &\sim \text{Student-t}(\mu_{ijm}, \sigma, \nu) \\
\mu_{ijmk} &= \beta_{0,k} + \beta_{1,k} \cdot \text{Crop}_i + \beta_2 \cdot \text{Hydric}_i + \beta_3 \cdot \text{Elevation}_i + \beta_4 \cdot \text{Slope}_i \\
&\quad + \beta_5 \cdot \text{Sprinkler}_i + \beta_6 \cdot \text{AWS}_i + f(P_{\text{anomaly},i}, ET_{\text{anomaly},i}) + \alpha_j + \gamma_m \\
\alpha_j &\sim \text{Normal}(0, \sigma^2_{\text{field}}) \\
\gamma_m &\sim \text{Normal}(0, \sigma^2_{\text{year}}) \\
f(\cdot) &\sim \text{GP}(0, k)
\end{aligned}$$

Where:

- y_{ijm} is the consumptive water use change for observation i in field j and year m.
- μ_{ijmk} is the modeled mean water savings for an observation belonging to conservation strategy k.
- $\beta_{0,k}$ is the group-specific intercept for conservation activity k.
- $\beta_{1,k}$ is the group-specific slope for crop type, given conservation activity k.
- β_2 through β_6 are the population-level fixed effects.
- α_j is the random intercept for field j.
- γ_m is the random intercept for year m.
- σ and ν are the scale and degrees-of-freedom parameters of the Student's t-distribution.

