THESIS

ASSESSING THE SALINITY EFFECTS AND ECONOMIC FEASIBILITY OF ON-FARM DESALINATION TECHNOLOGY IN IRRIGATED SEMI-ARID REGIONS

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Kaitlyn Barnes

Department of Civil and Environmental Engineering

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Master's Committee:

Advisor: Ryan Bailey

Suellen Melzer
Sybil Sharvelle

ABSTRACT

ASSESSING THE SALINITY EFFECTS AND ECONOMIC FEASIBILITY OF ON-FARM DESALINATION TECHNOLOGY IN IRRIGATED SEMI-ARID REGIONS

High salinity levels in areas with intensive agricultural practices can inhibit agricultural productivity. Semi-arid regions where irrigation is used to support crop growth are particularly impacted by the quality of surface and groundwater sources. In this study, we use a combined numerical modeling and economic analysis approach to estimate the regional impact of an on-farm desalination technology on multi-decadal salinity fate and transport and explore whether the technology is viable to improve soil health, crop yield, and long-term profitability. A subsurface salt transport model (MODFLOW-RT3D) is applied to a 50,600-ha (125,000 acres) region in southeastern Colorado located within the Arkansas River Valley. The model simulates the reactive transport in soils and groundwater of 8 major salt ions (Ca^{+}, Mg^{2+}, Na^{+}, K, SO_4^{2-}, CO_3^{2-}, HCO_3^{-}, and Cl^{-}). Simulated values of average soil water concentration (TDS) are used to estimate crop relative yield with and without salt removal at various removal rates (Baseline – no salt removed; Unit removal – average of 60% salt removed; 100% salt removal) and time periods (5, 10, 15, 20, 25 years after desalination begins). The Unit removal rate is calibrated to align with a solar powered, reverse-osmosis desalination system that is currently being tested in semi-arid study area. For the Unit rate of 60% salt removal, the average TDS of the study area was found to decrease by an average of 20% over a period of 20 years, resulting in an increase in crop yield of 1.6 – 2.3%. Using data on regional production costs, crop prices, and the costs of building and operating the desalination system, we calculate the Net Present Value of production with the desalination unit. The results indicate that desalination does increase economic returns, particularly for high-valued specialty crops, such as melons and onions; however, these benefits are considerably less than the costs of operating the desalination technology.

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1.INTRODUCTION

High salinity levels in areas with intensive agricultural practices can inhibit agricultural productivity. The demand for increased agricultural production continues to put pressure on finite resources such as soil and water, resulting in unsustainable use and degradation of resources. This is seen in the semi-arid regions of the world using irrigation as a primary means to support crop growth (Tavakoli-Kivi et al., 2019; Barron et al., 2015; Inam et al., 2015; Kaner et al., 2017; Zarzo et al., 2013). There are many causes of resource degradation. In soil and water specifically, intensive irrigation practices such as irrigating with poor quality (i.e., high saline) water decrease land productivity and increases the risk of losing farmland due to this degradation (Kopittke et al., 2019). The salinity of irrigation water has been thoroughly studied and found to negatively impact crop growth and yields by preventing the uptake of water by plants, as well as inhibiting the transpiration and photosynthetic processes occurring on the leaf surface (Munns et al., 2002; Sahab, 2020; Safdar, 2019; Bauder et al., 2004). Sodicity, relating to the salt composition and the proportion of sodium in the water, also has a negative impact on crop growth. One method of quantifying sodicity is by the sodium adsorption ratio (SAR). The SAR impacts the physical properties of soil (Läuchli, and Epstein, 1990). Irrigating with poor quality water causes a transport of salts into the rootzone and into other water sources such as groundwater and surface water due to runoff, leaching, and groundwater return flows. These salts can have a lasting effect on soil, groundwater, and surface water salinity due to the movement of water through the system (Wichelns and Qadir, 2015; Pulido-Bosch et al., 2018; Bouwer, 1987). Salt accumulation is a global challenge that influences all aspects of the environment, including the physical, chemical, and biological properties of soil, all of which are key to soil conservation. In return for non-polluted water and healthy soils, crops can grow to their greatest potential (Sahab, 2020; Shainberg and Letey, 1984).

There have been many attempts at decreasing soil salinity in agricultural areas to improve crop yield. A variety of methods are currently used by producers and serve as temporary solutions to improve the optimization of water use. Not all methods are equal in effectiveness or applicability, but it is necessary to have a variety of options to accompany the diverse cropping systems. One such method is planting deep-rooted perennial plants to reduce salt pollution by decreasing the amount of saline water passing beyond the root zone. This helps lower the water table and prevents salts from accumulating in shallow soil layers (Safdar et al., 2019). The use of fertilizer can also be used to balance the available nutrients in soil by increasing the concentration of macronutrients (N, P, K and Ca) needed by the specific crop. Planting salt tolerant crops is a method suggested by Safdar et al. (2019) and a logical solution many producers use to continue profiting from land without implementing new conservation practices (Safdar et al., 2019; Bauder et al., 2004). This method however, and the development of salt tolerance genotypes, is considered counterproductive in the long run given that fewer sustainable efforts will be implemented to prevent the continued pollution of soils (Kaya and Higgs, 2002; Läuchli and Lüttge, 2002). Out of all methods used to reduce soil salinity, leaching is the most widely adopted, highly effective, and commonly used (Abrol et al., 1988, Section 3.2.1; Kaya et al., 2002; Bauder et al., 2004). Leaching is a method of applying more water than the plant needs so that salts can be moved below the root zone (Bauder et al., 2004; Hoffman and Genuchten, 1983). According to Hoffman and Genuchten (1983) if the leaching requirement is met then the correct amount of water is applied to prevent salt buildup, keeping the soil root zone salinity lower than the crop threshold. If salinity is above this threshold there will be a decrease in crop yield (Hoffman and Genuchten, 1983; Letey, 1993) This leaching fraction is calculated to limit salt storage and prevent drainage (Dudley et al., 2008). Unfortunately, while this common practice helps eliminate salinity issues in the root zone, if not managed correctly, it can worsen the salinity pollution in groundwater and other water sources (Wichelns and Qadir, 2015; Pulido-Bosch et al., 2018; Bouwer, 1987). While removing salt from the crop root zone is an effective method, it is a temporary solution to increasing soil salinity (Safdar et al., 2019) and other desalination techniques have drawn more attention in the recent years.

On-farm desalination is a technique that can be used on a small scale to remove salt from irrigation water. Small scale desalination technology for agriculture was used as early as the 1970's when the first desalination plant in Spain was installed to desalinate brackish water (Zarzo et al., 201). The systems are designed using a variety of filtration technology including reverse osmosis (RO), forward osmosis (FO), membrane distillation (MD), pervaporation (PV), and solar desalination such as distillation (Burn et al., 2015). Energy costs for these systems can be high but can be minimized by using renewable energy sources such as wind and solar, especially for remote areas (Burn et al., 2015; Acevedo et al., 2020; Chaibi, 1999). According to Burn et al. (2015) other contributors to decreasing cost include proximity to irrigated fields, using existing infrastructure for water distribution, blending processed water with source water (Zarzo et al., 2013) and utilizing discharged salt brine.

Desalination technology for agricultural systems has been employed in areas of Spain, Australia, Oman, the United States, and Italy, to name a few of the key regions. Spain was one of the earliest adopters of the technology and is currently a leader in municipal and agricultural water desalination (Zarzo et al., 2013; Quist-Jensen et al., 2015). According to Al Jabri et al. (2019) two communities in Spain have farmers' associations that built RO desalination plants for crop irrigation. The Nijar Brackish Water RO desalination plant in Almeria has a capacity of 25,000 m^3/d and serves 2,400 farmers with a total irrigated area of 8,400 hectares (ha). The Cuevas de Almanzora brackish water RO desalination plant in Almeria has a capacity of 30,000 m^3/d and serves 1,800 farmers with a total irrigated area of 5,800 ha. Each plant is built and run in cooperation with the local government. The irrigation water used on the farm is mixed with water from other sources such as harvested rainwater, surface, and ground water, and is used mainly to irrigate tomatoes, lettuce, cucumber, and melons. The use of desalination technology is historically beneficial to the farmers in Spain because of the well-established marketing schemes and infrastructure, including their larger sized desalination plants to supply agriculture water.

On the contrary, Oman's desalination systems are less feasible according to Al Jabri et al. (2019) because they are utilizing small desalination units on crops that are less profitable. Hundreds of farmers utilized the small-scale RO units and communicate individually with vendors. There are many options moving forward to optimize their system including mixing desalinated water with lower quality water to irrigate high-value crops, but further work is needed in Oman for this development (Al Jabri et al., 2019). A study done by Barron et al. (2015) assessing the suitability of desalination in Australia suggests that given the accessibility and reliability of the water source, the use of groundwater for desalination is the most feasible option for on-farm desalination. The Department of Primary Industries and Regional Development (Government of Western Australia) has a publication with resources for farmers who are interested in implementing desalination technology. Resources include details on select membrane technologies, regulations for farm water supply, and general guidelines for determining farm suitability among other resources. A variety of methods are being researched and used in Italy to counteract rising water scarcity. As for Malta, Italy, a case study focused on the use of desalination technology on the island has been completed by Aparicio et al. (2018). The study considers using RO filtration, a deep well for source water, and a pumping rate of 160 m^3/day. Malta consists of mainly dryland agriculture except for the vineyards which are irrigated. It was concluded that desalination was profitable for land with a minimum area of 1 ha of grape production that was already developed with built infrastructure and irrigation systems. Desalination was the best option compared to using treated water which is common throughout Italy (Lopez et al., 2008; Massarutto, 2000) because of the small amount of water needed to irrigate vineyards (Aparicio et al., 2018). As water scarcity persists, agronomic and environmental benefits of desalination are driving interest in the technology worldwide.

While there are many benefits of on-farm desalination technology, drawbacks include energy costs, capital and maintenance costs, spatial coverage of small units, and the discharge of brine output from the filtration system. According to the review of Burn et al. (2015) and the studies of Al Jabri et al. (2019), Aparicio et al. (2018), Kaner et al. (2017), Bales (2021), Barron et al. (2015), and Zarzo et al. (2013), the cost of desalinating water for agriculture in many cases is most economical for high value crops. A few examples of high-value crops include vegetables, flowers, ornamental and horticultural plants, fruits, grapes for wine production, parsley, greenhouse-grown strawberries, and nut trees. Technology adaptation in urban areas is already seen as feasible, given the population growth and higher benefit/cost ratio. The diminishing availability of high-quality surface and groundwater in densely populated areas may further encourage development. In addition, the technology has shown to be profitable for high-value crops that are sensitive to salinity. According to Kaner et al. (2017) desalination water used for high-value crops is justified for current market prices when using mid-to-large-scale plants (>1 MCM/yr or 811 AF). A variety of desalination technologies have been assessed by Burn et al. (2015) to understand which best suits specific environments, salinity level, and price range but a knowledge gap still lies in understanding the spatial and temporal impact that on-farm desalination has on soil water and groundwater salinity in a regional agricultural system. Furthermore, there is a need to understand the feasibility of such technology for individual producers and the costs and benefits associated with implementation.

