ECONOMIC ANALYSIS OF FARM RESPONSE TO DROUGHT IN THE SAN LUIS VALLEY, COLORADO

Summary

A two stage optimization model is developed that simulates the Doctrine of Prior Appropriation, Rio Grande flow and available groundwater and estimates net returns from cropping activities in the San Luis Valley, Colorado. The objectives of the model are to maximize the quantity of river diversions in the first stage and maximize net returns in the second stage. The results of the analysis indicate that crop production activities are dependent more on available groundwater than on surface water diversions from the Rio Grande. Net returns from crop production are influenced more by reduced aquifer levels than reduced river flow.

Introduction

Agriculture accounts for nearly 90% of consumptive water use in the western United States (Gibbons (1986)). Agricultural producers continue to experience increased competition for limited water resources with growing urban populations. Brajer and Martin (1990) state that water is not becoming scarce, but rather cheap water is becoming scarce as water markets develop.

Agricultural producers adapt to increased groundwater pumping costs, higher market values for voluntary water transfers and environmental constraints on water through improved irrigation efficiency and reduced consumption (Moore, Gollehon and Carey (1992)). Surface water, with flows that are uncertain from year to year and groundwater from aquifers with declining water levels, represent the primary source of irrigation water for agricultural production. Sustained and severe drought conditions impact surface and groundwater supplies, adding an additional element of uncertainty to agricultural production.

Most institutional arrangements for water allocation in the west are based on the Doctrine of Prior Appropriation whereby the first person or organization that puts water to a beneficial use obtains a decree amount and the highest priority right to that water through adjudication in water courts where they exist. The Doctrine of Prior Appropriation is said by some economists to be economically inefficient because it fails to promote water conservation in the face of growing scarcity (e.g., Burness and Quirk (1979); Tietenberg (1992)). In general, water markets that could in principle, allocate water to higher economic valued uses value use do not exist or are poorly organized. So market signals that have the potential to promote higher economic valued end uses are not present. Brajer and Martin (1990) contend that water is a social good and vital necessity with attributes beyond its market value, so it should not be treated as a normal commodity.

These arguments characterize much of the current competition for water in the San Luis Valley of Colorado where increasing urban populations along the Front Range in Colorado and in New Mexico and Texas are seeking additional water sources to meet growing demands for uses outside agriculture, including endangered species habitat. Irrigated agriculture could provide a source for transferring water supplies to meet these growing demands since it typically absorbs the greatest amount of water in its use, and is of low economic value at the margin for many crops. The value of water to agricultural production and how agricultural producers respond to decreased water supplies in the face of drought by changing the mix of crops produced is an important issue in the west for water policy analysis.

This section is a portion of the regional research supporting a sustained drought study for the Rio Grande Basin from the San Luis Valley of Colorado to Fort Quitman, Texas. The headwaters of the Rio Grande begin as snow melt in the San Juan Mountains in Colorado and flow to the Gulf of Mexico after traveling through New Mexico and Texas. Water demands along the river have increased as populations increase, particularly in Albuqureque, New Mexico, El Paso, Texas and Ciudad Juarez, Mexico.

The purpose of this paper is to develop a model that simulates the Doctrine of Prior Appropriation in Colorado, identifies producer response to restricted water supplies, and estimates the value of water to agriculture in the study area. This study provides a foundation for studies into the relaxation of institutional constraints by developing an analytical method for identifying the value of irrigation water for agricultural production. The area of study is the Closed Basin portion of the San Luis Valley in south-central Colorado. The primary focus of the study is on changing surface water flows, however an extensive aquifer is also accounted for in the analysis. A model addressing the major surface and groundwater hydrologic features and the cropping patterns of producers in the region is developed. By analyzing income changes due to low water flows, the value of irrigation water to agricultural production in the study area may be determined.

Background

Rio Grande flow at the Colorado-New Mexico state line depends on snowpack the Rio Grande Compact, and behavior of Colorado agricultural producers. What ends up at the Colorado-New Mexico state line depends through the Rio Grande Compact on river flow at Del Norte, Colorado, the amount of water diverted for agriculture in Colorado and the delivery requirements specified in the Rio Grande Compact of 1938. The Rio Grande water has been over-appropriated. That is, more water has been allocated to users than is generally available from the river. Junior rights may not receive water during the growing season when surface water flows are low because senior rights, especially Rio Grande Compact requirements, take precedence.

The San Luis Valley in Colorado consists of approximately 3,200 square miles with an average elevation of about 7,700 feet. The Valley receives more water than most deserts in the country. The average annual rainfall is 7 to 10 inches, with more than half of the precipitation occurring between July and September. Crop production is difficult without supplemental water for irrigation. The short growing season of 90-120 days also limits the choice of crops (Doesken and McKee (1989)).

Conjunctive use of surface and groundwater provides the water necessary to irrigate crops in the San Luis Valley. Groundwater in the San Luis Valley is obtained from an Unconfined Aquifer, which is separated from a Confined Aquifer by a series of clay formations 10 to 80 feet thick. The study area is in the northern portion of the Valley that is referred to as the Closed Basin because it is internally drained. An alluvial divide prevents water in the Closed Basin from draining into the Rio Grande. Irrigation water diverted from the Rio Grande or pumped from the aquifer within the Closed Basin that is not used by evapotranspiration does not return to the Rio Grande, but recharges the Unconfined Aquifer within the Closed Basin.

Econometric [Nieswiadomy (1985); Ogg and Gollehon (1989); Moore and Negri (1992)] and mathematical [Bryant, Mjelde and Lacewell (1993); Kulshrestha and Tewani (1991)] techniques have been used to describe water use by agricultural producers and to derive the value of water to crop production. Existing models that address river diversions for agriculture have excessive data requirements and many do not consider the Doctrine of Prior Appropriation. Wurbs and Walls (1989) developed a model that addresses prior appropriation by accounting for water rights assigned to reservoir storage facilities in Texas. Bredehoeft and Young (1983) analyzed a river basin delivering water to a single irrigation ditch for three areas with hypothetical rights and decrees allocated. A mathematical model is developed for the analysis addressed in this paper that explicitly accounts for the Doctrine of Prior Appropriation.

Methods

The value of water to the San Luis Valley is determined using a two stage optimization model that accounts for river flow, groundwater pumping, and effective rainfall. The Doctrine of Prior Appropriation is addressed in the first stage of the model to allocate river water from the Rio Grande to the irrigation ditches and canals holding the highest priorities. Rio Grande Compact requirements are calculated outside the model so all river flow within the model may be diverted for agricultural production. Municipal and industrial uses are not considered in the analysis because agriculture accounts for 97% of water use in the San Luis Valley. The amount of water diverted represents the amount of water available for crop irrigation. The area includes eight storage reservoirs that provide some water for agricultural production, but are not considered in the analysis because they are small and have junior water rights. Cropping and irrigation decisions are dependent upon the amount of surface water that is available and whether groundwater rights are owned by the producer. Cropping patterns and the associated net returns from irrigation water are estimated in the second stage of the model based upon crop production functions and costs of production for the primary crops produced in the study area.

The impact of decreased water supplies on crop production is analyzed by parametrically decreasing the amount of river flow and volume of available aquifer water and estimating the change in the value of crop production. The proportion of groundwater in the aquifer that may be pumped economically is not known with certainty. By parametrically decreasing available groundwater and surface water, the relative importance of groundwater pumping and surface water sources will be identified.

The Colorado Division of Water Resources has partitioned the state into seven water divisions organized around major drainage basins or series of rivers. The Rio Grande is in Water Division Three. River flow and diversion records are maintained by Water Districts, representing river basins. The San Luis Valley has six Water Districts with Water District 20 representing the Rio Grande river basin. The Rio Grande accounts for 70.1% of diversion rights in Water District 20 where 91 other sources (creeks and streams) also provide water. The Rio Grande accounts for 337 of the 861 water rights in Water District 20. Historical diversion records indicate that the Rio Grande accounted for over 93% of actual diversions from 1986 to 1995 in Water District 20. Simulating cropping activities that divert water from the Rio Grande is sufficient to account for most of the water diverted for irrigation in the Closed Basin.

Irrigation ditch/canal companies own the water rights in the San Luis Valley and producers own shares, each of which receives the same amount of water. Each ditch/canal company owns a suite of water rights with different priorities and decree amounts. Water right, decree amount, geographic location, and decree date were obtained from the Colorado Division of Water Resources. Five irrigation ditches/canals are included in the simulation - four actual irrigation ditches/canals and one to account for diversions to cropping activities outside the study area. Cropping activities are simulated only for representative agricultural areas along the four irrigation ditches/canals explicitly included in the model. Four of the 101 irrigation ditches on the Rio Grande account for over 60% of water rights within the study area. Explicitly included in the simulation model are the Rio Grande Canal, Farmer's Union Canal (now the San Luis Valley Irrigation District), Prairie Ditch, and the San Luis Valley Canal. Table 4.1 identifies the number of acres serviced by each of the four irrigation ditches in 1995, the number of shares held by each ditch and the annual assessment for diverting water from the ditch. If there is no call for water, a shareholder does not pay the assessment. All other ditches are combined into a single diversion "ditch" with the priority and decree amount of individual diversions maintained. For allocating water among appropriators the geographic location of the irrigation ditches (specifically the upstream-downstream relationship)

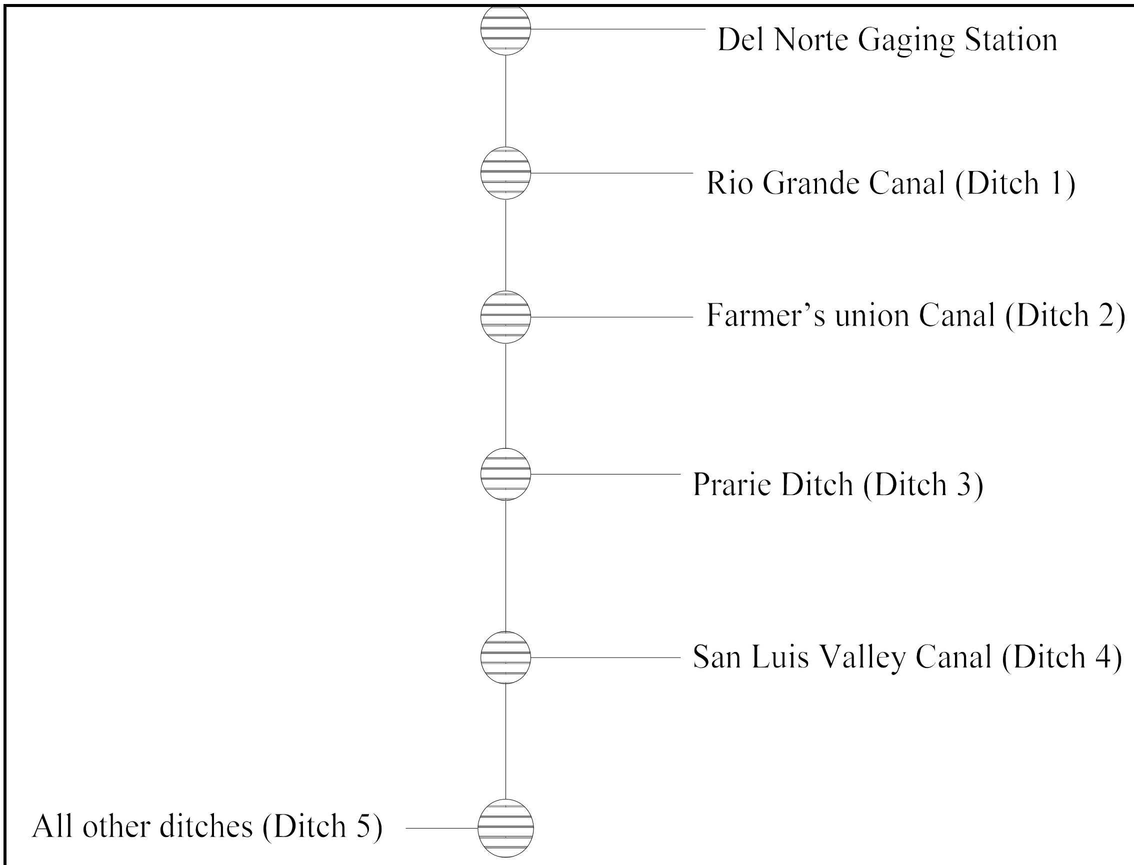

Figure 1 Schematic of Study Area Showing Irrigation Ditches/Canals and Ditch Number Identifier used in Simulation Model, San Luis Valley, CO.

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not relevant because a downstream ditch with senior rights is allocated water by the model before a junior upstream user and a vast majority of return flows accrue to the aquifer. The five canals/ditches represent the nodes addressed in the river flow model where water is diverted from the river. A schematic of the Rio Grande with the irrigation ditches and canals included in the simulation model is given as Figure 4.1. Crop production is simulated for representative agricultural areas that divert irrigation water from the four irrigation ditches explicitly included in the simulation model.

Table 1. Canals / Ditches Modeled in the Analysis, Acres Serviced by Canal/Ditch, Number of Shares Held by the Canal/Ditch, and Annual Assessment for Each Share, San Luis Valley Colorado.

Canal/Ditch	Acres	Number of shares	Assessment
Prairie Ditch	13,196.40	250	$300/share
Rio Grande Canal	75,701.90	7152.825	$60/share
San Luis Valley Canal	10,051.50	13280	$7.50/share
San Luis Valley Irrigation District	7,933.10	No Shares[11]	$1200/quarter-section

Groundwater in the study area is pumped from the Unconfined Aquifer that lies below much of the valley floor. Precise data for the amount of water in the aquifer are not available, but are estimated for this study. The depth to the blue clay series that separates the Unconfined from the Confined Aquifer represents the depth of the Unconfined Aquifer. This depth changes from north to south and west to east in the study area.