B.5 HYBRID AGENT BASE MODEL ROUTINE

Model simulations incorporate some degree of realism regarding water users' choices to participate or not participate in conservation in any given year. Among the cohort of agents that choose to participate in any year, given their unique responses to the policy on offer, the model uses the characteristics of the agents' fields and dynamic weather traces to predict field-scale CCU outcomes. The model routine enforces rules on the frequency and duration of conservation program participation for any given agent. Agents are allowed to participate in conservation for a maximum of two consecutive years and a maximum of 4-of-10 years. Single scenario simulations may be carried out for a set time period. Alternatively, ensembles of simulation outputs may be generated using a Monte Carlo framework. The time series model outputs may be summarized to provide a view of general trajectories and associated uncertainties for adoption rates and consumptive water use savings.

```
#'
#' ############################################
#  Main Hybrid-ABM Routine
#' ############################################
#' @description This function simulates the adoption and dis-adoption of a water
#' conservation policy over time. It uses a hybrid approach where a Bass diffusion
#' model determines the number of new adopters each year, and a Bayesian choice
#' model determines which agents are most likely to adopt and continue the practice.
#'
#' @param n_periods The number of years to run the simulation.
#' @param p The innovation coefficient (p) for the Bass model.
#' @param q The imitation coefficient (q) for the Bass model.
#' @param population_agents A data frame of bootstrapped agent profiles.
#' @param population_fields A data frame of agricultural field characteristics.
#' @param choice_model The fitted brms model for predicting adoption choice.
#' @param ccu_model The fitted brms model for predicting conserved consumptive use.
#' @param policy_scenario A single-row tibble defining the policy attributes.
#' @param met_trace A data frame with annual ET and Precipitation anomalies
#' of length = n_periods.
```

```
#'
#' @return A list where each element is a data frame of the active adopters
#'   and their calculated water savings for that year.
############################################
############################################

# ABM Function Call
run_abm <- function(n_periods = 30, p = 0.01, q = 0.3, population_agents,
      population_fields, choice_model, ccu_model, policy_scenario, met_trace) {

  # Prepare the data for prediction by combining agents and fields
  prediction_data <- dplyr::bind_cols(population_fields, population_agents) %>%
    mutate(
      conservationPractice = policy_scenario$conservationPractice,
      conservation_activity = policy_scenario$conservation_activity,
      compensationRate = policy_scenario$compensationRate,
      scaledCompensationRate = (
        policy_scenario$compensationRate -
          scaling_params[["compensationRate"]][["mean"]]) /
          scaling_params[["compensationRate"]][["sd"]],
      conservedFraction = policy_scenario$conservedFraction,
      scaledConservedFraction = (
        policy_scenario$conservedFraction -
          scaling_params[["conservedFraction"]][["mean"]]) /
          scaling_params[["conservedFraction"]][["sd"]],
      waterShepherding = policy_scenario$waterShepherding,
      eastSlopeMatch = policy_scenario$eastSlopeMatch
    )

  # Run the choice model
  # Get draws indicating agent willingness to participate in the policy
```

```
optIn_potential <- add_epred_draws(
  prediction_data,
  object = choice_model,
  allow_new_levels = TRUE,
  ndraws = 200
) %>%
  group_by(PARCEL_ID) %>%
  summarise(p_potential = mean(.epred))

# Create the final agents table
agents_for_abm <- prediction_data %>%
  left_join(optIn_potential, by = "PARCEL_ID") %>%
  mutate(
        status = "Non-adopter", # Set agent current status
        consecutive_years_adopted = 0, # Counter for Rule 1
        # List-column to store 10-yr history (1=adopted, 0=not adopted).
        # The newest year is at the end of the list.
        adoption_history_window = replicate(n(), rep(0, 10), simplify = FALSE)
      )

# Add status column to track agent status over time
adopters_trace <- list()

# Approximate market size as the sum of the adoption probabilities
# across all agents
market_size <- sum(agents_for_abm$p_potential)

# Main ABM simulation loop
for (t in 1:n_periods) {
  #get previous year adopters
  previous_adopters_ids <- agents_for_abm %>%
```

```
  filter(status == "Adopter") %>%
  pull(PARCEL_ID)
#get previous year non-adopters
non_adopter_ids <- agents_for_abm %>%
  filter(status == "Non-adopter") %>%
  pull(PARCEL_ID)

# Model recruitment of new adopters
market_penetration <- length(previous_adopters_ids) / market_size
remaining_market <- market_size - length(previous_adopters_ids)
# Implement Bass model for simulating interactions among agents
num_to_recruit <- if (remaining_market <=0) 0 else {
  round((p + q * market_penetration) * remaining_market)
}
# Outputs from the choice model indicate which agents are likely adopters
newly_adopted_ids <- if (num_to_recruit > 0 && length(non_adopter_ids) > 0) {
  current_non_adopters <- agents_for_abm %>%
    filter(PARCEL_ID %in% non_adopter_ids)
  #pull adopters from weighted random sample where weights are choice
  #probabilities from choice model
  slice_sample(
    current_non_adopters,
    n = min(num_to_recruit, nrow(current_non_adopters)),
    weight_by = p_potential
  ) %>% pull(PARCEL_ID)
} else {
  c()
}

##### Inflow (Adoption) #####
# Implement rule so that agents are only eligible for recruitment if they
```

```
# have been in the pool for < 4 of the last 10 years

# Get all current non-adopters
current_non_adopters_data <- agents_for_abm %>%
  filter(PARCEL_ID %in% non_adopter_ids)

# Find eligible agents by checking 10-year history
eligible_non_adopters_data <- current_non_adopters_data %>%
  mutate(history_sum = map_int(adoption_history_window, sum)) %>%
  filter(history_sum < 4)

newly_adopted_ids <- if (num_to_recruit > 0 &&
                         nrow(eligible_non_adopters_data) > 0) {
  slice_sample(
    eligible_non_adopters_data,
    n = min(num_to_recruit, nrow(eligible_non_adopters_data)),
    weight_by = p_potential
  ) %>% pull(PARCEL_ID)
} else {
  c()
}

##### Outflow (Dis-adoption) #####
# Implement rule so that agents must exist the pool of adopters if
# they have been in the pool for 2 consecutive years

  disadopted_ids <- if (length(previous_adopters_ids) > 0) {

  # Get all current adopters
  current_adopters_data <- agents_for_abm %>%
    filter(PARCEL_ID %in% previous_adopters_ids)
```

```
  # Force dis-adoption for agents after 2 consecutive
  # years of participation
  forced_disadopt_consecutive <- current_adopters_data %>%
    filter(consecutive_years_adopted >= 2) %>%
    pull(PARCEL_ID)

  # Use adoption probabilities to allow other agents to leave
  # the pool
  remaining_adopters_data <- current_adopters_data %>%
    filter(!PARCEL_ID %in% forced_disadopt_consecutive)
  # identify disadopters based on 1-(choice probabilities) from
  # the choice model
  probabilistic_disadopted_ids <- remaining_adopters_data %>%
    filter(runif(n()) > p_potential) %>%
    pull(PARCEL_ID)

  # Combine all disadopted IDs for this year
  union(forced_disadopt_consecutive, probabilistic_disadopted_ids)

} else {
  c()
}

#### Set Agent State ####

# Get the final set of adopters for this year
current_adopter_ids <- setdiff(previous_adopters_ids, disadopted_ids)
# Add the new adopters
current_adopter_ids <- union(current_adopter_ids, newly_adopted_ids)
```

```
# Get the weather anomalies for the simulation year
current_year_weather <- met_trace[t,]

# Update the master agent state table
agents_for_abm <- agents_for_abm %>%
  mutate(
    # Create helper column: 1 if agent is adopting this year, 0 if not
    is_adopter_this_year = (PARCEL_ID %in% current_adopter_ids)
  ) %>%
  mutate(
    # Update main status
    status = ifelse(is_adopter_this_year, "Adopter", "Non-adopter"),

    # Update consecutive years counter
    # If adopting, increment counter. If not adopting, reset to 0.
    consecutive_years_adopted = ifelse(
      is_adopter_this_year, consecutive_years_adopted + 1,
      0
      ),

    # Update 10-year history
    # Take the last 9 elements (drop oldest) and append the new status (1 or 0)
    adoption_history_window = pmap(
      list(adoption_history_window, is_adopter_this_year),
                                   ~ c(tail(..1, 9), as.integer(..2)))
  ) %>%
  dplyr::select(-is_adopter_this_year) # Remove helper column

# Filter the main table for tracing current agent data and
adopters_trace[[t]] <- agents_for_abm %>%
  dplyr::filter(PARCEL_ID %in% current_adopter_ids) %>%
```

```
      mutate(
        et_anomaly = current_year_weather$et_anomaly,
        pr_anomaly = current_year_weather$pr_anomaly,
      ) %>%
      # run the CCU model for each participating agent
      add_predicted_draws(
        ccu_model,
        ndraws = 1,
        re_formula = NA,
        value = "ccu_prediction"
      ) %>%
      mutate(
        #compute the total area of conserved land in hectares
        conserved_hectares = hectares * conservedFraction,
        #compute the total area of conserved land in m2
        conserved_m2 = conserved_hectares*10000,
        #convert to a positive depth of CCU
        ccu_m = ifelse(ccu_prediction > 0, 0, -ccu_prediction),
        #compute the total savings, if the choice was made
        ccu_m3 = conserved_m2 * ccu_m,
        #convert to acre-feet
        ccu_af = ccu_m3 * 0.000810714,
        totalPrice_usd = (acres*conservedFraction) * compensationRate,
      )
    cat("Year", t, ":", length(current_adopter_ids), "adopters\n")
  }
  return(adopters_trace)
}
```