The objective of this study is to explore the regional effects of on-farm desalination in an irrigated semi-arid region and provide guidance on economic viability of the technology. This objective is accomplished through use of numerical groundwater modeling and a cost-benefit analysis (CBA). The coupled groundwater flow and salinity transport model MODFLOW-RT3D is applied to a 500 km^2 region in the Lower Arkansas River Valley, Colorado, to quantify the regional system effects (soil salinity, groundwater salinity, crop yield) of removing salt from irrigation water over a forecasting period of 25 years. Salt removal amounts from irrigation water were used from a research-based desalination unit, operated in Alamogordo, New Mexico to achieve realistic removal amounts for on-farm desalination (Acevedo et al., 2020). In addition to Unit removal, Baseline (no salt removal) and Total (100%) salt removal were also simulated. Two scenarios were considered to understand the impact of applying desalination. The first scenario applied desalination to all fields in the study area, simulating salt removal over the entire region. The second scenario looked at applying desalination to only 28 fields in the study region, selected based on the presence of a shallow water table, which often results in elevated soil salinity and consequent crop yield reduction. Agronomic factors including crop root depth and growth stage were used to set simulation parameters and analyze data in a manner useful to agriculture producers. The CBA includes capital and operational costs of implementing desalination technology, profit values account for crop production profits using Otero County, Colorado agronomic data.

2.METHODS AND MATERIALS

Various methods were used to quantify system effects of removing salt from irrigation water. One method was using the coupled MODFLOW-RT3D groundwater flow and salinity transport model to simulate the system effects of removing salt from irrigation water on soil salinity, groundwater salinity, and crop yield. The second method was an economic analysis performed by using a cost-benefit analysis (CBA) to explore the viability of using on-farm desalination technology in a semi-arid irrigated system. To both prevent and address salinity issues, models can be used to simulate future salinity and economic conditions, providing information that can be used to advise stakeholders on best management practices and guide technological advances.

2.1 Study Region

Numerical modeling and the CBA were applied to the Lower Arkansas River Valley (LARV), an agricultural region in southeast Colorado. The study area (Figure 1) is in Otero County with a small percentage of the eastern section in Bent County. From a regional outlook, 11% of Otero County is cropland and the remaining 88% is pastureland (with 1% other). Results from the 2017 Ag Census show that out of the 687,530 farm acres in the county 49,291 acres are irrigated.[1] According to the Annual Statistical Bulletin for Colorado[2] the southeast region of the state, encompassing the study area, is a principal producing district for barley, corn, sorghum, winter wheat, cabbage, cantaloupe, onions, and sweet corn. In addition to these crops, alfalfa, pastureland, spring grain, bean, pumpkin, squash,

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[1] https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Colorado/cp08089.pdf

[2] https://www.nass.usda.gov/Statistics_by_State/Colorado/Publications/Annual_Statistical_Bulletin/Bulletin2020.pdf

sunflower, and other vegetables have historically been grown in the region and were included in the model for the respective year and location grown (Tavakoli-Kivi et. al., 2019).

The model boundary specifically encompasses an area of 125,000 acres. The climate is semi-arid with a normal annual precipitation of 13 inches/year.[3] Fields are irrigated using sprinkler, drip, and flood irrigation, flood being the most predominant method in the study area. The water source is either surface or groundwater, with the latter using a network of pumping wells (see locations in Figure 1, black dots). (Morway et al., 2013). Surface irrigation water is diverted from the Arkansas River through a series of canals (see Figure 1, orange lines) and is regulated in compliance with Colorado water law (Morway and Gates, 2012). Groundwater levels are generally shallow (< 2-3 m below ground surface; Morway et al.,

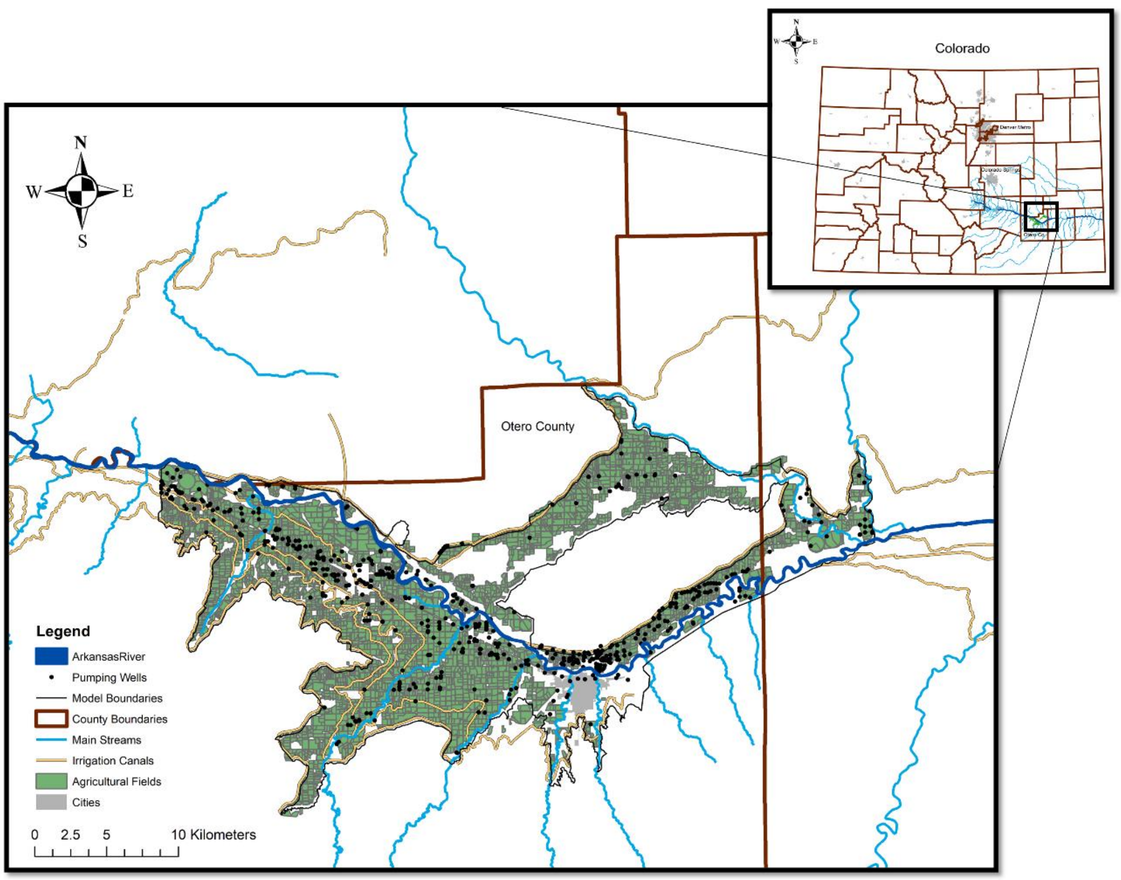

Figure 1. Location of model study region, showing the Arkansas River and its tributaries, main irrigation canals, agricultural fields, and pumping wells.

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[3] https://climate.colostate.edu/normals/p_annual_norm.html#

2013), leading to 1) up flux of groundwater salts to the soil profile, and 2) high rates of groundwater discharge and associated salt mass loading to the Arkansas River and its tributaries.

2.2 Groundwater Flow and Salinity Transport Modeling with MODFLOW and RT3D

MODFLOW (Harbaugh, 2005; Niswonger et al., 2011) and RT3D (Clement et al., 1997) are used in this study to simulate soil water and groundwater storage, soil water and groundwater flow, groundwater discharge to streams, and salt ion transport in soil and groundwater. MODFLOW is a computer program that solves the groundwater flow equation for groundwater head in time and space (*x*, *y*, *z* directions), subject to aquifer properties (hydraulic conductivity, specific yield) and subsurface sources and sinks (infiltrating water, pumping, canal recharge, groundwater-surface water exchange). MODFLOW uses a grid of cells, applied to the study aquifer, to solve the equation, with a water balance equation written and updated through time for each cell in the grid. RT3D is a computer program that solves the groundwater solute mass balance equation for solute concentration in time and space, subject to aquifer properties (longitudinal dispersivity), groundwater flow rates (provided by MODFLOW), groundwater sources and sinks (provided by MODFLOW), solute concentration of groundwater sources and sinks, and chemical reactions. RT3D uses the same grid cells as employed by MODFLOW, with a solute mass balance equation written and updated through time for each cell in the grid. Originally applied only to saturated areas of an aquifer, the RT3D code was updated by Bailey et al. (2013) to include solute transport variably saturated systems, i.e. soil systems. This version of code requires the use of the Unsaturated Zone Package (UZF) (Niswonger et al., 2006) of MODFLOW, to provide vertical flow rates and volumetric water content in the unsaturated zone (i.e. root zone and soil profile). The resulting advection-dispersion-reaction-mixing equation for the updated RT3D code is:

$$\frac{\partial\left(C_k\theta\right)}{\partial t}R_k = -\frac{\partial}{\partial x_i}\left(\theta v_i C_k\right)+\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C_k}{\partial x_j}\right)+q_f C_{f_k}+\theta r_f-\rho_b\frac{\partial\overline{c}_k}{\partial t} \qquad k=1,2,...,m \qquad (1)$$

The term on the left-hand-side of the equation denotes changes in mass storage; the terms on the right-hand-side of the equation denote advection, dispersion, groundwater sources and sinks, chemical reactions, and sorption, respectively. This equation is written for each solute in the soil-groundwater system, and for each cell of the grid. C_k and C_l are the concentration of the k^{th} dissolved-phase solute [$M_f L_f^{-3}$], with f denoting the fluid phase; D_{ij} is the hydrodynamic dispersion coefficient [L^2T^{-1}];v is the velocity of groundwater (provided by MODFLOW) [$L_b T^{-1}$] with b denoting the bulk phase; θ is the volumetric water content [$L_f^3 L_b^{-3}$]; q_f is the volumetric flux of water representing sources and sinks [$L_f^3 T^{-1} L_b^{-3}$] such as irrigation water, canal and seepage, groundwater discharge to the river, or pumped groundwater; C_f is the concentration of solute in the source or sink water [$M_f L_f^{-3}$]; r_f represents the rate of the reactions that occur in the dissolved phase [$M_f L_f^3 T^{-1}$]; R_j is the retardation factor for species j and denotes solute sorption; ρ_b is the bulk density of the porous media [$M_b L_b^{-3}$] and K_{d_j} is the partitioning coefficient for the jth species [$L_f^{-3} M_b$]; $\overline{c}_k$ is the total solid phase concentration of aqueous species k.