For analytical purposes, the Unconfined Aquifer was divided into nine separate cells determined by the depth to the blue clay series, with each aquifer cell treated as a bowl containing an amount of groundwater dependent upon its volume. Water does not move between aquifer cells in the model during the cropping season. Recharge from drainage and recharge pits percolates only into the aquifer below which crop production is occurring. Aquifer recharge occurs from percolation from irrigation ditches and canals, watershed runoff, precipitation, and leakage from artesian wells. Two-thirds of aquifer recharge occurs during the cropping season and is allocated equally to each aquifer cell in the model. At the start of each simulation, an quantity of water is allocated to the nine aquifer cells in a way consistent with the movement of recharge water across the Valley. That is, each aquifer cell is allocated an amount of water equal to its share based upon the depth and holding capacity of the cell. Since water flows to the lowest point, the deepest aquifer cells receive water first and others receive water only if there is sufficient water.

The specific yield for most portions of the aquifer is approximately 0.20, which is used in this analysis (Emery (1970); Woodward-Clyde-Sherard and Associates (1967)). In general, the aquifer locations cover areas from northwest to southeast with surface areas that range from 4,480 to 65,920 acres. The amount of water simulated in the nine aquifer cells (2.46 million acre feet) compares well with other estimates of the Unconfined Aquifer (Woodward-Clyde-Sherard and Associates (1967)). Most producers in the study area do not apply surface water directly to their fields, but rather divert the water to holding ponds (known as recharge pits) which recharge the aquifer. All water diverted to recharge pits percolates to the aquifer, but is not available for pumping until the next time period. The aquifer is also recharged through inefficient irrigation of applied water by crops. The amount of aquifer recharge from surface and groundwater sources is dependent upon the irrigation technology used. In the Closed Basin, all irrigation is by relatively new center pivot equipment. Therefore, recharge rates are considered to be the same on each representative farm.

Thirty-three representative agricultural areas were used to simulate crop production along each of the irrigation ditches/canals included in the analysis. Representative agricultural areas were determined by the soil characteristics, source of surface water used for irrigation (ditch/canal), and groundwater source. The 47 primary soil types in the study area range from clay loam to gravelly sandy loam. These were partitioned into sand and sandy loam soils for the crop simulation model. These two soils account for a majority of the variation in soil characteristics. Representative agricultural areas were restricted to diverting surface water from a single irrigation ditch/canal and could pump groundwater from only the aquifer cell beneath the farm. The equipment complements and financial status of most farms in the Closed Basin are similar and were treated as such in the model. Farms within the study area were assumed to be price takers because the amount of production for any crop does not influence national prices. Even though Colorado is one of the leading producers of potatoes in the country, San Luis Valley production of this crop represents only 6% of national production. Alfalfa represents 4% of national production and barley 2.7%.

Historic crop acreage for grain (primarily barley and spring wheat), potatoes, and alfalfa on each quarter section in the study area from 1983-1994, representing the primary crops produced, was obtained from the USGS in Albuquerque, New Mexico. Malting barley is often grown with contracts from the Coors Brewing Company, but the higher prices received were not considered in the analysis. The seed variety most frequently grown (Moravian III) for both brewery contracts and feed is the same. Some vegetable crops, particularly carrots, lettuce and peas are gaining popularity, but are not considered primary crops so were not addressed in the analysis. Land around the periphery of the valley floor is used for grazing cattle, but cattle operations were not considered in the analysis.

The model was calibrated using river flow data for ten years that were obtained from the USGS for Del Norte, the gauging station furthest upstream on the Rio Grande. The baseline model results for diversions and cropping patterns were compared to historic stream flows, diversions and cropping patterns to ensure that reasonable results were obtained.

Hydrology Model Development

A mass balance river flow model that diverts water by priority and decree amount was developed in GAMS (Brooke, Kendrick and Meeraus (1988)). The model maximizes the total amount of water diverted while satisfying each decree by priority. When river flow is insufficient to satisfy all users, junior decrees are not provided water. Water available from each irrigation canal/ditch is used in the second stage of the model to simulate crop growth and estimate the value of crop production.

Five equations establish the constraints and water allocation amounts. First, diversions at each node must be less than or equal to the decreed water right held by the ditch at that node for each time period and must also be less than or equal to the amount of water in the river as shown in Eqs. 1 and 1a. River flow is simulated for six time periods to account for the cropping season.

$$Divert_{i,t} \leq Waterright_{i} \quad i = 1-123; \;\; t = 1-6 \tag{1}$$

$$Divert_{i,t} \leq Flow_{i,t} \tag{1a}$$

where i is the right (i = 1-123), and t is time (t = 1-6)

To simplify the analysis, water rights for ditches with consecutive priorities were grouped together and considered a single water right with a single priority, which reduced the total number of water rights from 337 to 123. That is, when a single irrigation ditch or canal owned priority numbers 1, 2 and 3, they were combined to priority 1 with a diversion right equal to the sum of decrees for the three rights.

Second, river flow at the first node is the same as the constant entered into the model as the flow for that time period. At the second and subsequent nodes, river flow is reduced by the amount of water diverted by upstream ditches (Eqs. 2 and 2a).

$$Flow_{i,t} = Inflow_{t}, \;\; for \; i = 1-123; \; t = 1-6 \tag{2}$$

$$Flow_{i,t} = Flow_{i,1t} - Divert_{i-1,t} \tag{2a}$$

Third, the highest priority ditches receive water before more junior priorities, even when the higher priority ditch is geographically located downstream from the junior priority. The objective of the first stage of the model is to maximize the total amount of water diverted to irrigation ditches constrained by the priority and decree amount of each irrigation ditch using Eq. .3. This weighted equation limits diversion of water at any upstream ditch to zero in each time period if there are downstream ditches with higher priorities and river flow is not sufficient to satisfy all rights.

$$Objective = \sum_{i=1}^{123} \sum_{t=1}^{6} 1 / Priority_i^2 * Divert_{i,t} \tag{3}$$

Equation 4 is used to identify the irrigation ditch receiving water and the amount of water diverted for each right.

$$Ditch_{l,t} = \sum_{I=1}^{123} Divert_{i,t} \quad for\ each\ Owner_i = DitchID_i \tag{4}$$

The volume of water in the aquifers is dependent upon the initial condition, quantity of water added from recharge pits, drainage of water not consumed by crops and the amount of water removed through pumping activities. Water added through recharge pits is positive when a representative farm diverts water from an irrigation ditch/canal. That is, to ensure all surface water is used in the analysis, to reflect operations in the San Luis Valley, all water diverted from an irrigation ditch/canal is used by the representative farm, either in recharge pits, or surface applied to a field by flood irrigation. Since all cropping activities in the study area use center pivot irrigation systems, a charge is assessed for flood irrigation activities to artificially force use of recharge pits. The amount of surface water available, water from irrigation ditches/canals less the amount of water surface applied represents the amount of water applied to recharge pits.

Water not used by plants ("Drain") is calculated using Equation 5.

$$Drain_{q,t} = \sum_{M=1}^{33} (1 - ETA_M) * Wapplied_{M,t} * RtnFrac_{M,q} \tag{5}$$

Where: *Drain* = amount of water seeping into aquifer
q = aquifer identifier (1-9)
t = time periods (1-6)
M = farm (1-33)
ETA = irrigation efficiency by farm
Wapplied = amount of irrigation water applied to crops, and
RtnFrac = proportion of non consumption returning to aquifer.

Pumping costs are included in the variable costs and are applied at a rate of \$37.50 - \$40.00/acre foot (pumping costs for alfalfa are higher) for all representative agricultural areas while costs to apply surface water are \$5/acre foot.

Bredehoeft and Young (1983) found that the optimum capacity for wells in their study area (the Platte River Valley of Colorado) was about one-half the capacity of wells actually installed. Increased well capacity provided insurance against low river flows, reduced the variance of expected income, and maximized expected income. Pumping rights are required to remove water from the aquifer in the study area of the San Luis Valley. Pumping capacity for the analysis was determined using 1500 gallons/minute wells, which are common in the study area, and the total area of the farm. Estimated pumping capacities for some farms in the study area were higher than crop requirements, but groundwater rights are frequently less than pumping capacity. Representative agricultural areas were constrained to pumping no more than the minimum of the groundwater right plus the amount of recharge from recharge pits, the farm pumping capacity, or their proportion of the amount of water remaining in the aquifer. The farm proportion of aquifer water is based upon their proportion of total surface area above the aquifer.

Crop Growth Simulation Model

A crop growth simulation model was used to develop coefficients for the optimization model production functions (Cardon, 1990). Second and third order polynomial equations, depending upon the crop, represent the results of the crop growth simulation model better than other functional forms. Equation 6 describes the general form of the crop growth function used for all crops to derive the relative yield variable:

$$Y = a + bX + cX^{2} + dX^{3} \tag{6}$$

Where: Y = relative yield
a = intercept coefficient
b = slope coefficient
X = amount of water applied (acre inches)
c = slope coefficient, and
d = slope coefficient.

The relative yield variable (Y) is constrained to less than or equal to one in the model because production functions for all crops do not have a global maximum. Coefficients (Table 2) for crop growth functions were derived through regression analysis of data from the crop growth simulation model. The model employs a daily time-step to simulate the relationships between water and soil, water and plant growth and yield and evapotranspiration to derive relative yield parameters based upon water available for plant growth. It simulates water movement through the soil profile and water uptake by the plant. Site specific input files were generated to reflect growing conditions and hydraulic properties of soils in the study area (Rawls, Ahuja and Brakensiek (1992); U.S.D.A.

(1988)). Crop growth was simulated with the number of irrigation events varied from 0 to 24 for potatoes (fewer irrigations for alfalfa and barley) to generate production functions for each crop. All nutrients except water were assumed adequate for normal crop production and effective rainfall was included as a parameter.

Table 2. Crop Growth Coefficients for Crop Production Functions (Eq. 6)

	A	b	c	d
Sandy Soils				
Alfalfa	0.06106	0.12290	-0.00395	0.00000
Barley	0.24736	-0.01420	0.00573	-0.00016
Potatoes	-0.01130	0.05690	-0.00080	0.00000
Sandy Loam Soils				
Alfalfa	0.48808	0.09000	-0.00389	0.00000
Barley	0.38689	0.06960	0.02024	-0.00245
Potatoes	0.40019	0.16650	-0.01585	0.00052

Total water applied to crops is determined using Eq. 7 and is constrained to be less than the combined amount of surface water applied and pumped from the aquifer. Net irrigation is calculated using Eq. 4 where irrigation efficiency of the irrigation system is addressed.

$$Wapplied_{M,t} = \sum_{c=1}^{3} (Wapprate_{M,c,t} * Cropacre_{M,c}) \qquad (7)$$

Where: *Wapplied* = total amount of water applied to crops

M = farm (1-33)

t = time period (1-6)

c = crop (alfalfa, barley, potatoes)

Wapprate = a free variable determined by the model, and

Cropacre = number of acres planted to each crop.

$$Nir_{M,c} = 12 * \sum_{t=1}^{6} Wapprate_{M,c,t} * Eta_{M} \tag{8}$$

Where: Nir = net irrigation amount

M = farm (1-33)

t = time period (1-6)

c = crop (alfalfa, barley, potatoes)

Wapprate = a variable determined by the model, and

Eta = irrigation efficiency parameter.

The objective of the second stage of the model is to maximize the sum of net returns from all crops and farms in the study area. Moore, Gollehon and Carey (1994) determined that the choice of acres on which to produce crops is the first decision made by producers and the cost of water was second. Therefore, the costs for shares of irrigation ditch water are not included in the optimization, but are subtracted from returns net of other variable costs. The coefficients for price and variable costs are included in Table 3.

Table 3. Price and Variable Costs for Alfalfa, Barley and Potatoes

	Alfalfa	Barley	Potatoes
Price	$85.00/ton	$3.26/bu	$5.50/cwt
Variable Cost/Acre	$129.60	$179.66	$596.12

Variable Cost/Yield	$24.25	$0.34	$0.12

Results and Discussion

The first stage of the model identifies river diversions to irrigation ditches consistent with actual diversions. Deliveries of 153,720 and 72,600 acre feet are needed to satisfy Rio Grande Compact requirements for 100% and 50% flow levels respectively. The amount of water available for diversion is 423,964 acre feet when river flow is 100% and 211,982 acre feet when river flow is at 50% of normal. The initial aquifer volume is 2,461,440 acre feet which declines to 1,230,720 acre feet when the aquifer is at 50% of capacity.

The crop production portion of the model accounts for over 88% of crop acreage for the base year. Six of the seven representative agricultural areas with no groundwater rights do not produce crops when 100% of river flows are available, regardless of available aquifer water. These agricultural areas are included in the model to account for surface water diversions even though crop production does not occur. The model accounts for 100% of crop production on farms holding both surface water and groundwater pumping rights.

The amount of water available from river flow for crop production, which is the amount of water diverted to irrigation ditches/canals, is included in Table 4 for 100% and 50% flows for each irrigation ditch/canal.

Table 4. Water Diversions for Each Irrigation Ditch/Canal with 100% and 50% of River Flow Available

Ditch/Canal	Amount of River Diversions (Acre Feet)	
	100% River Flow	50% River Flow
1	77302.2	44889.6
2	16630.5	0.0
3	13923.7	1071.0
4	11053.2	0.0

5	305054.4	166021.4

The amount of water used for crop production on each representative farm, the irrigation ditch from which water was diverted, total acres available for crop production and the number of acres on which crop production occurred are included in Table 5. A 50% decline in river flow and available groundwater results in a reduction of 17,522 acres from full production of 144,973 acres when full water is available. Seven of the 33 representative agricultural areas reduce crop production in response to declining water supplies with 14,668 acre feet less water applied to crops.

Acres producing alfalfa, barley and potatoes are included in Tables 6 - 8. Alfalfa production remains constant as river flow declines. A 50% reduction in both groundwater and surface water results in an 11% decline in alfalfa production. When there are no river flows and available water in the aquifer is at least 50% alfalfa production is decreased by 17% compared to the results when full water is available from both groundwater and surface water sources.

Table 5. Representative Farm, Irrigation Ditch/Canal from which Water is Diverted, Acres Available for Crop Production, Acres Cropped, and Amount of Water Applied when River Flow and Aquifer Volume are Full and Reduced by 50%

Farm	Ditch / Canal	Acres Available	Acres Cropped		Water Applied to Crops (Acre Feet)	
			100% Flow and Aquifer	50% Flow and Aquifer	100% Flow and Aquifer	50% Flow and Aquifer
1	1	14,268	14,268	14,268	38,005	38,005
2	1	11,316	11,316	11,316	28,693	28,693
3	1	12,792	12,792	12,792	33,109	33,109
4	1	13,776	13,776	13,776	36,439	36,439
5	1	3,936	3,936	3,936	10,831	10,831
6	1	3,444	3,444	3,444	2,811	2,811
7	1	3,936	0	0	0	0
8	1	3,444	0	0	0	0
9	1	5,412	0	0	0	0
10	2	7,380	7,380	7,380	20,682	20,682
11	2	2,952	2,952	2,952	7,082	7,082
12	2	1,968	0	0	0	0
13	2	12,792	12,792	12,792	10,353	10,353
14	2	2,952	2,952	0	2,416	0
15	2	3,444	3,443	3,443	2,794	2,794
16	2	1,968	1,967	0	1,593	0
17	2	1,476	0	0	0	0
18	2	2,460	2,460	2,460	2,124	2,124
19	2	2,460	2,460	0	2,161	0
20	2	1,968	1,968	1,968	5,083	2,284
21	2	984	490	0	1,432	0
22	2	4,428	4,428	4,428	3,861	3,861
23	2	3,444	3,444	3,444	2,602	2,602
24	2	1,476	0	0	0	0
25	3	984	330	25	738	57
26	3	984	984	984	2,893	2,893
27	3	8,856	8,855	8,855	7,232	7,232
28	3	3,444	3,444	3,444	2,708	2,708
29	3	4,428	4,428	4,428	4,164	4,164
30	4	5,904	5,904	5,904	4,914	4,914
31	4	7,380	7,380	0	6,227	0
32	4	2,952	2,952	2,952	2,338	2,338
33	4	4,428	4,428	4,428	12,792	12,792

Table 6. Acres of Alfalfa Produced with Different Quantities of Water Available

Proportion of	Proportion of River Flow (%)

Aquifer Available (%)	100	50	0
	---------------- Acres	-------------	
100	24,425	24,425	24,425
50	21,751	21,751	20,331
0	5,306	4,444	0

Barley production requires less water than either alfalfa or potatoes, but the value of barley as a crop enterprise is less than either of the other two crops. To attain the highest net returns, production should be shifted away from lower value crops to higher value crops when water becomes scarce. The simulation model reflects the change in crop mix by reducing the amount of barley produced when water shortages occur. A 50% reduction in surface and groundwater causes a 9.8% reduction in barley production. Barley production is reduced by 33.3%, compared to production under full water availability conditions, when no river flow is available and 50% of the aquifer is available. This decline is larger than either the reduction in alfalfa or potato production, reflecting the shift away from lower value products and applying water to higher value products.

Table 7. Acres of Barley Produced with Different Quantities of Water Available

Proportion of Aquifer Available	Proportion of River Flow (%)		
	100	50	0
	----------------Acres	--------------	
100	64996	59245	63961
50	58622	58622	43329
0	6877	4576	0

Potatoes are the highest value crop in the study area. As the highest value crop, irrigation of other crops should be reduced and the water applied to potatoes when river flows and available water in the aquifer decline. Potato production declines by 13.1% when river flow and available groundwater are reduced by 50%. When river flow is reduced to zero and 50% of aquifer water is available, potato production declines by 12.9% compared to production with full river flow and aquifer levels. The reduced potato acres is consistent with expectations when river flows are reduced to zero. However, the proportion of total acres for each crop produced remains relatively stable with 100% compared to 50% available surface and groundwater. Alfalfa production represents the same proportion (16.9%), barley production increases slightly (from 44.8% to 45.5%) and potato production declines slightly (from 38.3% to 37.5% of all production).

Table 8. Acres of Potatoes Produced with Different Quantities of Water Available

Proportion of	Proportion of River Flow (%)		
Aquifer Available	100	50	0
	-----------------Acres--------------		
100	55552	55247	55222
50	48585	48280	48367
0	5858	5553	0

Total net returns from crop production with river flow and available groundwater varied from 100% to 0% are shown in Table 9. When available groundwater from the aquifer remains at 100%, reducing the river flow has only a minor impact on overall crop production. When river flow is reduced to zero, net returns show an increase because shares for irrigation ditch/canal water are not purchased, resulting in lower overall costs. Net returns are reduced $1.4 million when river flow is reduced by 50% but available water from the aquifer remains at 100%. When river flow is 100% and available aquifer water is reduced by 50% net returns are reduced $10.7 million. When river flow and available aquifer water are reduced by 50%, net returns are reduced by nearly $11 million. A 50% reduction in available aquifer water is more costly than a 50% reduction in surface water, in the short run, by over $9.3 million.

Table 9. Total Net Returns from Crop Production with River Flow and Aquifer Volume Declining from 100% to 0%

Proportion of	Proportion of River Flow (%)		
Aquifer Available	100	50	0
	------- Net Economic Value of Returns ($) --------		
100	83,866,156	82,511,569	84,405,297
50	73,187,984	72,927,298	70,0799,34
0	9,841,168	8,235,602	0

Conclusions

The results of this analysis show the importance of the unconfined aquifer to crop production in the San Luis Valley and particularly in the study area. Net returns decline sharply when aquifer water is depleted, but are relatively unaffected by declining river flows.

Rio Grande flows are, however, important for crop production and recharging the Unconfined Aquifer. When river flow declines, irrigation diversions decline, and less water is available for aquifer recharge. As long as there is significant river flow, crop production is somewhat unaffected until very low flow levels are present. Net returns are $3.1 million higher when Rio Grande flows are 100% of normal with 50% of the aquifer, compared to returns when river flow and aquifer volume are both 50% lower. These results should be interpreted with caution because cropping decisions in a static single season simulation do not account for future events.

Recharge to the aquifer and allocation of water at the beginning of the simulation to each aquifer cell, based upon its volume and depth, were accounted for in the simulation model. However, recharge is allocated equally in each time period, and the movement of water between aquifer cells during the cropping season is not addressed. Additional research is required to refine the aquifer dynamics for both intra- and inter-year analysis. More information is required about the spatial variability of specific yields for various parts of the aquifer cells. Anecdotal evidence indicates that the aquifer cells should dry up from east to west, an artifact of aquifer dynamics that is not addressed in a static single season model.

More robust findings would result from a dynamic model that accounted for declining aquifer levels in the cropping decisions by producers. The simulation model presented in this analysis can be used to provide input data for a discrete dynamic programming model. In the model presented, producers were free to deplete groundwater supplies because short run decisions address only the current time period and do not consider future production possibilities.

Appendix A: Documentation of GAMS Model Parameters and Input Files for Economic Analysis of Farm Response to Drought, San Luis Valley, Colorado

San Luis Valley Water Rights and Supplies

Agriculture is the primary industry in the San Luis Valley (SLV) of Colorado where natural precipitation is insufficient for producing most crops. Crop production in the SLV depends upon water flow in the Rio Grande during the cropping season and water drawn from the Unconfined Aquifer, which lies below the Closed Basin. Surface and groundwater are allocated by the doctrine of prior appropriation. A water right and priority are established by an individual or organization that applies water to a "beneficial use". The water right is maintained by continuing to use the water for the "beneficial use" for which the right was established and obtaining a decree from the water court which legally establishes the priority date and decree amount of the water right. Irrigation ditch companies own surface rights for Rio Grande water. Producers own shares of the ditch and are allocated water based upon the number of shares they own and the amount of water diverted to the irrigation ditch from the river. Each ditch share receives an equal amount of water based upon the total number of shares issued by the ditch and the amount of water in the ditch, so when river flows are low, all shares are affected equally. Groundwater rights are property of the well owner. River diversions are controlled and monitored by the Division Engineer to ensure water is allocated accurately to water right holders.

Water supplies in the SLV are threatened from two different sources. First, increased demands for limited water supplies from metropolitan areas along the Colorado Front Range and nearby states are threatening to change the historical use of water in the SLV. The growing urban populations of New Mexico and Colorado are searching for additional sources of water for municipal and industrial uses. Over 97% of the water in the SLV is applied to agriculture, which is generally considered a low valued use activity for water. Second, the amount of water flowing in the Rio Grande is dependent upon the amount of moisture accumulating as snow in the mountains over the winter. A sustained drought would impact river flow and water storage in the Unconfined Aquifer, thus affecting agricultural production. The purpose of this study is to provide decision makers, producers and water managers additional information about the value of water to agricultural production in the SLV, a topic which has not been analyzed.

The impact of exporting water out of the SLV or a sustained drought would have the same effect on agricultural production in the Valley - less water available for crop production. The analysis in the main text addresses the response to a sustained drought, which provides the same results as decreased water supplies from diversions to municipal and industrial uses outside the SLV.

The response to sustained drought in the SLV is analyzed by simulating changes in cropping patterns and calculating the value of water by estimating the change in the value of crop production. A two-stage nonlinear optimization model is developed in GAMS (General Algebraic Modeling System) to allocate river water to irrigation ditches by priority and decree (Brooke, Kendrick and Meeraus). The objective of the first stage is to maximize the amount of water allocated to ditches dependent upon the amount of water in the river. The first stage of the model allocates water to irrigation ditches based upon priority, decree and river flow for growing season months (April – September). A monthly time step is used in the GAMS model, so each simulation consists of six time periods.

The objective of the second stage is to maximize the value of returns from crop production, determined by simulating irrigation and cropping decisions, constrained by available water, soil type, cropping history, and location. Cropping and irrigation decisions are based upon the amount of irrigation water available for crop production that is represented by the amount of water diverted to irrigation ditches from the river. The model identifies the changes in net returns from producing different crops when water shortages occur. Acres allocated to each crop on each farm were based upon the ten year average of crops grown. Yields for each crop are derived from crop production functions generated by a crop growth simulation model.

River water is allocated to five irrigation ditches and applied on 33 representative agricultural areas along the Rio Grande. The GAMS model is included as Appendix A3.A with the input files used by the GAMS model and additional data to explain the model formulation in additional appendices. The remainder of this appendix includes a description of the optimization model that is not included in Chapter 3, the sources of data, and identifies the data manipulations required to obtain the correct format for successfully solving the model.

Selection of Water Source to Simulate

The Colorado Division of Water Resources has partitioned the state into seven water divisions organized around major drainage basins or series of rivers. The SLV study area is in the Rio Grande Basin designated as Water Division Three. Water divisions were historically subdivided into Water Districts, a classification which is no longer practiced, although data are maintained by these designations. The study area is in Water District 20, which contains 91 sources of water (rivers and streams) with 454 irrigation ditches and canals holding 861 water rights.

Simulating all the water sources and diversion nodes within the study area is too extensive to include in a river flow model. The Rio Grande accounts for 337 of the 861 water rights and 101 of the 454 irrigation ditches and canals in the study area. When decrees without a priority assignment and decrees for reservoir storage are not included (see Section A3.2 for details), the Rio

Grande accounts for 77.3% of all water decreed in Water District 20. Water rights for reservoir storage are junior and represent a very small proportion of total diversions from the Rio Grande. Water rights without a priority are deleted from consideration because they cannot be simulated and are also of very junior rights. Since the Rio Grande accounts for most of the decrees in study area, only irrigation ditches on the Rio Grande are simulated.

Six of the 101 irrigation ditches on the Rio Grande account for nearly 77% of diverted water from the Rio Grande. These irrigation canals and ditches (Rio Grande Canal, Farmers Union Canal, Monte Vista Canal, Prairie Ditch, San Luis Valley Canal, and the Empire Canal) account for a total of 56% of all diversions in Water District 20. The Rio Grande Canal, Farmers Union Canal, Prairie Ditch and San Luis Valley Canal account for over 60% of Rio Grande diversions, are in the study area, and are explicitly included in the model. The Monte Vista and Empire Canals divert water from the Rio Grande, but apply it to acreage south of the river. All other ditches are combined into a single diversion "ditch" that maintains the priority and decree amount of individual diversions. The geographic location of the five ditches (specifically the upstream-downstream relationship) is not relevant because the priority and decree amount determine which ditches receive water. A downstream ditch with senior rights is allocated water by the model ahead of a junior upstream user.

Irrigation Ditch/Canal Data Analysis

The data were analyzed to determine if a limited number of ditches could adequately represent water diversions in the study area and to determine the proportion of diversions in Water District 20 provided by the Rio Grande. The methods used to determine which water sources and irrigation ditches to include in the model are identified in this section. The objective of the analysis is to identify the river source providing the majority of water for diversion to irrigation ditches and identify the irrigation ditches and canals that are likely to divert the majority of the water. The analysis in the remainder of this section addresses the relationship between the decrees for the six largest irrigation ditches and "all other" diversions to establish how representative the ditches included in the model are of all Rio Grande diversions. The proportion of decrees allocated to the four irrigation ditches explicitly included in the model can be derived from the tables.