The RT3D code of Bailey et al. (2013) was further updated by Tavakoli-Kivi et al. (2019), who modified the code to include the salinity equilibrium chemistry (SEC) module, which simulates the fate and transport of eight major ions (Ca^+, Mg^{2+}, Na^+, K, SO_4^{2-}, CO_3^{2-}, HCO_3^-, and Cl^-) in irrigated systems. The SEC includes the eight ions, ten complexed species, and five solid species (i.e. salt minerals: $CaSO_4$, $CaCO_3$, $MgCO_3$, NaCl, $MgSO_4$), subject to precipitation-dissolution reactions of salt minerals, aqueous complexation, and cation exchange. The concentration of the eight ions at equilibrium is determined using a stoichiometric approach of solving mass balance and mass action equations. For the chemical transport of the eight ions in the soil and groundwater system, Equation (1) is written and solved for each of ion, for each cell of the grid, for each time step of the simulation period. Please see Tavakoli-Kivi et al. (2019) for more details on the SEC module. This new version of RT3D is termed RT3D-Salt and will be referred to as such throughout the remainder of the manuscript.

2.3 MODFLOW-RT3D Simulations for the Study Region

2.3.1 Overview of Models

In this study, the calibrated and tested MODFLOW model (Morway et al., 2013) and RT3D-Salt model (Tavakoli-Kivi et al., 2019) of the study region are used to explore the effects of desalination technology on soil salinity, groundwater salinity, and crop yield. Results for estimated crop yield are used to perform a cost-benefit analysis to explore the economic viability of these systems. The MODFLOW grid consists of grid cells 250 m by 250 m (~15.5 acres, the approximate size of a representative cultivated field in the study region), resulting in a grid with 127 rows and 213 columns (see Figure 2). Subsurface sources and sinks consist of infiltrating water from rainfall and irrigation (canal water and pumped water), evapotranspiration (ET) of crops and natural vegetation, groundwater pumping from irrigation wells, seepage from earthen canals, groundwater discharge to the Arkansas River and its tributaries, and seepage from the Arkansas River and its tributaries. The model was tested against groundwater head observed from a network of monitoring wells, groundwater return flows to the Arkansas River, and crop ET (Morway et al., 2013).

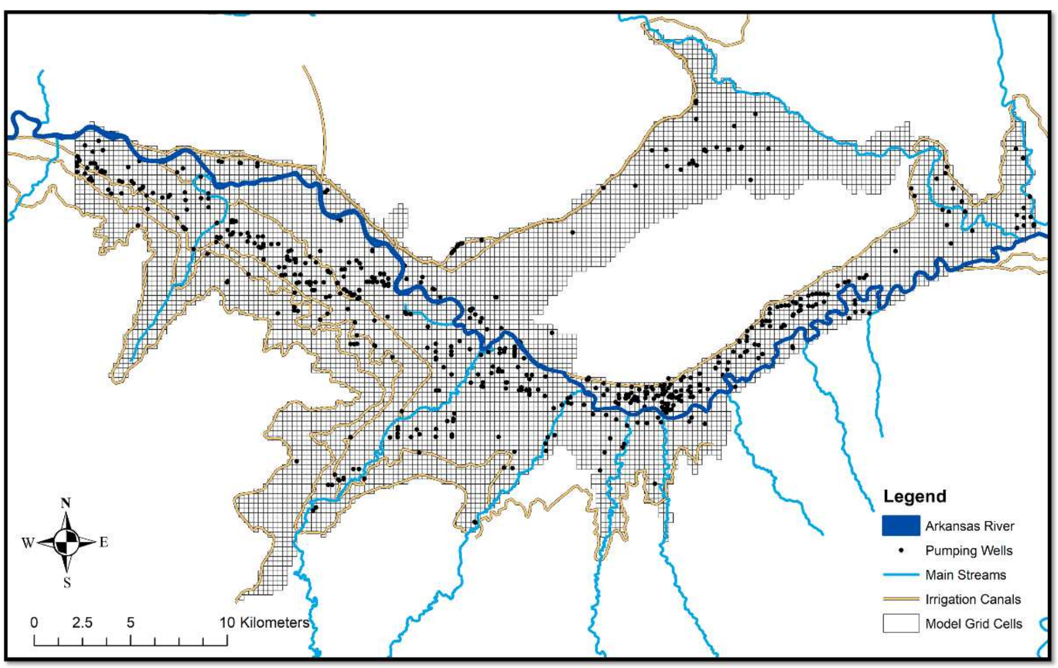

Figure 2. Location of model study region showing the model grid, stream network, irrigation canals, and the location of pumping wells.

The RT3D grid is the same as that used for MODFLOW. Salt ion mass sources and sinks consist of irrigation water, pumping, canal seepage, and groundwater-surface water interactions, for each concerned grid cell. Salt ion mass also changes due to groundwater transport (advection), dispersion, and chemical reactions (see Equation 1), such as precipitation-dissolution, complexation, and cation exchange. As grid cells in the model contain parcels of land from various fields, the model accounts for the different crop types planted throughout the cell by determining the percentage that each crop covers for an individual grid cell. The model was tested against soil salinity from irrigated fields and groundwater salt ion concentrations observed from the network of monitoring wells (Tavakoli-Kivi et al., 2019) for the 2006-2009 time period. The MODFLOW model uses a weekly time step, whereas the RT3D-Salt models use a daily time step, to update cell values.

Salt ion concentrations in irrigation water are derived from two sources: canals, in which the concentrations are specified based on data from water sampling; and groundwater, in which the concentrations are simulated by RT3D-Salt and hence update daily within the model. As the models are applied in this study to quantify the effect of desalination technology, the RT3D-Salt code was modified to handle various reductions in irrigation salt ion concentrations.

2.3.2 Simulation Scenarios

The MODFLOW and RT3D-Salt models were run for a 25-year forecast period and results were used to evaluate 1) decreases in soil salinity and associated crop yield, and 2) groundwater salinity. Groundwater salinity is included due to its effect on soil salinity through groundwater pumping for irrigation. Groundwater salinity can also affect downstream irrigation users, as groundwater discharges water and loads salt ion mass to the Arkansas River. Simulated soil salinity is used to estimate the relative impact on crop yield using the relative yield equations of Maas (1993). To do this, simulated salt ion concentrations in the root zone (0-1 m below the ground surface) were summed to determine a concentration of total dissolved solids (TDS) (mg/L) for each grid cell, which was converted to a value of electrical conductivity (EC) (dS/m) using TDS-EC relationships from sampled groundwater in the region

(Bailey et al., 2019). The EC of soil water was then converted to a saturated paste EC (EC_{sat}) using the simulated water content from the MODFLOW simulation and specified porosity of each grid cell. The EC_{sat} values were then used as an input variable in calculating crop relative yield using the crop-specific equations from Maas (1993) (Tanji and Kielen, 2002). More details are provided in Section 2.3.5.

Two scenarios were considered when analyzing data: (1) removal of salt from all irrigated fields in the region and (2) removal of salt from only 28 fields. Scenario 1 is simulated to provide an end-member analysis, whereas Scenario 2 is simulated to provide a more realistic adaptation of the desalination technology and determine effects of on-farm desalination on nearby fields. To determine the 28 fields to select, 7 cross sections were delineated based on water table gradients simulated in Morway et al. (2013), to attempt to capture the movement of salinity, and thereby the effects of desalination on salt leaching, along groundwater flow paths. These cross-sections are shown in Figure 3 and are evenly spaced running along the Arkansas River following the gradient from high to low water table elevation

Figure 3. Spatial view of the 7 cross sections used in Scenario 2. Each cell within the cross section is outlined in black, cells with desalination applied are highlighted in teal (blue). Agricultural fields in the study region are outlined in green.

and adjoining perpendicular to the river. For Scenario 2, desalination was applied to the four fields with the highest groundwater elevation in each cross section (see highlighted cells in Figure 3). Each scenario was designed to help understand possible best-case scenarios for soil health, crop yield, and downstream irrigation users.

2.3.3 Time Step Information

Simulations were run on a daily time step to get the monthly average in July for soil water salt ion concentrations. The original RT3D-Salt model of Tavakoli-Kivi et al. (2019) runs for the period 2006-2009. Given this time-period, 2006 was determined as year 1 and the model cycled through 2006-2009 data to simulate a 25-year forecast. The monthly average was determined using data from 5 days out of the month of July, each sample day being 7 days apart. Data were analyzed for years 5, 10, 15, 20, and 25. This time-period is specific to the time of the growing season given that plants are more effected by salinity at certain growth stages. The period was decided on by considering the growth curve for crops and choosing the point of highest yield potential when foliage was at its peak. The peak period of irrigation was also considered given that July is typically the driest month in the Arkansas Valley region, with consequent heightened irrigation.

2.3.4 Soil Parameters

The model discretized the soil and aquifer system using 6 layers. The top two layers, representing the root zone, are 0.5 m in thickness, and the third layer is 1.0 m in thickness. The thicknesses of layers 4-6 are divided evenly over the remaining aquifer depth to the bedrock (Tavakoli-Kivi et al., 2019). Average root depth of crops, specifically of those crops considered in the model and grown in the region, was used to determine how many layers to consider when analyzing soil water concentration. Based on NRCS data for effective root zone depth, the top two layers, or 1 m of soil, were considered. Effective root zone depth is the top 50% of the root zone (USDA, 2005). When analyzing soil water concentration in Scenario 1, layers 1 and 2 were averaged. In Scenario 2, layer 4 was used to analyze salt concentration in groundwater, and this layer typically represents the zone of shallow groundwater in the region.

2.3.5 Relative Yield

Relative yield (Yr) was calculated to understand how crop performance would change when the growth limiting factor of water salinity decreased with the removal of salt from the irrigation water. The relative yield is a helpful index to understand the growth potential for each crop, given the competition that is imposed by saline conditions. Converting TDS to EC is necessary to calculate crop relative yield. A conversion factor [TDS (mg/L) / 1020] (Bailey et al., 2019), based on relationships between TDS and EC_w using salinity analysis results from hundreds of groundwater samples, is used to determine soil water EC_w (dS/m). The concentration calculated by the model is for a variably saturated groundwater system and therefore needs to be converted to EC_{sat} to be used in the relative yield equations. EC_{sat} is calculated using the porosity (θ_s) and water content (θ) of each grid cell. In the model, porosity is specified for each grid cell in each layer and is assumed to not change with time. In Scenario 1 the porosity values for soil layers 1 and 2 were averaged. Water content is simulated by the MODFLOW model, using the UZF package, and therefore updated at each flow model time step. To calculate $EC_{sat,}$ water content was divided by porosity and then multiplied by EC_w [$EC_{sat} = EC_w\ (\theta/\theta_s)$]. EC_{sat} is then input into the relative yield equation [$\mathrm{Yr} = 100 - \mathrm{b}(\mathrm{ECw} - \mathrm{a})$] (Maas, 1993; Tanji and Kielen, 2002) along with the crop threshold *a* and slope *b* specific to each crop type. Due to the high content of gypsum ($CaSO_4$) in the soils of the study (Tavakoli-Kivi et al., 2019), crop salinity threshold values were adjusted per USDA's recommendation for gypsiferous soils by adding 2 dS/m to each threshold value *a* provided by the source. Outlier data points were removed from all TDS and EC_{sat} data sets for Scenario 1 before performing analysis due to the outlying data's impact on regional averages. The range of EC_{sat} outliers includes simulated values greater than 40 dS/m. This value was chosen based on outlying data from a box plot for each time period and salt removal condition.