Overall, Water District 20 contains 454 irrigation ditches with 17707.331 cubic feet per second (CFS) in decrees. Associated with these ditches are 861 total water rights. The 12418.4 CFS in decrees on the Rio Grande accounts for 70.1% of all decrees in Water District 20 (Table A3.1). Included in these data are many decrees without a priority assignment and decrees for reservoir storage. Decrees without a priority assignment are ignored because they cannot be simulated without arbitrarily assigning a priority and their dates of appropriation are recent. River flow would have to be above normal to satisfy these decrees. Above normal flows are not considered in this analysis.

Table A.1. Total Decrees from WD 20, Rio Grande and Six Ditches with Largest Decrees

Location	**Decrees (CFS)**	**% of WD 20**
Water District 20	17707.331	100.0
Rio Grande	12418.440	70.1
Top 6 Decrees	10119.670	57.0

Table A.2. Irrigation Canals and Ditches with Largest Decrees in Water District 20

Ditch Name	**Decree (CFS)**
Rio Grande Canal	3856.50
Farmers Union Canal	2111.90
Empire Canal	1526.92
Prairie Ditch	1101.06
Monte Vista Canal	1022.31
San Luis Valley Canal	500.98

The six ditches with the largest decrees in Water District 20 that divert water from the Rio

Grande are included in Table A3.2 along with the decree amount. The six irrigation ditches and canals account for 57% of all decrees in Water District 20.

Decrees for reservoir storage are not relevant to the economic analysis which addresses allocation of surface water to agricultural production. Six irrigation ditches contain decrees with no priority for diversion to reservoirs and the appropriation and adjudication dates are very recent. The six ditches are listed in Table A.3 along with the amount of the decree, source of water and appropriation/adjudication dates. According to Colorado water law, the appropriation date establishes the priority of the decree. These ditches are not considered in the analysis because they represent junior rights for reservoir storage with no priority assignments. These ditches represent 3950 CFS that do not need to be addressed in the model. Removing the requirement to provide water to these ditches decreases the total decrees in Water District 20 to 13757 cfs (Table A.4). Total decrees allocated to the Rio Grande are 11868.44 CFS, or 86.3% of

Table A.3 Water District 20 Reservoir Decrees with No Priority and Late Appropriation/Adjudication Dates Not Included in the River Flow Model

Ditch Name	River Source	Decree Amount (CFS)	Appropriation/ Adjudication Date
Continental Reservoir Rio Grande Exchange	San Antonio	2500	1968/1990
Santa Maria Reservoir Rio Grande Exchange	San Antonio	350	1968/1990
Continental/Santa Maria Reservoir Exch.	San Antonio	300	1981/1990
Rio Grande/Santa Maria Reservoir Exch.	Rio Grande	300	1981/1990
Rio Grande/Continental Reservoir Exchange	Rio Grande	250	1983/1990
Santa Maria/Continental Reservoir Exchange	San Antonio	250	1964/1990

all decrees for Water District 20 (excluding the data in Table 3.3). According to these data, using the Rio Grande as a representative water source seems adequate because the Rio Grande accounts for nearly all the decrees in Water District 20.

Table A.4 Total Decrees from WD 20, Rio Grande and Six Ditches with Largest Decrees after Decrees Listed in Table A3.2 Deleted

Location	Decrees (CFS)	% of WD 20
Water District 20	13757.33	100.0
Rio Grande	11868.44	86.3
Top 6 Decrees	10119.67	73.5

A number of the ditches on the Rio Grande have decrees with no priority, and are therefore not included in the model. Table A.5 lists the ditches, canals, decree, and appropriation dates for the decrees with no priority that divert water from the Rio Grande.

Table A.5 Irrigation Ditches and Canals Diverting Water from the Rio Grande in Water District 20 with No Priority Number

Irrigation Ditch	Decree (CFS)	Appropriation Date
Centennial Ditch	164.80	11/01/1959
Empire Canal	1,021.00	11/01/1959
Farmers Union Canal	1,310.45	11/01/1959
Monte Vista Canal	681.54	11/01/1959
Prairie Ditch	734.04	11/01/1959
Rio Grande Canal	2,208.00	11/01/1959
Rio Grande Res./Santa Maria Res. Exchange	300.00	04/30/1981
Rio Grande Res./Continental Res. Exchange	250.00	07/31/1983
Tres Rios No. 1	6.50	12/31/1991
Tres Rios No. 2	6.50	12/31/1991
Tres Rios No. 3	0.85	12/31/1991
Tres Rios No. 3	2.00	12/31/1991
Tres Rios No. 4	1.50	12/31/1991
Tres Rios No. 4	2.00	12/31/1991

When all decrees for reservoir storage are deleted from the data for Water District 20, 774 of the original 861 decrees remain. This data refinement leaves 380 of the original 454 irrigation ditches and canals with a total of 7415 CFS to address.

As shown in Table A.6, after deleting diversions for reservoir storage and decrees with no priority, the total amount of decrees in Water District 20 declines to 7415 CFS. The Rio Grande accounts for over 77% of the remaining decrees while the six largest ditches on the Rio Grande account for over 56% of all diversions in Water District 20. The Rio Grande's proportion of Water District 20 water rights declined because many of the water rights without a priority assignment represented Rio Grande diversions.

Table A.6 Total Decrees from WD 20, Rio Grande and Six Ditches with Largest Decrees after Decrees with no Priority Number Deleted

Location	Decrees (CFS)	% of WD 20
Water District 20	7415.183	100.0
Rio Grande	5729.260	77.3
Top 6 Decrees	4164.640	56.1

The six ditches diverting the largest amount of water account for over 72% of diversions from the Rio Grande (Table A.7). There is a considerable drop between the sixth largest ditch (by decree amount) and the next largest, which is the Rio Grande Lariat Ditch with 106.8 CFS. This decree

Table A.7 Six Irrigation Canals and Ditches with Largest Decrees in Water District 20 After Deleting Decrees in Acre Feet and No Priority

Ditch Name	Decree (CFS)
Rio Grande Canal	1648.5
Farmers Union Canal	801.45
Empire Canal	505.92
Prairie Ditch	500.98
Monte Vista Canal	367.02
San Luis Valley Canal	340.77

represents less than a third of the San Luis Valley Canal, which is the sixth largest and is less than two percent of all Rio Grande decrees.

Not only is the amount of the decree critical in modeling producer response to a sustained drought, so too is the priority of the right. A severe and sustained drought means that not all priorities will be satisfied. The selection of irrigation ditches to include in the model is also based upon whether the simulated ditches have senior rights which will continue to receive water during periods of low river flow. The ditches that receive water during low river flows are determined by analyzing which ditches received water during average historic Rio Grande flows.

Decrees on the Rio Grande, excluding those deleted because they represented reservoir rights or were rights with no priority assignment, were ordered by the priority assigned by the Division of Water Resources to determine which irrigation ditches and canals receive water when river flows are below normal. These priorities are not sequential, so a new priority number was assigned that is sequential from 1-323. As shown in Table A.8 and Figure A.1, of priorities higher than 75, the six largest irrigation ditches account for only 3.3% of decrees. However, the 75 decrees with the highest priorities account for only 8% of all water decreed from the Rio Grande. The top 100 priorities account for 1038.2 CFS of river flow. When the river flow is 1038 CFS, the six largest ditches would account for 44.8% of all water diverted for agricultural irrigation from the Rio Grande.

The ten year (1986-1995) daily average, minimum, and maximum monthly stream flow for the critical agricultural irrigation months for the Rio Grande as measured at the Del Norte gauging station are included in Table A9. These data indicate that, when river flows are average, the six ditches with the largest decrees would divert most of the water in May, June and July. However, during the remaining months, the decrees from all other ditches could divert the majority of the water from the Rio Grande. River flows at the maximum levels allow the six largest ditches to divert most of the water in all months. When flows are minimum, however, the six ditches with the largest decrees would receive only minimal water.

Table A.8 Comparing Priority and Decree of the Six Ditches with the Most Decrees and all Other Ditches with the Percent of Total Flow Required to Satisfy all Decrees

Priority	Decree of Others	Decree of 6	All Others % of Required Flow	Top Six % of Required Flow	Required Flow
Priority <=25	111.44	3.00	97.4	2.6	114.44
25< Priority <=50	91.34	0.00	98.5	1.5	205.78
50< priority <=75	209.40	11.20	96.7	3.3	426.38
75< priority <=100	161.18	450.60	55.2	44.8	1038.16
100< priority <=125	128.30	450.70	43.4	56.6	1617.16
125< priority <=150	150.64	277.90	41.7	58.3	2045.70
150< priority <=175	31.15	780.42	30.9	69.1	2857.27
175< priority <=200	79.30	422.85	28.7	71.3	3359.42
200< priority <=225	49.07	848.43	23.8	76.2	4256.92
225< priority <=250	44.48	287.47	23.0	77.0	4588.87
250< priority <=300	153.91	632.07	22.5	77.5	5374.85
Priority >300	354.41	0.00	27.3	72.7	5729.26

Table A.9 Rio Grande Daily Average, Minimum and Maximum Flow for 1986-1995 at Del Norte During Critical Months for Agricultural Irrigation

Month	Average Flow (CFS)	Minimum Flow (CFS)	Maximum Flow (CFS)
April	738.3	227.0	3,580.0
May	2,547.4	561.0	6,920.0
June	3,321.4	1,020.0	7,150.0

July	1,488.2	260.0	6,120.0
August	715.4	189.0	2,450.0
September	530.2	207.0	1,240.0

All of the minimum river flows occurred in either 1990 or 1994. According to the priorities and decrees listed in Table A3.8, the six ditches with the most decrees would receive very little water during these years. However, from the data in Table A.10, addressing actual diversions, the six ditches accounted for 50.1% and 57.0% of all diversions from the Rio Grande during these low flow years.

While the data in Table A.9 provide an indication of the amount of water decreed for diversion, they provide no information on who actually is diverting water for irrigation. To gain a better understanding of which ditches are receiving water with various river flow levels, the actual diversion data are analyzed. Of the total diversions identified for Water District 20 the Rio Grande accounts for an average of 93.4% over the nine years of data analyzed. The six ditches with the largest decrees account for 63.8% of all Rio Grande diversions and 59.6% of all diversions in Water District 20.

Table A.10 identifies total annual diversions for 1987-1995. During the lowest flow year, 1988, these six ditches and canals accounted for over 57% of all water diverted from the Rio Grande. In years with higher river flows, the six ditches account for most of the water diverted. In the year with the highest river flow (excluding 1987 which appears to be an anomaly), the six ditches with the most decrees accounted for over 72% of all water diverted from the Rio Grande.

Table A.10 Actual Rio Grande Diversions for the Six Ditches and Canals with the Most Decreed Water, all Other Ditches and Rio Grande Flow for 1987-1995 as Measured at the Del Norte Gauging Station

Year	Diversions of Six Largest (CFS)	Diversions of All other Ditches (CFS)	Rio Grande Flow (CFS)
1987	168,260.6	77,766.3	512,914.0

1988	106,361.9	78,871.5	219,240.0
1989	119,730.1	87,781.5	249,102.0
1990	132,843.6	92,818.5	265,165.0
1991	172,573.0	89,810.1	306,256.0
1992	140,434.1	86,126.1	245,601.0
1993	206,203.4	90,743.2	330,533.0
1994	155,188.3	93,207.9	272,279.0
1995	258,590.0	98,782.2	419,169.0

The results of this analysis indicate that the six ditches containing the most decrees adequately represent water diverted for agricultural irrigation from the Rio Grande.

Table A.11 Decree and Priority for Irrigation Ditches that did Not Divert Water During the Years 1987-1995

Irrigation Ditch/Canal	Priority	Decree Amount (CFS)
ALDRICH D	176	0.80
ANTLERS PARK D	266	1.06
BIEDEL D	80	20.00
BLANCA CNL	195	69.68
CARP LAKE D	232	1.00
CHADWELL SEPG OVERFLOW	323	12.00
DEL NORTE AUG PLAN	48	2.90
DIEHL D	318	4.50
DUNNING MILL D	103	0.60
ENTERPRISE D	81	19.60
FISHBACK D 1	273	1.00
FISHBACK D 2	263	0.90
HECKER D	287	3.20
HELEN AND JULIA D	205	1.00
HERMANTHAL D	66	2.80
HILTON CR RIVER D	206	2.70
HOSSELKUS D	292	0.01
JESSUP D 1	174	1.72
JOHN ANDERSON D	77	3.20
KENILWORTH CNL	163	4.10
KNOBLAUCH D 1	115	3.86
LEASE,DAVIS AND BINGLE D	31	6.08
LOMA D	16	4.90

MEADOW OVERFLOW	30	67.00
MELLOTT AUG PLAN	2	0.14
MOORE D	306	6.00
RIO G SAN LUIS ENL SEEP	308	8.64
SCHACHERAL D	73	3.00
SHOUP D	282	0.50
SLOUGH D	177	2.00
SONDLES D	310	2.00
STANLEY KNAPP PUMP	321	6.00
STEWART D	322	20.00
TOWN OF CENTER AUG PLAN	76	0.40
WASON D	148	26.00

Analyzing nine years of data, 35 irrigation ditches and canals did not divert water in any year (Table A.11). These 35 ditches and canals hold decrees for 309.3 CFS which, because no water was diverted, are assumed to be non-active rights for this analysis. By removing these ditches from the analysis, the total amount of water decreed from the Rio Grande falls from 5729.3 CFS to 5420.0 CFS. The six ditches with the largest decrees represent 76.8% of diversions from the Rio Grande.

Eleven of the 35 ditches not included in the analysis hold priorities higher than 100 accounting for more than 130 CFS in decrees (Table A.8). Removing these decrees from the analysis allows the six ditches with the most decrees to account for more of the water in a drought situation.

Water Rights

Four of the six irrigation ditches and canals that account for most diversions from the Rio Grande are within the Closed Basin portion of the SLV. Water diversions for the Rio Grande Canal, Farmers Union Canal (now called the San Luis Valley Irrigation District), Prairie Ditch and the San Luis Valley Canal are explicitly simulated in the model. The Empire Canal (now called Commonwealth) and Monte Vista Canal are included in the “all other” category for which water diversions are accounted for the model, but crop production is not simulated. Diversions by all irrigation ditches or canals are accounted for to ensure available water for ditches explicitly addressed in the model is accurate.

The priority of water rights represents one of the key variables for determining which irrigation ditches receive water. The original data from the Division of Water Resources contained over 300 water right priorities for the six irrigation ditches with the most decrees and the single representative ditch which accounts for all other diversions. To simplify the data files, water rights for ditches with consecutive priorities were grouped together and considered a single water right with a single priority, which reduced the total number of priorities to 123. That is, when a single irrigation ditch or canal owned priority numbers 1, 2 and 3, they were combined to priority 1 with a diversion right equal to the sum of decrees for the three rights.

Each of the ditches were grouped together in relation to their geographic location in the SLV and the priority for each right identified as shown in Appendix A3.B and decree amount as shown in Appendix A3.C. The first number in the appendices is the numeric identifier and the second number represents the priority of the right in Appendix A3.B or the decree amount in Appendix A3.C. For example, the first 22 entries in Appendices A3.B and A3.C represent the priorities and water rights for the Rio Grande Canal which is located the furthest west of any ditches. In the priority file (Appendix C) and water right file (Appendix .D) water rights 55-123 represent the priorities and decrees for irrigation ditches that are not explicitly simulated in the model with representative agricultural areas. Appendix E identifies which irrigation ditches are associated with each numeric identifier.

Defining Representative Agricultural Areas

Representative agricultural areas were derived based upon location of the irrigation ditches and canals in relationship to soil characteristics, and locations of the underlying aquifers developed as a proxy for the Unconfined Aquifer. The Director of the San Luis Valley Water Conservation District provided a detailed map of the SLV which identified the areas serviced by each irrigation ditch and canal. These locations were mapped into a spreadsheet according to the U.S. Bureau of Land Management system of land subdivision (Quadrant, Township, Range and Section). The study area lies between Townships 39 and 43 North within Ranges 7 and 12 East. The map generated by combining the irrigation ditch areas, aquifer areas and classifying areas by soil characteristics is included in Appendix F.

Forty-seven representative agricultural areas were initially identified. However, when nine years of crop data were analyzed, no crops included in the model (alfalfa, barley and potatoes) were grown on four of the farms. In addition, ten of the farms were located on acres that did not own rights to surface water. Therefore, only 33 representative agricultural areas are simulated with two different soil types (sandy loam and loamy sand) that withdraw groundwater from 9 separate aquifers and divert surface water from five irrigation ditches or canals. Not all representative agricultural areas have access to groundwater, but all receive a portion of the surface water available. The methods used to define the acres of each crop, farm size, aquifers, soil characteristics, and allocation of surface and groundwater for the representative agricultural areas are included in the following sections.

Defining Crop Acres

Ten years of cropping data by quarter-section were obtained from the USGS for the study area. The data include the number of acres and location of each crop grown from 1983-1994.

Spreadsheet maps were generated documenting the location of the primary crop grown on each quarter-section to gain an understanding where different crops are grown in the study area. An example of this type of map is included in Appendix G. By knowing the Township, Range and Quarter-section of each crop, it can be mapped to the location of each representative farm so that the exact number of acres of each crop grown during the ten years can be placed directly at the farm location.

The primary crops for the region are alfalfa, barley and potatoes. Much of the barley is grown under contract with the Coors Brewing Company, but the higher prices paid for the grain is not considered in this analysis. The model simulates crop production on 112,129 acres which include 16,124 acres of alfalfa, 51,451 acres of barley, and 44,554 acres of potatoes. These data represent the ten year average production acres for each crop. Using the average acres allocated to each crop over a historical period accounts for crop rotation sequences. For example, barley and potatoes are generally grown on the same fields. A ten year average accounts for the proportion acres allocated to each crop and accounts for crop rotations and changing cropping patterns. Acreage allocated to each crop is constrained to the average maximum acres of the crop grown during the ten years. That is, a representative farm is constrained in the model to producing no more alfalfa than has been historically produced on the given acres of the farm. The maximum acres of each crop are defined in the input file CropLimit.txt as presented in Appendix H.

The maximum size of each representative farm is the sum of the acres allocated to each crop. The model input file representing farm size is included as Appendix .I. Representative farm sizes range from 154 to 12,847 acres as identified in the input file Farm Acre.txt.

Defining Aquifers

The Unconfined Aquifer represents the sole source of groundwater for agricultural production within the study area. The depth to groundwater, depth to the bottom of the aquifer, and the dynamics of return flows from irrigation activities presented complications when trying to model the single large aquifer. The aquifer is simulated in the model by dividing the Unconfined Aquifer into nine separate smaller aquifers with similar characteristics that were defined through three steps.

First, the blue clay layer, which separates the Unconfined from the Confined Aquifer, represents the depth of the Unconfined Aquifer, which changes from north to south and west to east in the Closed Basin. The depth to the blue clay layer for all parts of the Unconfined Aquifer by Township, Range and Section were obtained from the Colorado Division of Water Resources and incorporated into a spreadsheet. The standard deviation of the depth to the blue clay layer for all cells within a defined aquifer ranged from 5 to 9.3 feet or about 8%. Depths to the blue clay ranged from 50 to 130 feet.

Second, the elevation of each Section within the study area was derived from topographic maps of the region. Aquifers defined for the model were further divided by grouping areas of similar elevations. The elevation of the study area ranges from 7,545 in the northeast to 7,760 feet in the west. The standard deviations of the differences between elevations within an aquifer ranged from 5.6 to 8.9 feet.

Third, to prevent the height of the aquifer from being above the surface, the relative elevation of the blue clay layer was determined by subtracting the depth to blue clay from the elevation at the surface. Each aquifer was then defined by identifying those cells (Sections) with similar relative elevations of the blue clay layer and height to the surface. In general, the aquifer locations cover areas from northwest to southeast with surface areas that range from 4,480 to 65,920 acres.

Aquifer volume, representing the amount of water available for pumping, is addressed as a parameter for the first time period in the GAMS model as V(o). Water available from the aquifer changes during the cropping season. Withdrawals for irrigation, recharge from water placed in recharge pits, and drainage from irrigation due to sprinkler inefficiencies (IrrigEff.txt) and non-consumptive use by crops (RtnFrac.txt - not included as an appendix because the parameters are constant (0.95) for all farms) make the aquifer volume dynamic.

Defining Areas with Similar Soil Characteristics

Colorado County Soil Surveys for Alamosa, Conejos, Costilla, and Rio Grande were used to identify the soil characteristics for the optimization model and for the crop growth simulation model used to derive the crop coefficients. The study area consists of over 44 different soil types that represent more than 50% of the soil in a given section. Soil classifications for the primary soil in each Section were identified to determine if the area could be represented by a few soils. The soils generally range from loamy sand to gravelly sandy loam. For the simulation model soils were identified as either sandy or loamy sand to account for the most likely differences between the actual soils found in the area. The soil type associated with each representative farm, the ditch and aquifer where they withdraw water are included in Appendix J. The specific soil characteristics are not included explicitly in the model. Crop coefficients for each production function are determined by the soil type and assigned accordingly to each representative farm.

Allocation of Surface Water to Representative agricultural areas

Ditch shares are used in the model to allocate water from irrigation ditches and canals to representative agricultural areas. Ditch shares are distributed differently in the study area, depending upon the irrigation ditch company. When the irrigation ditches were built, shares were distributed equally to producers diverting water from the ditch so that all farms of the same size were entitled to the same amount of water. Over time, ditch shares were sold or traded until today when shares are not owned in proportion to the size of farm. For example, quarter sections on the Rio Grande Canal hold from 5-35 shares with each share receiving the same amount of water. The number of shares owned by each quarter section within the model is not known.

The Farmer's Union Canal (San Luis Valley Irrigation District) is unique because it issues each farm on the ditch one share for each quarter-section of cropland and water is then allocated equally to each share holder. Farm share of each ditch was determined by running the model with water allocated proportionate to farm size, then changing proportions until the historical cropping patterns for all farms were simulated. Each representative farm's share of water from irrigation ditches and canals is identified in the FarmShare.txt input file included as Appendix AK.

Surface water is not typically applied directly to fields for crop production within the study area. Between 80-95% of the irrigated acreage in the study area use recharge pits where surface water is diverted to a reservoir from which water is pumped to the center pivot for irrigation or drains directly into the aquifer through infiltration. A small cost penalty that is higher than pumping costs is applied within the GAMS model to prevent irrigation activities that apply surface water diverted from irrigation ditches directly to the field. For simplicity, in this analysis all water applied to recharge pits adds to available water in the aquifer for the farm associated with that aquifer. Representative agricultural areas are constrained to pumping no more than their combined groundwater right and recharge amount which are tracked separately throughout the simulation. Groundwater rights are separate and distinct from surface water rights, so surface water used to recharge the aquifer may be pumped without infringing upon the groundwater right.

Allocation of Groundwater to Representative Agricultural Areas

Groundwater pumping is constrained by whether a farm owns a groundwater right, the pumping capacity of the farm and available groundwater. Data for groundwater rights for the study area were obtained from the Colorado Division of Water Resources. Rights were correlated to the representative agricultural areas through Township, Range and Section as identified in the data. Groundwater rights are defined in CFS, which were converted to acre feet (AF) per month for inclusion in the model. Groundwater rights for each of the 33 representative agricultural areas are identified in Appendix L. Representative agricultural areas that do not have a groundwater right may only pump groundwater if they have added water to the aquifer through recharge pits.

Pumping capacities for each representative farm were determined by estimating the potential amount of water that could be applied to fields if center pivots were run continuously 24 hours/day for the length of the growing season. The number of center pivots on each farm is a function of total farm acres - one center pivot for each 130 acres of cropland.

The amount of groundwater in the aquifer may decline over time from decreased snow melt infiltration and if return flows from irrigation and recharge pits are not sufficient to maintain the aquifer at capacity. Representative agricultural areas are further restricted to pumping less than their aquifer share, which is based upon the size of the farm. That is, the farm's aquifer share is a function of the total acres that are above the aquifer. Aquifer share, as defined for the input file for the model, is included as Appendix M.

The amount of applied water available for crop growth is determined by the irrigation efficiency of the irrigation systems. Center pivots in the study area are of similar age and efficiency and are therefore treated that way in the analysis. An efficiency rating of .80 is used for all systems in the analysis as defined in the IrrigEff.txt input file (not included as an appendix because the parameter is constant for all farms, but may be adjusted for model refinement in the future).

Costs and Returns

Enterprise budgets were developed from budgets generated by Colorado State University (Dalsted et al.), data from the Colorado State University custom rates survey (Tranel et al.) and local data generated by Agro Engineering (ter Kuile). Crop budgets for each crop analyzed are included in Appendices N - P . The crop budget identifies variable and fixed costs of all pre-harvest, harvest and operating costs.

Description of Crop Growth Simulation Model

Coefficients for crop production functions were developed for the crops considered in the GAMS model using the crop growth simulation model developed by Cardon (1990). The modified van Genuchten-Hanks model combines a FORTRAN model developed by van Genuchten that simulates transpiration and redistribution of water and the Hanks BASIC model that simulates irrigation/infiltration. The model employs a daily time-step to simulate the relationships between water and soil, water and plant growth and yield and evapotranspiration (ET) to derive relative yield parameters based upon water available for plant growth. It simultaneously simulates water movement through the soil profile and water uptake by the plant through a series of equations from the two separate models. Site specific input files were generated to reflect growing conditions in the study area. The remaining paragraphs of this section describe the crop growth simulation model parameters used.

The crop growth simulation model requires data for the hydraulic properties of the simulation site, specifically the water content, matric potential and hydraulic conductivity. Water contents were varied from 0.02 to 0.50 cm^3/cm^3 in increments of .02, as shown in Appendix Q for sandy loam soils and Appendix .R for sandy soils, to calculate matric potential and hydraulic conductivity. Matric potential, as identified in the last column of Appendices Q and R for sandy loam and sandy soils, is calculated using equation A3.1.

$$H=He\ (\Phi/\Phi_s)^{-b} \qquad \text{(A3.1)}$$

Where: H = matric potential

He = air entry water potential constants (-15.98 for sandy soils and -30.20 for sandy loam soils)(Rawls, Ahuja and Brakensiek)

Φ = soil water content

Φ_s = soil water content at saturation

b = constant parameter equal to 2.87 for sandy soils (Ghosh) and 3.5 for sandy loam soils (Campbell).

The unsaturated hydraulic conductivity is estimated using a single hydraulic content measurement and a moisture retention function (Campbell):

$$K = K_{sat}(\Phi/\Phi_s)^{B} \qquad \text{(A3.2)}$$

Where: K = unsaturated hydraulic conductivity

K_{sat} = saturated hydraulic conductivity (468 cm/hr for sandy soils and 62.16 cm/hr for sandy loam soils) (Rawls, Ahuja and Brakensiek)

Φ = soil water content

Φ_s = soil water content at saturation

B = parameter equal to 4.48 for sandy soils (Ghosh) and for sandy loam soils (Campbell)(unitless).

The data from these equations are included in input files to run the crop simulation model. Appendix A3.R provides an example of the "Han.dat" (for the Hanks portion of the model) input file that includes irrigation, rainfall, matric potential and hydraulic conductivity parameters. The number of irrigation events was varied to simulate changing water availability for to generate crop production functions. Alfalfa was provided up to 21, potatoes 24 and barley 16 irrigation events during the growing season with varying amounts of water. To limit the number of permutations required to generate an adequate production function, pair-wise combinations of possible irrigation strategies were simulated that required 2,047, 256, and 4,095 input files for each of the crops and for each soil type analyzed to be generated.