In the model, 2007 historical data was used for field-by-field crop type because the data available was more thorough than other years. Salinity threshold and slope values for each crop were based on data from the U.S Salinity Laboratory (Maas, 1993; Tanji and Kielen, 2002). Salinity threshold values for each crop indicate the salinity at which a crop can grow without resulting in a yield reduction. The slope of the fitted line indicates the severity of yield reduction - the greater the slope the more detrimental the impact of the salt on crop yield. If the specific crop being used in the model was not listed in the reference data a similar crop was used to perform the simulation accurately. Some of these estimates required choosing a specific crop variety, others simply required choosing a crop with comparable traits and growing requirements. Threshold and slope values, and specified crops selected were the following: Alfalfa (4, 7.3); Bean - common bean (3, 19); Corn - forage corn (3.8, 12); Melon - muskmelon (3, 8.4); Onion - bulb onion (3.2, 16); Pasture - tall fescue (6, 5.3); Pumpkin - scallop squash (5.2, 16); Spring Grain - wheat and barley (9,7); Squash - zucchini (7,10.5); Vegetable - pepper (3.5,14); Winter Wheat - wheat (8, 7.1). Figure 4 shows a graphical representation of EC_{sat} vs. Yield, for alfalfa, bean, corn, onion, sorghum, sunflower, and winter wheat. The relative yield can be used to calculate the actual yield, based on historical data or field trial data, by multiplying a crop's maximum yield potential by the relative yield percentage [maximum yield potential x relative yield = actual yield potential]. This is beneficial when

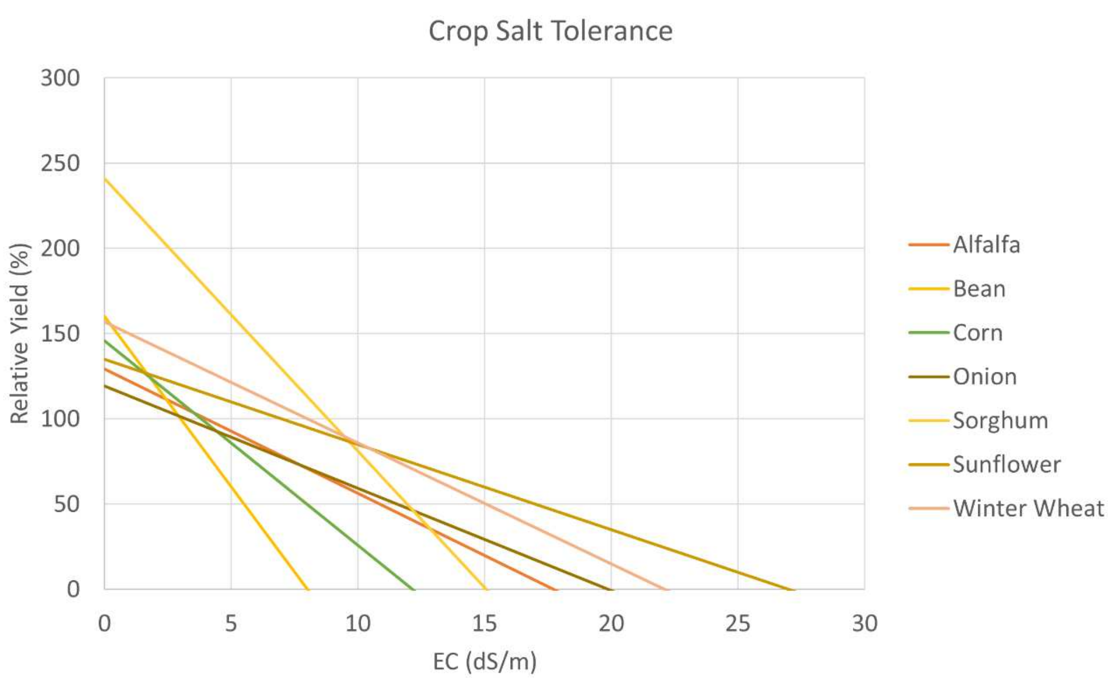

Figure 4. Crop salt tolerance based on EC (dS/m) and the relative yield (Yr). the relative yield equation from Maas (1993) was used along with incremental EC values, and the specific threshold and slope for each crop.

seeking to understand how yield will change with varying sustainability efforts such as removing salt from the irrigation water.

2.3.6 Salt Removal Amounts

Salt removal amounts were based on three different conditions as seen in Table 1. The first being no salt reduction, resulting in baseline values. Baseline values were considered the reference point for system conditions. Secondly, unit reduction refers to % reductions that likely will occur in on-farm scale desalination unit, based on experimental conditions at a site in Alamogordo, New Mexico where ion concentration values (mg/L) were recorded for source water (groundwater well) and for the desalinated water. Calcium (Ca^{+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K), sulfate (SO_4^{2-}), and chloride (Cl^{-}) were individually recorded (Acevedo et al., 2020). Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^{-}) were not recorded so the unit removal amount for these two ions was based on average values found for the 6 other ions. Salt removal amounts were chosen strictly for modeling purposes and will change based on desalination technology used, quality of source water, and other design and environmental factors. The third condition considered was removing 100% of the salt. Total removal of salt is not realistic for desalination units in the field, but this scenario is used to understand best case scenario or maximum impact.

Table 1. Percentage of salt removed from irrigation water for each removal amount considered.

	Percent of Salt Reduction		
Salt Ion	**Baseline (% removal)**	**Unit (% removal)**	**Total (% Removal)**
Ca	0	70	100
Mg	0	65	100
Na	0	70	100
K	0	50	100
SO4	0	65	100
CO3	0	50	100
HCO3	0	50	100
Cl	0	40	100

2.4 Economic Analysis

A cost-benefit analysis was performed to understand the monetary amounts associated with purchasing and using an on-farm desalination unit and its derived benefits of crop yield increase. The on-farm desalination unit being considered was that from Acevedo et al. (2020) in Alamogordo, New Mexico. This unit has the capability to irrigate about 1 acre throughout the growing season assuming an irrigation application amount of 20-24 acre/in for the study region in Otero County, Colorado. Analyses were carried out using Otero, County crop yield averages and acreage planted for each crop in the 500 km^2 study region. Using CSU Extension's Crop Enterprise Budgets[4], sale price and production costs were determined for years 2016-2020, for each of the ten crops (alfalfa, beans, corn, melon, onion, pasture, sorghum, spring grains, sunflower, vegetable). Total production costs are comprised of variable and fixed costs. Variable costs include costs associated with pre-harvest (tillage, fertilizer, herbicide, insecticide & fungicide, irrigation water assessment & labor, fuel, crop insurance, repairs & maintenance) and harvest (swath – 4 cuttings, rake (1/2 of all cuttings), bale (4x4 large bales), hauling), which varies as the quantity of goods produced changes. Fixed costs are defined as the general farm overhead which are expenses that cannot be tied to a single farm enterprise or commodity (e.g., equipment rental or storage costs, salary-based payments, subscriptions and dues, accounting and legal fees, liability insurance, etc.) (NRCS). 2007 crop cover data was used in the model while prices and costs were from 2017. We know that the growers switch crops during these years to maximize profit, but it has been assumed in the model that crops stay the same throughout the 25 years, so the same was done for the economic analysis.

The cost of the desalination unit includes capital and annual costs. The values used were for one desalination alternative, reverse osmosis (RO) technology. Capital costs are the following: material, labor to build and install, evaporation pond for concentrate disposal, renewable energy components, and labor to build and install system. Annual costs are the following: supplies and parts, replacement parts (5 year

[4] https://abm.extension.colostate.edu/enterprise-budgets/

prorated annually), unexpected replacement/repair parts (10% of capital cost), labor operation and maintenance.

2.4.1 Cost and Benefit Calculations

The following calculations were performed to determine the benefits and costs associated with on-farm desalination in respect to the yield change due to removing salt. Total benefits were calculated by multiplying the sale price by the quantity produced, by the relative yield (%), for a single cell and year. Sale prices for individual crops were taken from CSU Extension Enterprise Budgets. These prices are specific to Otero County Colorado and would vary for different market locations and years. Relative yield values were derived from model simulations as explained in Section 2.3.5. The quantity produced is the Otero County yield averages from the 2017 Census of Agriculture. Benefits are calculated as:

$$B_{it} = P * Q_{it} * Yr_{it} \quad (2)$$

where:

B = total benefits
P = sale price for specific crop
Q = quantity produced
Yr = relative yield
i = cell
t = year

Total costs were calculated by multiplying the variable costs by quantity produced, by relative yield and then adding the fixed costs, or general farm overhead, to this. Variable cost includes production costs for individual crops.

$$C_{it} = (VC * Q_{it} * Yr_{it}) + FC \quad (3)$$

where:

C = total costs
VC = variable costs
Q = quantity produced
Yr = relative yield
FC = Fixed costs
i = cell
t = year

2.4.2 Net Present Value

The net present value (NPV) was calculated to analyze the profitability of the projected investment in the desalination unit over a period of 25 years. A discount rate of 3% was used to calculate the present value of benefits (production profits) and costs. From this, the NPV is determined by subtracting the sum of discounted costs from the sum of discounted profits. In this context, the NPV can be interpreted as the present value of returns that a producer receives from his investment in the desalination unit. Two equations are used to determine the NPV without desalination and with desalination. The difference between the two is that the production profit and desalination cost in the second equation (Equation 5) uses total benefit and total cost values which consider the relative yield change due to salt removal, and the total capital cost of desalination. The first equation (Equation 4) accounts for the production costs and fixed costs associated with crop production in the total cost variable, whereas in the second equation these costs as well as the capital and annual cost of desalination is already incorporated into the production profit and desalination cost variables.

Without Desalination:

$$NPV = \sum_{t=0}^{25} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{25} \frac{C_t}{(1+r)^t} \quad (4)$$

Where:

B = total benefits
C = total costs
r = discount rate (3%)
t = year

With Desalination:

$$NPV = \sum_{t=0}^{25} \frac{Production\ Profit_t}{(1+r)^t} - Desalination\ Cost_0 \quad (5)$$

Where:

Production Profit = $B_{it} - C_{it}$
Desalination Cost = Initial Desalination Cost (Total Capital Cost)

3. RESULTS AND DISCUSSION

As expected, modeling results show that on-farm desalination results in a decrease in soil water salinity and an increase in crop relative yield. The use of desalinated water on one section of land was found to have a beneficial impact on surrounding land not using the technology, as water that is less saline is leached to the water table, carried by groundwater gradients to downstream fields, and then pumped by other users to irrigate crops. A general trend of TDS increasing from year 5 to 25 was seen for the baseline simulation, suggesting that without the use of desalination technology soil TDS concentrations would continue to increase by an average of 217 mg/L every 5 years. Year 10 and 20 were an exception to this trend as they had lower values than the previous years, which likely is attributed to the varying agronomic and environmental factors (i.e., wet year with higher infiltrations) for those specific time periods.