Planting, irrigation and rainfall dates for each of the crops simulated (alfalfa, barley and potatoes) are included in Appendices U - V. Rainfall is incorporated into the model the day after irrigation occurs because this is the standard practice for adding water to the simulation model and because rainfall in the study area is minimal during the growing season. Irrigation generally begins on 15 April for all crops and continues until just before harvest. Scheduling for irrigation events were derived from expert opinion (Colorado State University Cooperative Extension at the San Luis Valley Research Center and Agro Engineering).

A second input file, “Van.fmk” (for van Gunechten), is in the FORTRAN portion of the model which is generated once (Appendix W). Included in this file are the crop coefficients, potential ET, rooting depth, osmotic salt potential, and matric potential at which yield is reduced by 50%. The osmotic potential is not relevant for this study, but is included in the input file. In the row above these columns are additional soil property variables. The first variable, 468, represents the saturated hydraulic conductivity for sandy soils. Next is the total porosity followed by the matric potential at the inflection point defined by Hutson and Cass which is calculated as:

$$H_i = a(2b/(1+2b))^b \qquad \text{(A3.3)}$$

Where: H_i = pressure potential inflection point

a = air entry water potential (a constant equal to -15.98 cm for sandy soils and -30.20 for sandy loam soils)(Rawls, Ahuja and Brakensiek)

b = constant parameter equal to 2.87 for sandy soils (Ghosh) and 3.5 for sandy loam soils (Campbell).

Relative yield parameters for each crop are derived by taking the ratio of model generated ET to potential ET (USDA) for the study area. Figures 1 – 6 Provide the data points generated by the crop simulation model for each combination of irrigation strategies. Figures 7 – 12 show the production functions resulting from fitting a line to the point of maximum relative yield for each irrigation combination (no irrigation, one irrigation, two irrigations, and so on, with each irrigation at a different time).

FIGURES SUMMARIZING AGRONOMIC DATA FOR ECONOMIC ANALYSIS OF DROUGHT FOR AGRICULTURE, SAN LUIS VALLEY, COLORADO

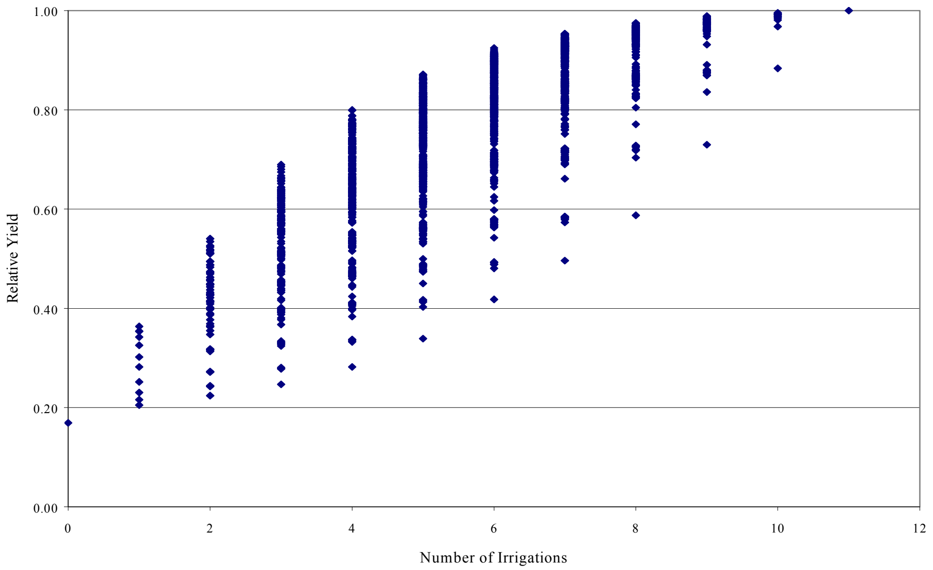


Figure 1. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Alfalfa on Sandy Soil

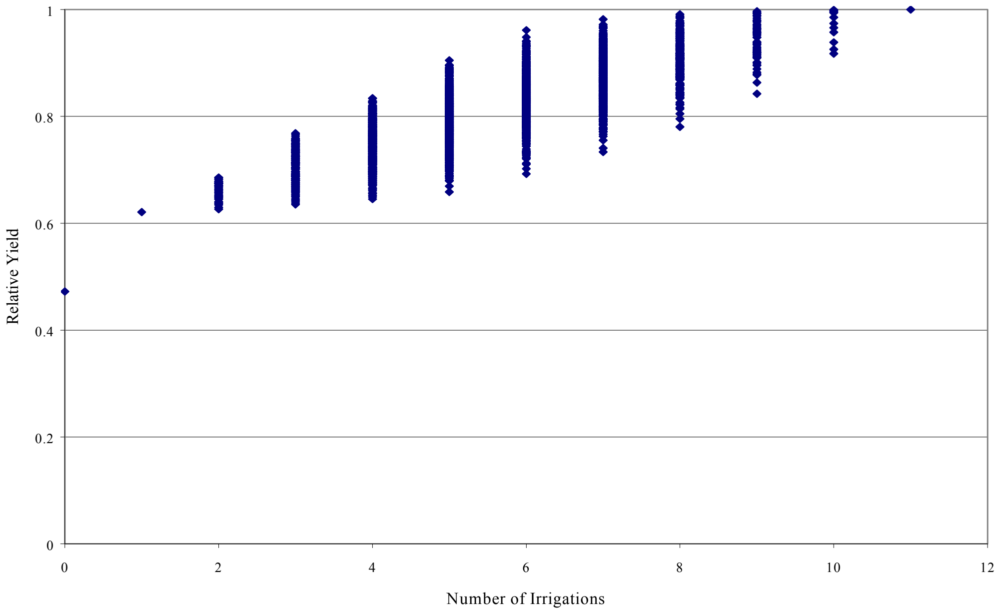


Figure 2. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Alfalfa on Sandy Loam Soil

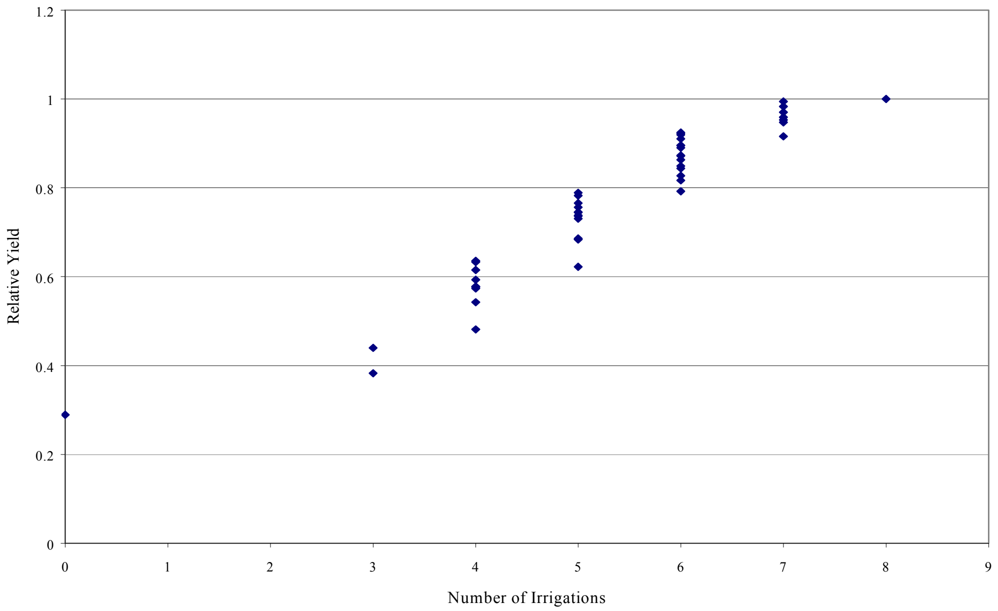


Figure 3. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Barley on Sandy Soil

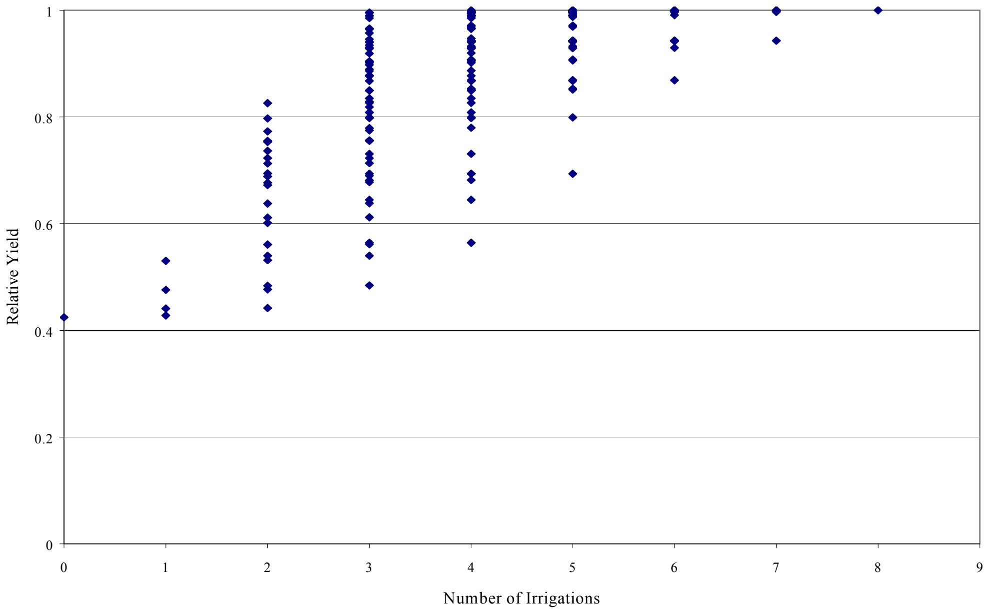


Figure 4. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Barley on Sandy Loam Soil

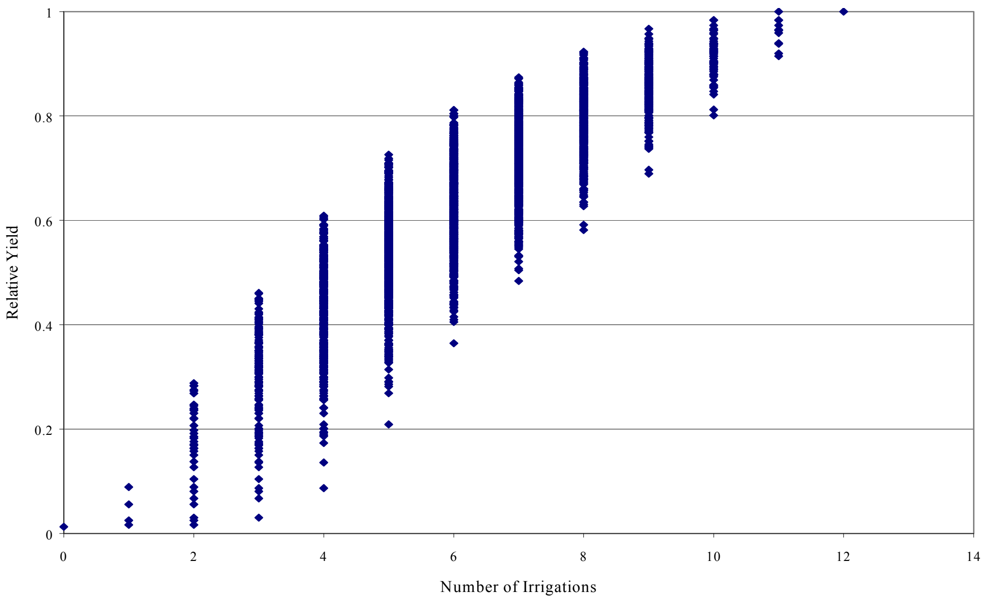


Figure 5. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Potatoes on Sandy Soil

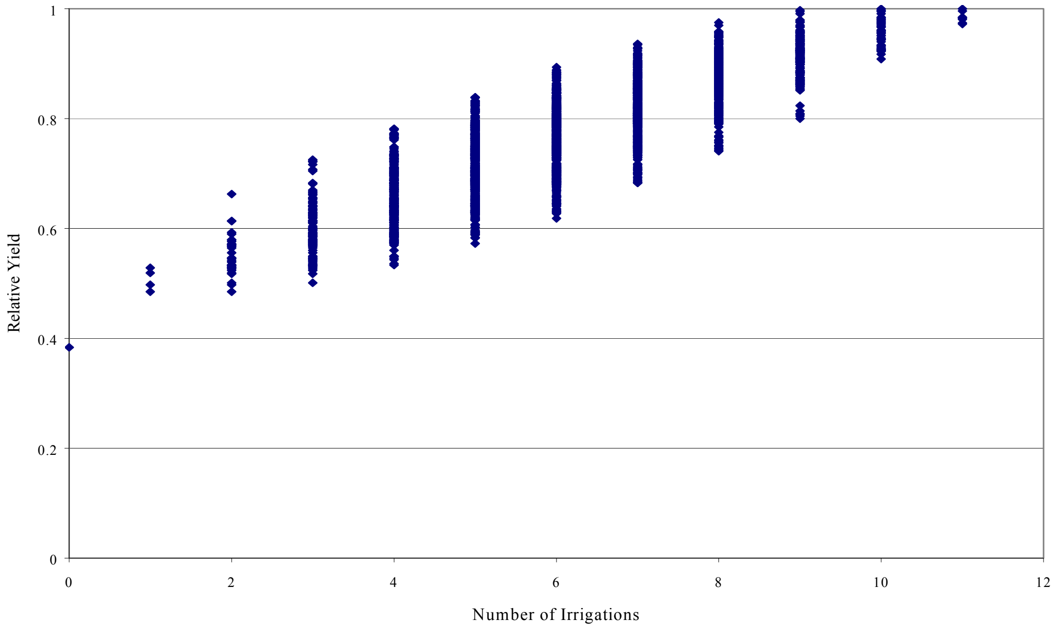


Figure 6. Relative Yield from Crop Growth Simulation Model with Each Possible Irrigation Combination for Potatoes on Sandy Loam Soil

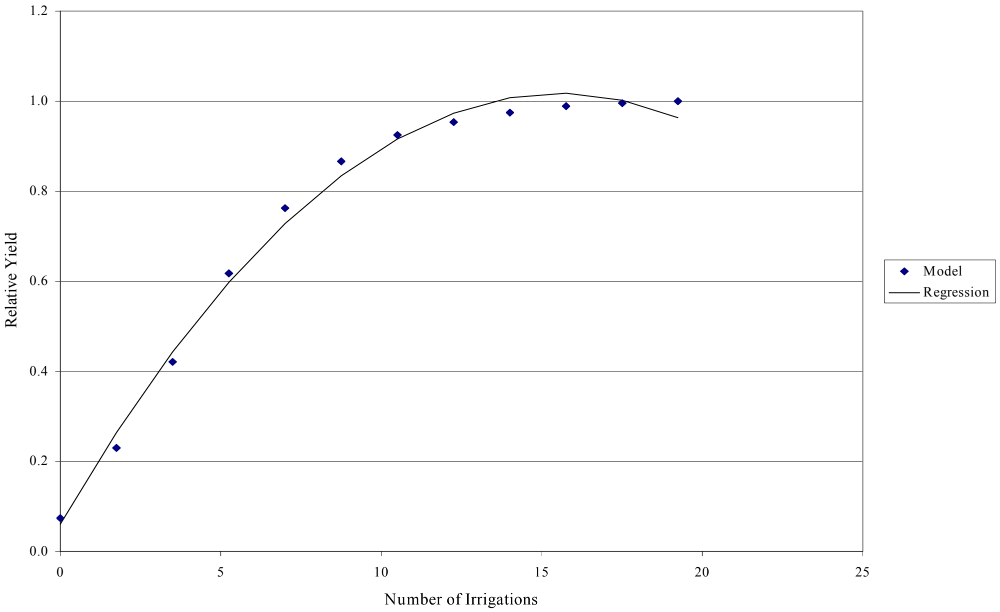


Figure 7.
Regression Results to Derive Crop Growth Coefficients for Alfalfa on Sandy Soil

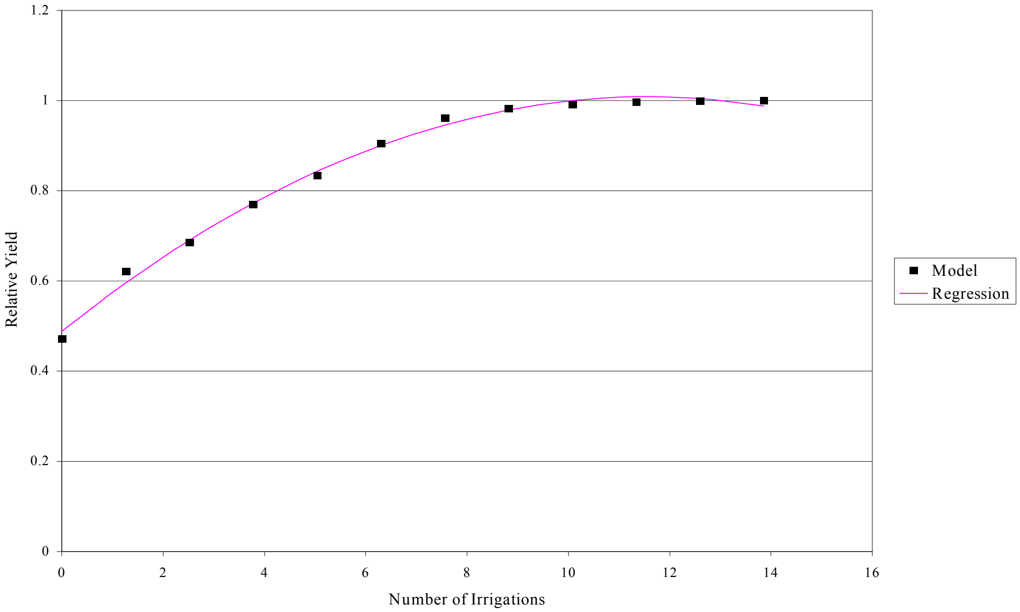


Figure
A3.8. Regression Results to Derive Crop Growth Coefficients for Alfalfa on Sandy Loam Soil

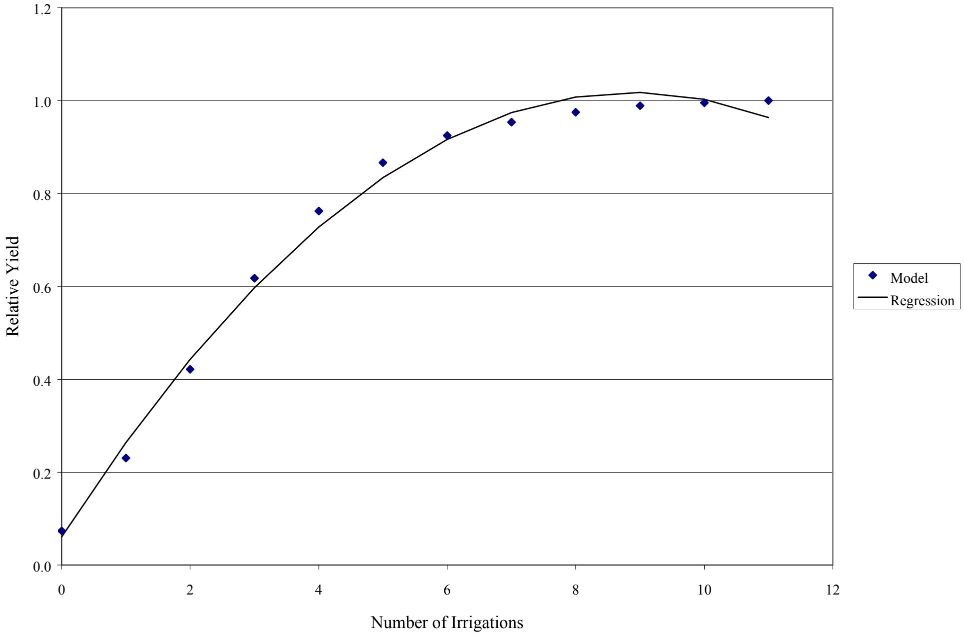


Figure 9. Regression Results to Derive Crop Growth Coefficients for Barley on Sandy Soil

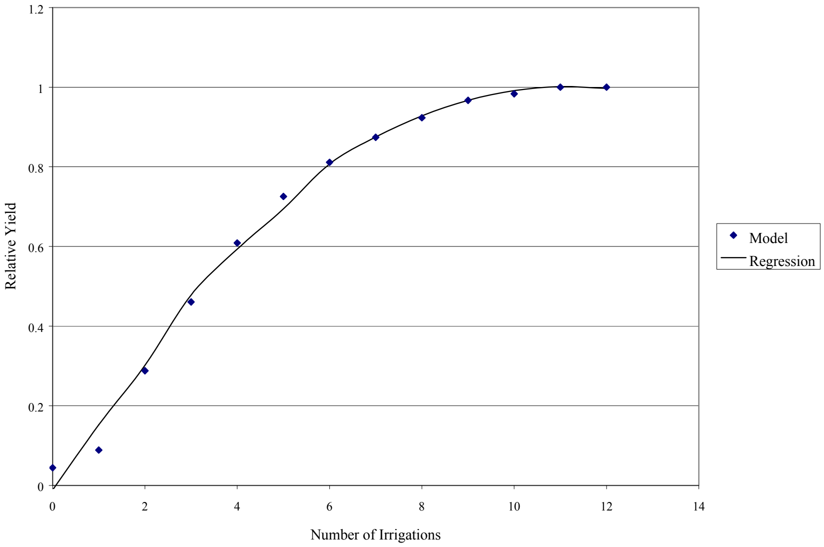


Figure A3.10. Regression Results to Derive Crop Growth Coefficients for Barley on Sandy Loam Soil

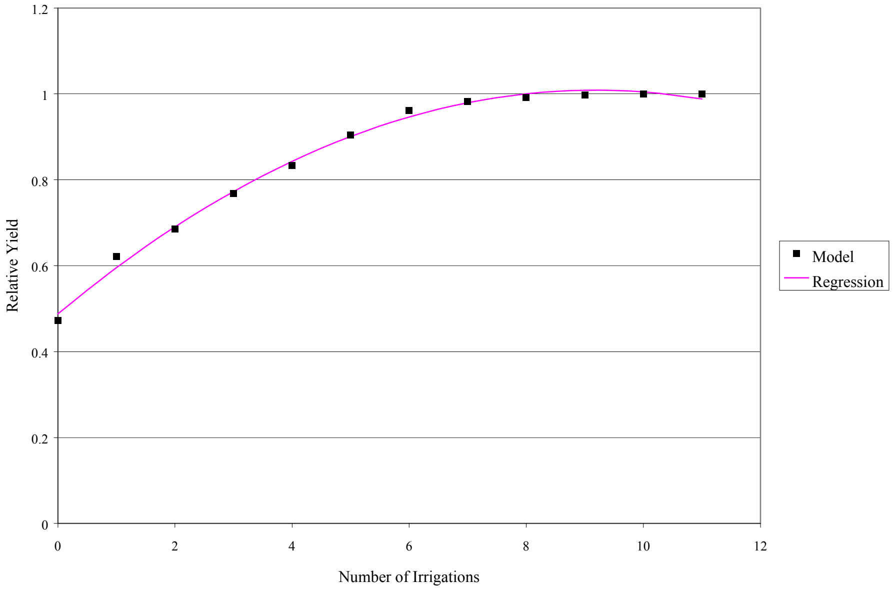


Figure A3.11. Regression Results to Derive Crop Growth Coefficients for Potatoes on Sandy Soil

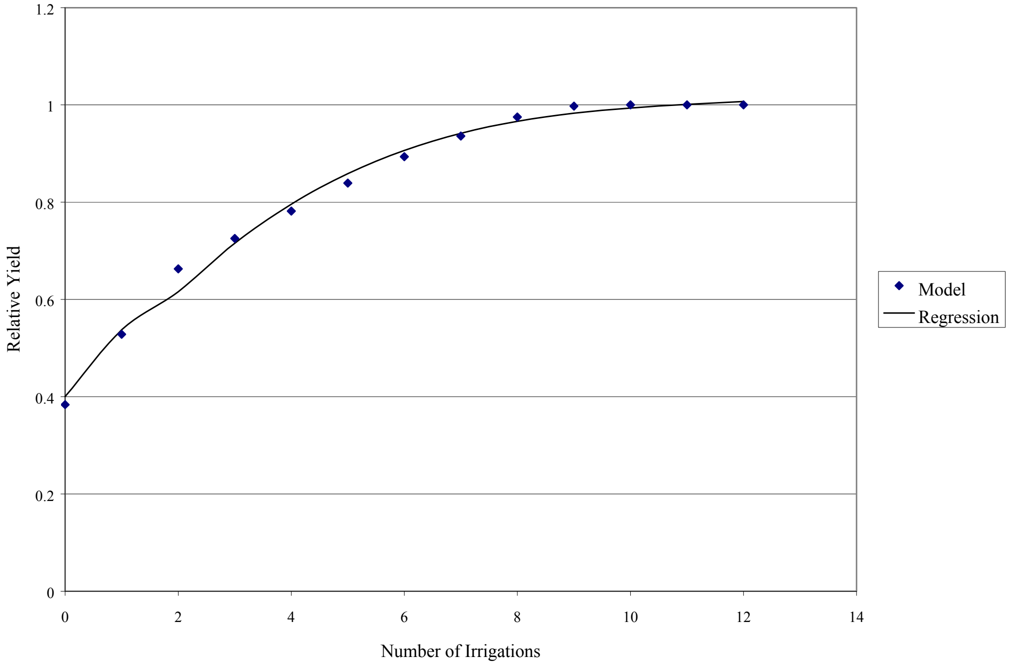


Figure 12. Regression Results to Derive Crop Growth Coefficients for Potatoes on Sandy Loam Soil