3.1 Scenario 1 – Removal of Irrigation Salt from All Fields

Salinity in the soil-aquifer system of the region decreased with the use of desalination technology for both scenarios. TDS average values for July are shown in Table 2 for each of the salt removal amounts. Figure 5 shows the cell-by-cell results of salt removal from irrigation water, TDS (mg/L), Relative Yield, and % change in TDS from the baseline, for (left maps) unit removal and (right maps) total removal. Overall, changes in the system are more pronounced for the scenario of total removal of irrigation salt vs. the scenario of unit removal of irrigation salt. Most fields in the study region are irrigated with surface water compared to groundwater, and therefore the mass of salt removed in irrigation water is much higher for surface water irrigation than for groundwater irrigation (Figure 5A, B, C, D). The salt mass removed is greatest for fields irrigated with the Catlin Canal and Fort Lyon Canal (red and yellow concentrated areas) with removal amount ranging from 8,000 – 34,000 kg annually. The mass removed from groundwater is substantially less, generally seeing a removal of less than 5,000 kg for both Unit removal of salt and Total removal. The TDS of soil water with Unit removal is generally in the range of 1,000 – 3,000 mg/L and for Total removal decreases to less than 500 mg/L for a significant area. The highest TDS values (> 6,000 mg/L) are mainly concentrated around the streams which flow into the Arkansas River. Percent change from Baseline (no salt removed) to Unit removal is a TDS decrease of about 40 – 60% for the agricultural producing regions. The areas that show no change are mainly the cities or non-agricultural producing land. The percent TDS change (decrease) from Baseline to Total removal is generally between 80-100%, showing about a 20% decrease in TDS between Unit removal and Total removal (Figure 5). There is a noticeable change in TDS throughout the 25 years (Figure 6) were regions more susceptible to higher change are differentiated from those which see a smaller salinity decrease. The July average for Baseline salinity levels shown in Figure 7 exceed 5,000 mg/L for each year. With desalination (100% removal) this level decreases to 3,000 mg/L in year 20. During each year there are unique factors that impact the TDS level (e.g., rainfall, temperature, irrigation quality, crop type, etc.) which contribute to the small fluctuation in values between the years. Although results show neither a linear increase nor decrease from year 5 to 25 there is always a decrease in TDS within each year (Figure 7).

Table 2. Scenario 1 simulated average values for TDS, ECsat, and relative yield for July of each year.

	Baseline (no salt removal)			Unit Salt Removal			100% Salt Removal		
Year	TDS (mg/L)	EC_{sat} (dS/m)	Y_r (%)	TDS (mg/L)	EC_{sat} (dS/m)	Y_r (%)	TDS (mg/L)	EC_{sat} (dS/m)	Y_r (%)
5	5126	2.65	77.31	4484	2.27	78.02	3965	1.97	78.40
10	5264	2.69	77.49	4276	2.13	78.37	3508	1.69	78.87
15	5031	2.75	77.52	3891	2.08	78.45	3095	1.60	78.95
20	5047	2.73	77.51	3799	2.04	78.55	2932	1.47	79.13
25	5544	2.76	77.30	4089	2.02	78.55	3073	1.40	79.13

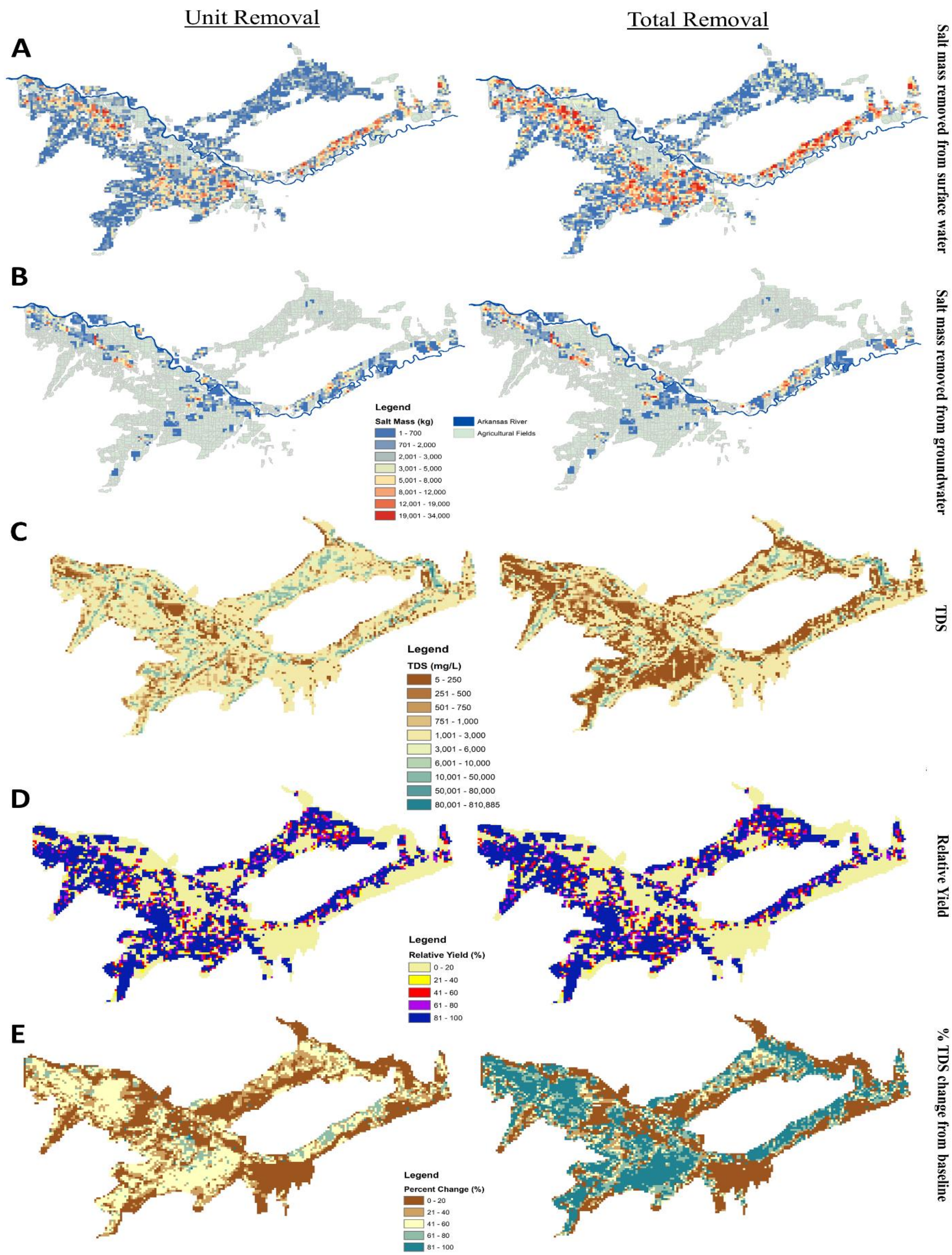

Figure 5. Scenario 1, simulation results for salt mass removed, TDS, relative yield, and percent TDS change from baseline. All values are averages from July of year 25 except for the salt mass removed in (A), values are yearly total.

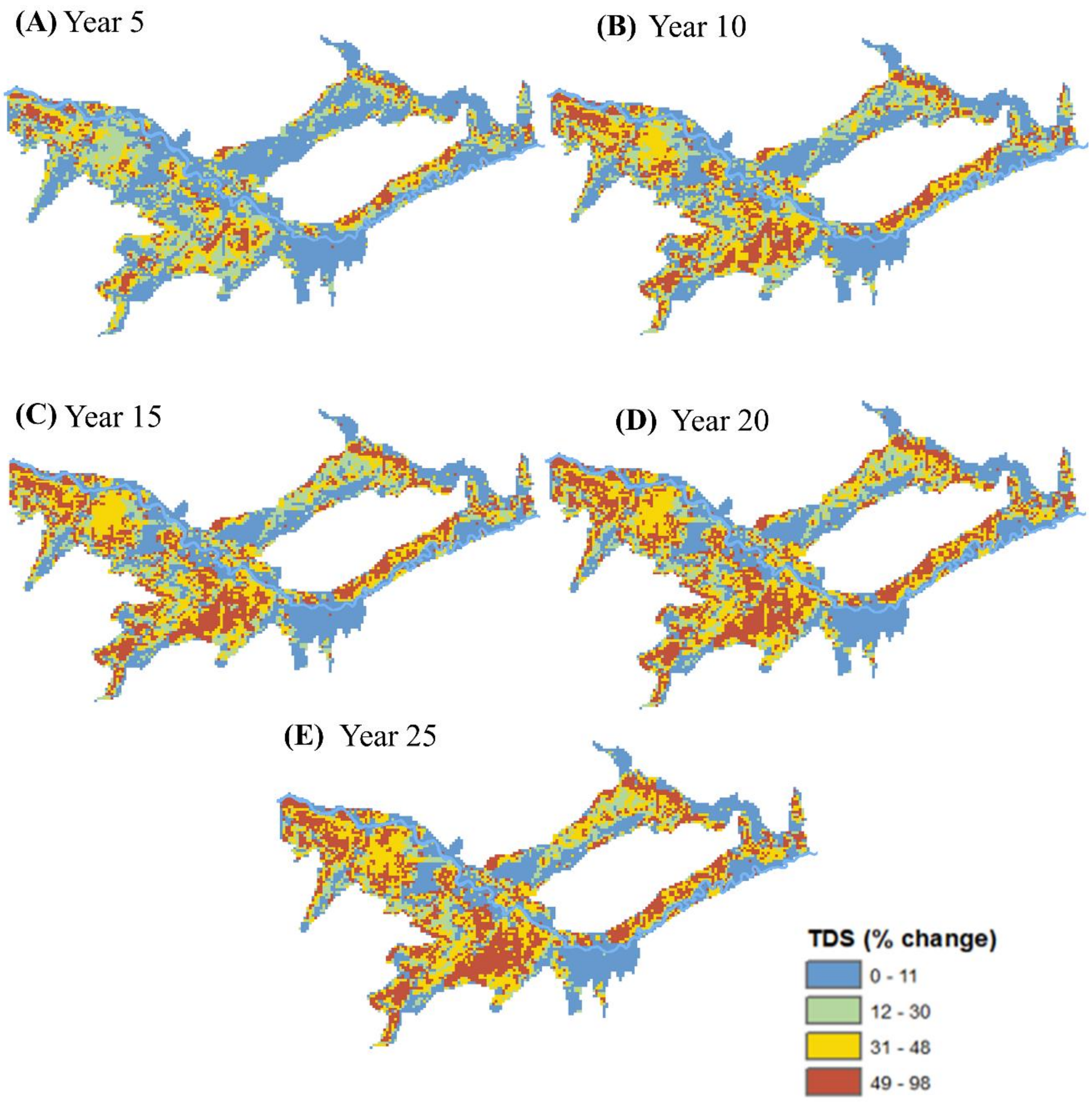

Figure 6. Scenario 1, average simulated percent change of TDS during July of year 5, 10, 15, 20, 25.

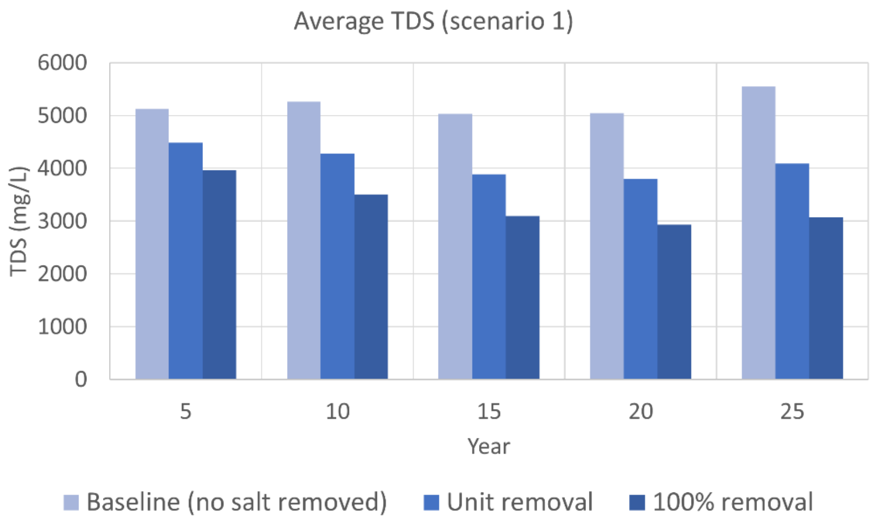

Figure 7. Average TDS for each year based on Baseline, Unit, and 100% (Total) salt removal.

Relative yield increased for each year desalination was applied as seen in the upward trend in Figure 8. Yield increase is the greatest when 100% of salt is removed. The difference between the Unit Removal and 100% Removal is minimal with an average difference of 0.5% for a given year. This slight change is noted in Figure 5 where there are no noticeable changes between the Unit and Total removal graphs. The yearly yield benefit resulting from Unit Removal and 100% Removal were the following: 0.71%, 1.09% (Year 5), 0.88%, 1.38% (Year 10), 0.93%, 1.43% (Year 15), 1.04%, 1.62% (Year 20), and 1.25%, 1.83% (Year 25). A histogram showing the distribution of relative yield for year 25, with Unit Removal, is shown in Figure 9. Over 2500 cells have a relative yield greater than 95%, each cell representing about 15.5 acres. Areas within the study region that have no yield (i.e., uncultivated areas) were not considered in the averages in Figure 8. As the histogram shows there are fields that reach 100% relative yield with desalination - the key to effective implementation of the technology would be to select these locations with maximum yield benefit.

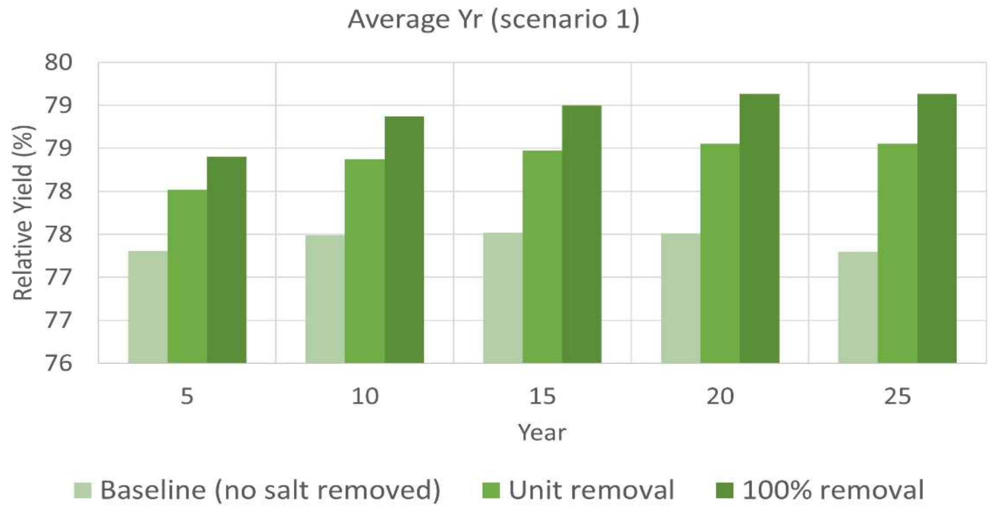

Figure 8. Average relative yield for each year based on Baseline, Unit, and 100% (Total) salt removal.

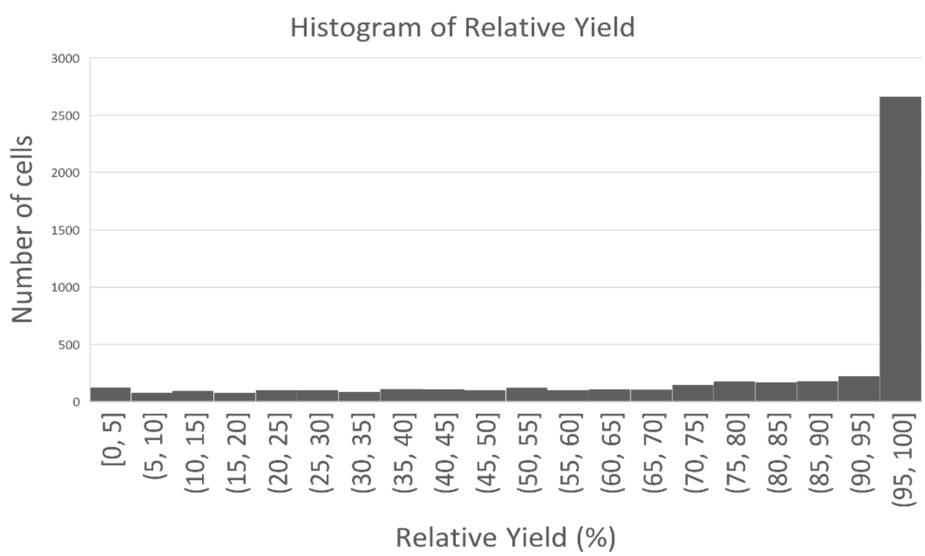

Figure 9. Histogram of Scenario 1, relative yield values for unit removal of salt after 25 years of desalination.

3.2 Scenario 2 – Removal of Irrigation Salt from Selected Fields

Removing salt from 28 fields in the study region resulted in a total salt mass removal of about 2,000 kg for each desalinated cell. A few cells had 8,000 – 12,000 mg/L of salt removed, four of which are irrigated by the Fort Lyon Canal (Figure 10A). The groundwater TDS for much of the region is less than 3,000 mg/L, shown in Figure 10B. The main production areas have lower TDS levels, generally less than 750 mg/L. The TDS % change from baseline ranges from 0-40% (Figure 10D). The locations with greater than a 40% change are cells that specifically have desalination applied or are close in proximity such that groundwater movement could impact the salinity. The regions with 20-40% change show that a significant decrease in TDS of groundwater is seen even for those fields without desalination and that regional salinity decreases with the use of only a few desalination units. Table 3 shows the July averages for TDS in each year for the three salt removal amounts.

There was not a significant change in relative yield for Scenario 2. Generally, relative yield is above 60% with most agriculture land yielding greater than 80%. Table 3 shows the slight increase in July's average relative yield from Baseline to Total removal for all years.

Total Removal

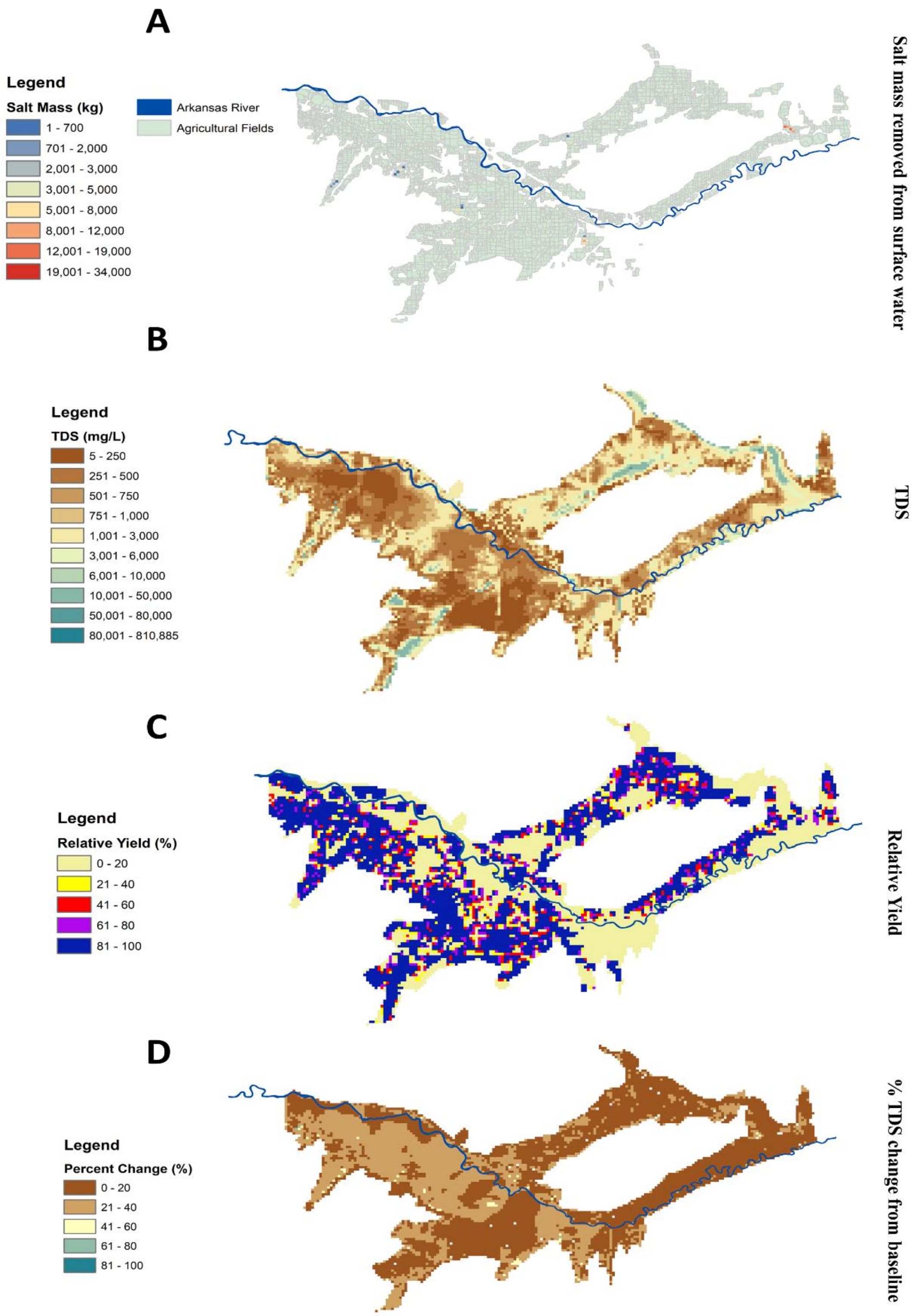

Figure 10. Scenario 2 simulation results for year 25. (A) Total salt mass removed from surface water in year 25. No removal occurred for groundwater (B) Average TDS in July of year 25 (C) Average relative yield for July of year 25. (D) Percent change from baseline.

Table 3. Scenario 2 simulated average values for TDS, ECsat, and relative yield for July of each year.

	Baseline (no salt removal)			100% Salt Removal		
Year	TDS (mg/L)	EC_{sat} (dS/m)	Y_r (%)	TDS (mg/L)	EC_{sat} (dS/m)	Y_r (%)
5	2098	1.61	79.18	1643	1.25	79.52
10	2088	1.58	79.33	1672	1.27	79.63
15	1914	1.61	79.44	1544	1.29	79.69
20	1937	1.58	79.49	1582	1.29	79.71
25	1985	1.56	79.52	1633	1.29	79.71

3.3 Comparison of Scenario 1 and Scenario 2

The primary difference in results from Scenario 1 and Scenario 2 were the salt mass removed and the TDS values. The salt mass removed is correlated with the number of cells that simulated salt removal and for Scenario 2 there were only 28 fields, whereas for Scenario 1 all fields had salt removal. This impacted the TDS values for each. The primary difference when comparing the TDS values is that Scenario 2 quantified TDS for groundwater and Scenario 1 quantifies TDS for soil water in the top 1 meter of the profile. In both cases TDS decreased but values were for different water sources. Soil water and groundwater would both be used by the crop. Groundwater would be pumped from a well and could be directly applied via irrigation without desalination, benefiting from the lower salinity levels. Soil water is a direct measurement of the salinity in the crop root zone. The increase in yield for Scenario 2 was expected to be smaller than values seen in Scenario 1 given that the quantity of salt removed from the system was significantly less when desalination was applied to only a fraction of the fields in the study area.

3.4 Economic Analysis

In the years following implementation of desalination, the producer would receive benefits from desalination in the form of increased production profit from better yields while at the same time paying for the annual costs of repairs and operation on the unit. For purposes of the CBA the length of the desalination implementation period is 25 years. The final NPV is considered as the (sum of) returns (profit) on the investment in the desalination unit, over 25 years. The yearly profits and costs are converted to the present value because we want to know how much profit is being made in each year if the value is converted to today's dollar value.

The capital cost associated with desalination was calculated to be $38,200 with an annual cost of $14,418. The discounted cost for a desalination unit is $289,108 over 25 years and is the same for each crop. The NPV is negative for each crop (Table 4). As shown with this data, the profit from improved yield cannot alone make up for the cost of desalination. The average NPV for onions is (-$216,994) and for a non-high value crop, such as alfalfa, NPV is (-$284,309). These values can be misleading if the improved production profits are not considered alongside NPV.

Table 4. Summary of profit, cost, and NPV for individual crops. The profit values include the yield increase from desalination and the baseline value with no salt removed over the 25-year period of analysis.

Crop	Average Baseline Production Profit ($/acre)	Average Production Profit with Desalination ($/acre)	Desalination Capital Costs ($/acre)	Annual Costs* ($/acre)
Cost of desalination			38,202.00	289,108.10
				NPV ($/acre)
Alfalfa	4,577.42	4,798.81		-284,309.25
Beans	395.23	465.848		-288,642.21
Corn	2,044.83	2,213.17		-286,894.89
Melon	42,030.89	51,417.93		-237,690.13
Onion	66,349.56	72,113.39		-216,994.67
Pasture	56.80	58.00		-289,050.05
Sorghum	2,448.61	2,605.91		-286,502.16

*Note: * Annual Cost is the average present value of desalination annual costs over 25 years period.*
All values are discounted to the present dollar values.

An increase in production profit was seen for all crops with desalination. (Figure 4) Desalination was found to be most profitable for high-value crops (onions, melons), followed by alfalfa, sorghum, and corn (based off $/acre for Unit salt removal). Melon profits increased by $9,387/acre and onions increased by $5,764/acre. Sorghum benefited the least with an increase of only about $157/acre. High-value crops occur least frequently over the entire study area but their value per acre is the greatest.

This analysis does not include environmental or social benefits, aside from what is calculated through yield improvements. The impact of high salinity on soil health, crop diversity, and many other ecological systems are largely non-quantifiable variables. It would be beneficial for producers to consider these in addition to the monetary costs and benefits. We see increased yield from desalination, but the cost of a desal unit is too high for most producers to realize a profit. This is where policy intervention may come in to play for desalination unit installation (e.g., farmer cooperatives, government subsidies, etc.) (Al Jabri et al., 2019), as well as further research to decrease unit costs. We have not considered the cost of relocating salt removed from irrigation water, another cost associated with desalination. As seen from Figures 5 and 9, the mass of salt removed is extreme, and must be deposited through permitting with state or national environmental agencies.

3.5 Comparison to other Studies and Future Avenues

Results from this study are consistent with others, in that high-value crops, melons and onion were the most profitable and resulted in the highest feasibility for desalination. Vegetable and fruit crops were found profitable in Burn et al. (2015), Al Jabri et al. (2019) and Zarzo et al. (2013) with the use of RO desalination technology. Farmers in Spain are currently using desalinated water to grow high value crops but in comparison to the on-farm desalination that was researched in this study, farmers in Southeast Spain rely on desalinated water deliveries from larger plants or communities of irrigators. This scale of production has an impact on the cost that producers pay for desalinated water and the feasibility of technology implementation. The use of Membrane Capacitive Deionization (mCDI) desalination is another type of desalination technology that is most beneficial for high-value crops such as greenhouse grown strawberries (Bales, 2021). RO technology was specifically used in this study to determine salt removal amounts but the benefit of desalinated water on crop growth would be comparable.

Corn is commonly found to be a less feasible crop for desalination and has specifically been noted so in Bales (2021) and Kaner et al. (2017). Forage crops were discussed in Al Jabri et al. (2019) as crops commonly grown by farmers in Oman with low production profits, but specific forage crops were not named. The lack of profit seen in Oman is partly due to the absence of irrigation system cooperation between farmers as well as the lack of market accessibility. The low feasibility of forage crops considered in this study, including alfalfa, sorghum, and corn, were consistent with these studies. Alfalfa and sorghum were specified in this study, in comparison to studies from Bales (2021) and Kaner et al. (2017) which just considered corn as the sole forage crop.

Desalinating irrigation water has been discussed as a necessary technique to supply agriculture with the water quantity and quality needed to support a growing population (Barron et al., 2015) while at the same time improving soil health (Burn et al., 2015). Our study supports the understanding that soil health and groundwater quality are improved through desalination of irrigation water by decreasing TDS. The SAR was not specifically simulated for this study but may also change due to desalination. The SAR for one field plot in the study region was within the range 1.5 – 2.0. The quality of water that infiltrates through the soil profile is known to have an impact on groundwater sources (Wichelns and Qadir, 2015; Pulido-Bosch et al., 2018; Bouwer, 1987). The simulations performed in this study support this correlation between the quality of applied water and groundwater, as we saw a decrease in shallow groundwater TDS when desalination was simulated.

Blended irrigation water is the process of mixing low-quality water with high quality, desalinated water. This process is used to decrease costs and efficiently use available water sources. Acevedo et al. (2020) uses this technique in producing water from the farm-scale desalination unit. The amount of water produced by the unit was considered when determining the acreage that one unit could irrigate and therefore cost savings associated with blending water were included in the CBA calculations in this study. Other studies including Burns et al. (2015), Al Jabri et al. (2019), and Barron et al. (2015), have also concluded that mixing water increases the volume available for irrigation, reduces costs of desalination, and helps with the feasibility of implementing the technology.

Continued research is needed to lower the cost of on-farm desalination technology, as it is not commonly adopted by individual producers (Burn et al., 2015) though is used on a larger scale by government utilities. It is possible to create farmer and government-supported cooperatives to aid in the building and operation of desalination systems, as seen in regions of the world currently utilizing desalination for agriculture purposes (Al Jabri et al., 2019). Understanding the social, economic, and environmental impacts of desalination could help with the adoption of technology, encouraging producers and communities to look at such change for the good of their community and culture. A study performed by Inam et al. (2015) worked to create a framework that included stakeholders from a Pakistani basin in addressing soil salinity problems. To do so, individual stakeholders were made key participants in understanding how different variables in the agriculture system were interconnected by creating Causal Loop Diagrams (CLD) and determining key variables contributing to their salinity issues. All variables fit under one of the following categories: agriculture, social and industrial, environmental, or government influence, and showed the diversity of variables impacting water pollution (Inam, 2015). Using this same concept, a simplified CLD was created for the implementation of on-farm desalination units in Otero County, Colorado (Figure 11). A DPSIR model was used prior to creating the CLD to capture all Demands, Pressures, States, Impacts and Results associated with the use of desalination technology (Figure 12). Interdisciplinary research focused on Food-Energy-Water-Systems (FEWS) shows beneficial results in working through multifaceted problems such as food production, sustainability, and rural development. Using techniques such as CLD’s and DPRIR models would be valuable to ensure effective implementation of desalination technology in the future.

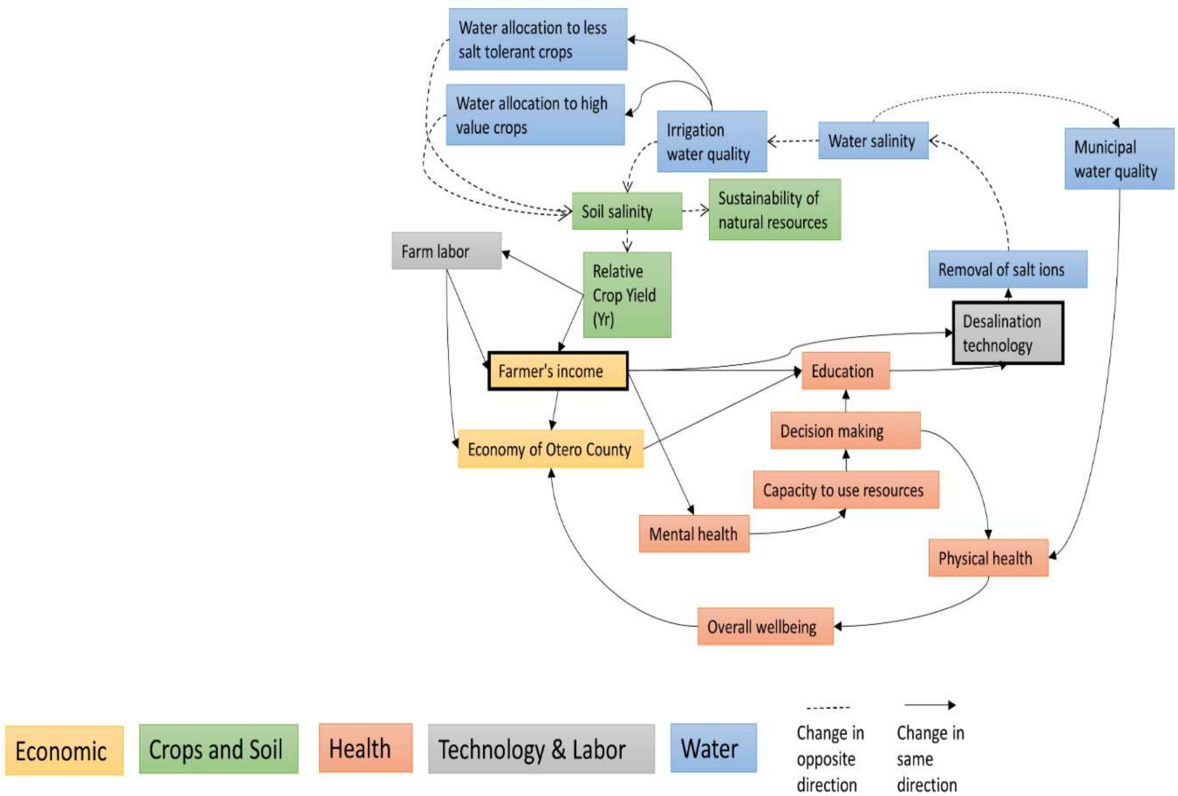

Figure 11. A Causal Loop Diagram showing the interconnected variables associate with implementing on-farm desalination technology in a semi-arid community that relies on agriculture as one of its main industries.

Drivers	Pressures	States (measurable)	Impacts	Responses
Economic : Farmer income and support they offer to the community **Environmental** : Water salination and soil health **Social:** Mental health of farmers **Physical health** of community due to 1. Water quality 2. Food quality and availability	**Resources:** water and soil quality **Technology updates:** need to stay relevant and up to date so operations can compete with local and national markets **Outside demand for water:** purchasing of water rights, buy and dry scenarios	Salinity of water and soil Crop yields Farmer income Soil health Mental health of farmers Conservation methods used on farmland (measure the % of land utilizing methods)	Environmental sustainability Cultural and social wellbeing	Desalination technology implementation Use of government supported programs

Figure 12. DPSIR chart categorizing variables that are either a driver, pressure, state, impact, or response of installing desalination technology in a semi-arid community that relies on agriculture as one of its main industries.

4. SUMMARY AND CONCLUSIONS

This study used a numerical modeling and cost-benefit analysis approach to explore the regional effects of on-farm desalination on soil salinity, groundwater salinity, crop yield, and the overall viability of implementing this technology in an irrigated semi-arid region.

The benefits of removing salt from irrigation water by means of farm-scale desalination resulted in a decrease of soil water TDS by an average of 40% with Total (100%) salt removal, and 20% with Unit salt removal, when considering desalination applied to the entire study region. Trends from the study are comparative to field data collected in the region (Morway et al., 2013). In 2012, EC_{sat} sample values were between 3.4 – 4.6 dS/m where simulated EC_{sat} in this study ranged from 2.7 – 5.5 dS/m for baseline values. Relative yield increased by an average of 2% with the same parameters. Scenario 1 and 2 (Total removal) each resulted in an average salt mass removal of about 4,500 kg, per cell (15.5 acres), for fields irrigated with surface water. The cells selected for Scenario 2 did not contain fields irrigated with groundwater, so no salt mass was removed from this source, but in Scenario 1 about 2,600 kg was removed from groundwater. While the greatest changes in TDS and relative yield were seen in Scenario 1, the most notable conclusion from Scenario 2 is that implementing desalination in only 28 cells resulted in an average decrease in TDS of 390 mg/L across the study area when considering Total removal. This is approximately a 20% decline compared to a 40% decline seen in Scenario 1. These benefits are seen as early as 5 years after the adoption of technology and continued to improve through year 25.

Production profit increased for all crops (onions, melons, alfalfa, corn, sorghum, beans, pasture) with specialty crops such as melons and onions showing the highest profit. Melon profits increased by about 22% and onions by about 9%. While production profits increased, the NPV for all crops was negative due to the high capital ($38,200) and annual ($14,418) costs. It is not feasible to assume that a single producer could invest in an on-farm desalination unit for their operation. It has been determined that on-farm desalination technology impacts a greater spatial region than just the land directly irrigated with desalinated water (see Section 3.2) and therefore would be more feasible if producers worked in collaboration with each other to invest in the technology. This would be mutually beneficial for current producers as well as future generations in preserving soil and water resources.

It is possible to create farmer and government supported cooperatives to aid in the building and operation of desalination systems. Understanding the social, economic, and environmental impacts of desalination could help with the adoption of desalination technology and encouraging producers to collaborate to reach production and sustainability goals.

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APPENDIX A.

VBA CODE FOR RELATIVE YIELD CALCULATIONS

```
'Calculate the composite relative yield for each grid cell
Public Sub CalculateRelativeYield()

Dim i As Integer, j As Integer, row As Integer, col As Integer
Dim nrow As Integer, ncol As Integer
Dim active() As Integer
Dim sum As Double, rel_yield As Double
Dim par_a() As Double, par_b() As Double
Dim crop() As Double
Dim cell_ec() As Double, cell_ry() As Double


'specify grid dimensions and number of crop types
nrow = 127
ncol = 213
ncrop = 13

'dimension the arrays
ReDim cell_ec(nrow, ncol)
ReDim par_a(ncrop)
ReDim par_b(ncrop)
ReDim crop(nrow, ncol, ncrop)
ReDim cell_ry(nrow, ncol)
ReDim active(nrow, ncol)


'read in the status of each cell
Worksheets("Active").Select
row = 1
For i = 1 To nrow
   col = 1
   For j = 1 To ncol
      active(i, j) = Cells(row, col)
      col = col + 1
   Next j
   row = row + 1
Next i


'read in the relative yield parameters for each crop type
Worksheets("Parameters").Select
```

```
col = 3
For i = 1 To ncrop
   par_a(i) = Cells(5, col)
   par_b(i) = Cells(6, col)
   col = col + 1
Next i


'read in the crop type for each cell
Worksheets("CropType").Select
row = 2
For i = 1 To nrow
   For j = 1 To ncol
      'read in crop portions for the current cell
      col = 1
      For k = 1 To ncrop
         crop(i, j, k) = Cells(row, col)
         col = col + 1
      Next k
      row = row + 1
   Next j
Next i


'read in the EC values for each grid cell
Worksheets("EC").Select
row = 1
For i = 1 To nrow
   col = 1
   For j = 1 To ncol
      cell_ec(i, j) = Cells(row, col)
      col = col + 1
   Next j
   row = row + 1
Next i


'calculate the relative yield for each cell
For i = 1 To nrow
   For j = 1 To ncol
      If (cell_ec(i, j) > 40) Then
         cell_ry(i, j) = -2
      ElseIf (active(i, j) = 1) Then 'only proceed if the cell is active
         'loop through the crop types
         sum = 0
         For k = 1 To ncrop
            rel_yield = 100 - (par_b(k) * (cell_ec(i, j) - par_a(k)))
            If (rel_yield > 100) Then
```

```
            rel_yield = 100
          End If
          If (rel_yield < 0) Then
            rel_yield = 0
          End If
          sum = sum + (crop(i, j, k) * rel_yield)
        Next k
        cell_ry(i, j) = sum
      Else
        cell_ry(i, j) = -5 'no data value for inactive cells
      End If
  Next j
Next i


'write out values to the sheet
Worksheets("RelativeYield").Select
row = 1
For i = 1 To nrow
  col = 1
  For j = 1 To ncol
    Cells(row, col) = cell_ry(i, j)
    col = col + 1
  Next j
  row = row + 1
Next i


End Sub
```

APPENDIX B.

VBA CODE USED TO CALCULATE TDS OBSERVATION DATA FOR SCENARIO 2. OBSERVATION DATA WAS SIMULATED FOR EACH CELL THROUGOUT THE 7 CROSS SECTIONS FROM TIME ZERO TO YEAR 25.

```
Public Sub GetAverageSum()

Dim ca_avg() As Double, mg_avg() As Double, na_avg() As Double, k_avg() As Double, so4_avg() As
Double, co3_avg() As Double, hco3_avg() As Double, cl_avg() As Double
Dim tds As Double

'number of observation cells; number of output times
nobs = 268 / 2
ntimes = 1465

'dimension the concentration arrays
ReDim ca_avg(ntimes, nobs)
ReDim mg_avg(ntimes, nobs)
ReDim na_avg(ntimes, nobs)
ReDim k_avg(ntimes, nobs)
ReDim so4_avg(ntimes, nobs)
ReDim co3_avg(ntimes, nobs)
ReDim hco3_avg(ntimes, nobs)
ReDim cl_avg(ntimes, nobs)
ReDim tds_avg(ntimes, nobs)

'calcium
Worksheets("Ca").Select
Row = 5
For i = 1 To ntimes
  'average values from layer 1 and layer 2
  col = 2
  For j = 1 To nobs
    ca_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
    col = col + 2
  Next j
  Row = Row + 1
Next i

'magnesium
Worksheets("Mg").Select
Row = 5
For i = 1 To ntimes
  'average values from layer 1 and layer 2
```

```
   col = 2
   For j = 1 To nobs
      mg_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'sodium
Worksheets("Na").Select
Row = 5
For i = 1 To ntimes
   'average values from layer 1 and layer 2
   col = 2
   For j = 1 To nobs
      na_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'potassium
Worksheets("K").Select
Row = 5
For i = 1 To ntimes
   'average values from layer 1 and layer 2
   col = 2
   For j = 1 To nobs
      k_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'sulfate
Worksheets("SO4").Select
Row = 5
For i = 1 To ntimes
   'average values from layer 1 and layer 2
   col = 2
   For j = 1 To nobs
      so4_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'carbonate
```

```
Worksheets("CO3").Select
Row = 5
For i = 1 To ntimes
   'average values from layer 1 and layer 2
   col = 2
   For j = 1 To nobs
      co3_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'bicarbonate
Worksheets("HCO3").Select
Row = 5
For i = 1 To ntimes
   'average values from layer 1 and layer 2
   col = 2
   For j = 1 To nobs
      hco3_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'chloride
Worksheets("Cl").Select
Row = 5
For i = 1 To ntimes
   'average values from layer 1 and layer 2
   col = 2
   For j = 1 To nobs
      cl_avg(i, j) = (Cells(Row, col) + Cells(Row, col + 1)) / 2
      col = col + 2
   Next j
   Row = Row + 1
Next i

'Calculate TDS and write out to spreadsheet
Worksheets("TDS").Select
Row = 5
For i = 1 To ntimes
   col = 2
   For j = 1 To nobs
      tds = ca_avg(i, j) + mg_avg(i, j) + na_avg(i, j) + k_avg(i, j) + so4_avg(i, j) + co3_avg(i, j) + hco3_avg(i, j)
+ cl_avg(i, j)
      Cells(Row, col) = tds
      col = col + 1
```

```
   Next j
   Row = Row + 1
Next i


End Sub
```

APPENDIX C

CROP AND THRESHOLD VALUES USED IN RELATIVE YIELD CALCULATIONS

Table 5. Crop and threshold values for specified crops.

Crop Type	Threshold (a) (dS/m)	Slope (b) (% per dS/m)
Alfalfa	4	7.3
Bean	3	20
Corn	3.8	12
Melon	3	8.4
Onion	3.2	6
Pasture	6	7.3
Pumpkin	5.2	10.5
Sorghum	8.8	16
Spring Grain	9	7.1
Squash	7	10.5
Sunflower	7	5
Vegetables	3.5	14
Winter Wheat	8	7.1