Appendix B: GAMS Code for Farm Income Maximization Model in Drought, San Luis Valley, Colorado

```
$INLINECOM { }
{In this model surface and groundwater share is attached to the farm rather than ditch.
 Farm ID, ditch ID, and aquifer ID are arbitrary and independent from one another.  }

SETS
   i  rights /1*124/
   l  ditches /1*5/
   c  crops /alfalfa, barley, potatoes/
   M  farms /1*33/
   t  months /1*6/
   q  aquifer cell /1*9/
   alias (i,j);

PARAMETERS

FarmAcre(M)       total farm acre limit on farm M  {acres}
$Include FarmAcre.txt

ETA(M)            irrigation efficiency by farm  {water consumed/water applied}
$Include IrrigEff.txt

PRICE(c)          per-unit-yield crop prices  {$/unit}
/Alfalfa    85.00
 Barley     3.26
 Potatoes   5.50/

PAVC(c)           per-acre variable costs  {$/acre}
/Alfalfa     129.60
 Barley      179.66
 Potatoes     596.12/

PYVC(c)           per-unit-yield variable costs  {$/unit}
/Alfalfa    24.25
 Barley     .34
 Potatoes   .12/

Vo(q)                 starting volume of aquifer cells  {70% of capacity, ac ft}
$Include aq0.txt

MTCHARGE(t)           aquifer recharge {ac ft}
$Include MtChg0.txt

DITCHID(l)            numeric ditch identifier {ordinal upstream to downstream}
```

```
$Include DitchID.txt

WATERRIGHT(i)      quantity of right i   {ac ft}
$Include WaterRight.txt

PRIORITY(i)           priority of right i   {ordinal earliest to latest}
$Include Priority.txt

OWNER (i)              maps ditch receiving diversion from right i
$Include Owner.txt

INFLOW (t)             monthly stream inflows {ac ft}
$Include Inflow0.txt

GWRT(M)                groundwater decree amount
$Include GWRight.txt

{DWCOST(M)          ditch share assessment {$}
$Include DWCost.txt}

ALLOCATION(l,t)    amount of water diverted in model PA   {ac ft}
;
                       {per-acre crop yield equation coefficients for crop c on farm M}
                       {functional form:   a + b*water +d*water^2 + e * water^3}

TABLE a(M,c)          intercept coefficients for production functions
$Include TableA.txt
;

TABLE b(M,c)          slope coeffiencts for production functions
$Include TableB.txt
;

TABLE d(M,c)          slope coeffiencts for production functions
$Include TableC.txt;
TABLE e(M,c)          slope coeffiencts for production functions
$Include TableD.txt
;

TABLE y(M,c)          Crop yield per acre
$Include TableY.txt
;

TABLE NIRL(M,c)    initial net irrigation level
$Include NIRL.txt
;
```

```
TABLE CropLimit(M,c)  acre limitation of farm M for each crop   {acres}
$Include Croplimit.txt
;

TABLE SHARE(M,l)      farm M's share of ditch l (each column sums to 1)  {decimal %}
$Include DShare.txt
;

TABLE PUMPCAP(M,q)  farm M's monthly pump capacity in aquifer cell q   {ac ft}
$Include PumpCap.txt
;

TABLE AQSHARE(M,q)      farms share of aquifer cell q {ac ft}
$Include AqShare.txt
;

TABLE RTNFRAC(M,q)   portion of farm M's nonconsumption returning to aquifer
                              cell q   {deci %}
              {each row sums to proportion of nonconsumption returning to aquifer}
$Include RtFrac.txt
;

VARIABLES
                 {River Flow Variables (monthly)}

FLOW(i,t)               stream flow at right i in month t   {ac ft}
DIVERT(i,t)             diversion for right i in month t   {ac ft}
DITCH(l,t)              amount of water diverted to ditch l in month t   {ac ft}

                 {Crop Growth Variables}

CROPACRE(M,c)      number of acres on farm M planted to crop c   {acres}
CROPY(M,c)            per-acre yield of crop c on farm M   {units/acre}
RELY(M,c)              relative yield parameter
NETRET(M,c)          per-acre net returns of crop c on farm M   {$/acre}
TOTNET(M)             total net returns including ditch share  {$/farm}

                 {Variables Describing Amount of Available Water}

DRAIN(q,t)              applied water percolating to aquifer cell q in month t {ac ft}
V(q,t)                     volume of available water in aquifer cell q in month t   {ac ft}
SURFACE(M,t)         amount of surface water applied to farm M in month t   {ac ft}
PUMPED(M,q,t)       amount of ground water applied to crop c on farm M in month t from
                           cell q {ac ft}
WAPPRATE(M,c,t)   per-acre water applied to crop c on farm M in month t   {ac ft/ac}
WAPPLIED(M,t)       total water applied to farm M in month t   {ac ft}
NIR(M,c)                net irrigation rate of crop c on farm M   {ac in/ac}
```

```
RECHARGE(M,q,t)   total water applied to recharge pits {ac ft}
SURFAPP(M,c,t)    amount of surface water applied directly to crop {ac ft}
SAPCST(M,c)       small cost for applying surface water directly to crop {$}
PUMPCST(M,q)      small cost for applying groundwater to crop {$}
RECHGLIM(M,q,t)   limit groundwater applied to crop to amount recharged by farm {ac ft}

OBJPA             objective function for prior appropriation  {ac ft}
OBJNFI            objective function for net farm income  {$};

POSITIVE VARIABLES  FLOW, DIVERT, DITCH, CROPACRE, CROPY, RELY,
DRAIN, V, SURFACE, PUMPED, WAPPRATE, WAPPLIED, NIR, RECHARGE, SAPCST,
SURFAPP;

EQUATIONS
                {River Flow Equations}

ERIGHT(i,t)          set waterright limit
EFLOW(i,t)           stream flow at right i
EDIVERT(i,t)         diversion for right i
EPRIORITY(i,t)       enforce prior approp
EDITCH(l,t)          determine amount of water in ditch
EALLOCATE(l,t)       water available from ditch to apply to crop

                {Water Availability and Application Equations}

EV(q,t)              volume of aquifer
EDRAIN(q,t)          amount of aquifer recharge from water applied to crops
ESURFACE(M,t)        amount of surface water applied on crop
EAQLIM(q,t)          limits pumping to ground water available
EWAPPLIED(M,t)       total water applied on farm M
EPUMPCAP(M,q,t)      limit farm level pumping to pump capacity
EWAPPLIM(M,t)        limit total water applied to pumped and diverted water
ENIR(M,c)            net irrigation rate of crop c on farm M
ERECHARGE(M,q,t) water reaching aquifer from recharge pits
ESURFAPP(M,c,t)      amount of surface water applied to field
ESURLIM(M,q,t)       limits amount of surface water available
ESAPCST(M,c)         applies cost to applying surface water directly to crop
EPUMPCST(M,q)        small pumping cost for groundwater
ERECHGLIM(M,q,t) limits pumping to what farm added to aquifer
ESURFAPLIM(M,t)      limits surface applied to amount available
EPUMPLIM(q,t)        limits total pumping to less than aquifer volume

                {Crop Growth Equations}

ERELY(M,c)           relative yield
ECROPLIM(M,c)        acre limit of crop c on farm M
EFARMACRE(M)         acre limit on farm M
```

```
ECROPY(M,c)          yield of crop c on farm M
ENETRET(M,c)         net return from crop production
ETOTNET(M)           total net returns

EOBJPA               objective function for prior appropriation
EOBJNFI              objective function for farm income;

ERIGHT(i,t)..     DIVERT(i,t) =l= WATERRIGHT(i);

EFLOW(i,t)..      FLOW(i,t) =e= INFLOW(t)        $(ord(i) eq 1) +
                              (FLOW(i-1,t) - DIVERT(i-1,t) $(ord(i) gt 1));

EDIVERT(i,t)..     DIVERT(i,t) =l= FLOW(i,t);

EDITCH(l,t)..     DITCH(l,t) =L= SUM(i,(DIVERT(i,t)*
                               (OWNER(i) eq DITCHID(l))));

EALLOCATE(l,t)..   DITCH(l,t) =E= ALLOCATION(l,t);

EV(q,t)..         V(q,t) =E= Vo(q) $(ord(t) eq 1) +
                          (V(q,t-1) + SUM(M,RECHARGE(M,q,t-1)) +
                          DRAIN(q,t-1)  - SUM(M,PUMPED(M,q,t-1))+MTCHARGE(t)
                      $(ord(t) GT 1));

EVLIM(q,t)..      VLIM(q,t) =L= 1.3 * V(q,t);

EDRAIN(q,t)..      DRAIN(q,t) =E= SUM(M, (1-eta(M))*
                                WAPPLIED(M,t)*RTNFRAC(M,q));

ESURFACE(M,t)..    SURFACE(M,t) =E= SUM((l),DITCH(l,t) * SHARE(M,l));



ERECHARGE(M,q,t)..
        RECHARGE(M,q,t) =E=(SURFACE(M,t) - SUM(c,SURFAPP(M,c,t)))
                                  * (AQSHARE(m,q) gt 0);

ESURFAPLIM(m,t)..  SUM(c, SURFAPP(m,c,t)) =L= SURFACE(m,t);

ESAPCST(M,c)..     SAPCST(M,c) =E= SUM((t), SURFAPP(M,c,t)) * 5;
EPUMPCST(M,q)..    PUMPCST(M,q) =E= SUM(t, PUMPED(M,q,t))* 1 ;

EPUMPCAP(M,q,t)..  PUMPED(M,q,t) =L= min(PUMPCAP(M,q), RECHARGE(M,q,t) +
        GWRT(M), (AQSHARE(M,q) * V(q,t)));

EPUMPLIM(q,t)..    SUM(M, PUMPED(M,q,t)) =L= V(q,t);
```

```
EWAPPLIED(M,t)..   SUM((c),WAPPRATE(M,c,t)*CROPACRE(M,c)) =E=
          WAPPLIED(M,t);

EWAPPLIM(M,t)..    WAPPLIED(M,t) =l=  sum(c,SURFAPP(M,c,t)) +
          SUM(q,PUMPED(M,q,t));

ENIR(M,c)..             NIR(M,c) =E= 12 * SUM(t, WAPPRATE(M,c,t))*ETA(M);

ERELY(M,c)..            RELY(M,c) =E= a(M,c) + b(M,c)*NIR(M,c) + d(M,c)*NIR(M,c)**2 +
                        e(M,c) * NIR(M,c)**3;

ECROPY(M,c)..           CROPY(M,c) =E= RELY(M,c) * y(M,c);

ENETRET(M,c)..          NETRET(M,c) =E= (PRICE(c)-PYVC(c))*CROPY(M,c) *
                        CROPACRE(M,c)  - PAVC(c)*CROPACRE(M,c)  - SAPCST(m,c) -
                        (CROPACRE(m,c) + .0000001)/FARMACRE(m)) *
                        SUM(q,PUMPCST(m,q));

ECROPLIM(M,c)..    CROPACRE(M,c) =L= CROPLIMIT(M,c);

EFARMACRE(M)..     SUM(c, CROPACRE(M,c)) =L= FARMACRE(M);

ETOTNET(M)..            TOTNET(M) =E= SUM(C, NETRET(M,c));
NIR.L(M,c) = NIRL(M,c);
NIR.lo(M,c) = .01;
RELY.UP(M,c) = 1;

EOBJPA..                OBJPA =E= SUM((i,t),(1/PRIORITY(I)**2) * DIVERT(i,t));

EOBJNFI..               OBJNFI =E= SUM((M,c), NETRET(M,c));

model PA /ERIGHT, EFLOW, EDIVERT, EDITCH, EOBJPA/;

model FARMALLOC /EALLOCATE, EV, EDRAIN, ESURFACE, ERECHARGE,
EWAPPLIED, EPUMPCAP, EWAPPLIM, ENIR, ERELY,
ESURFAPLIM, EPUMPLIM,  ECROPLIM, EFARMACRE, ECROPY,    ENETRET,
ESAPCST, EPUMPCST, ETOTNET,EOBJNFI/;

option NLP=MINOS5;
PA.OPTFILE = 1;

solve PA using dnlp maximizing OBJPA;    {solve water allocation via prior appropriation}

ALLOCATION(l,t) = DITCH.L(l,t);          {Amount of Water available for
                              crop = amount in ditch}
option NLP=MINOS5;
FARMALLOC.OPTFILE = 1;
```

```
solve FARMALLOC using dnlp maximizing OBJNFI;
Vo1(q) = V.L(q,"6");

{write output file for import into Excel}

option decimals = 2;
file out /rg5.txt/;
out.ap = 2;
put out;
out.pc = 5;
out.nd = 2;
out.pw = 255;

parameters
  SWAT(m,c)
  GWWAT(M,c)
  TWAPP(M,c)
  RCHG(M,c)
  precip(m,c);

swat(m,c)=0;
gwwat(M,c) = 0;
TWAPP(M,c) = 0;
RCHG(M,c) = 0;
precip(m,c) = 0;

put "Objective Value =" objnfi.l/;

loop(t, swat(m,c)=swat(m,c)+surfapp.l(m,c,t));
loop(t,
  loop(q, gwwat(M,c) = gwwat(M,c) +  PUMPED.l(M,q,t)));
loop(t, TWAPP(M,c) = TWAPP(M,c) + wapprate.l(m,c,t)*cropacre.l(m,c));
loop(t,
  loop(q, RCHG(M,c) = RCHG(M,c) + RECHARGE.l(M,q,t)));

loop(m,
   put "Farm", "Crop", "Acres", "Rel Yield", "Irrigation",
       "Surf Wat", "Ground Wat", "Recharge", "TotWat App", "Net Returns",
       "Crop Yield", "Surf App Costs"/;
   loop(c,put m.tl, c.tl, cropacre.l(M,c), rely.l(M,c),
         nir.l(M,c), swat(m,c), gwwat(M,c), rchg(M,c),
         twapp(M,c), netret.l(M,c), cropy.l(m,c), sapcst.l(M,c)/));
put //;

option decimals = 2;
file out2 /TOTNET5.txt/;
out2.ap =1;
```

```
put out2;
out2.pc = 5;
out2.nd = 0;
out2.pw = 255;

Parameters
 CropA(c);
 CropA(c) = 0;

put "Alfalfa", "Barley", "Potatoes" put/;
loop(c, cropa(c) = cropa(c) + sum(m, cropacre.l(m,C)));
loop(c, put cropa(c)) PUT /;
PUT "Farm", "Total Returns", "Diversion Costs", "Alfalfa", "Barley", "Potatoes"/;
LOOP(M, PUT ORD(M), TOTNET.L(M), {DWCOST(M), }cropacre.l(m, "alfalfa"),
cropacre.l(m, "barley"),
        cropacre.l(m, "potatoes"), put/);
```

Appendix C: GAMS Model Input File for Ditch Priority, San Luis Valley, Colorado

Ditch ID	Priority	Ditch ID	Priority	Ditch ID	Priority	Ditch ID	Priority
1	4	32	8	63	30	94	40
2	6	33	38	64	41	95	43
3	14	34	56	65	42	96	47
4	16	35	63	66	12	97	50
5	23	36	70	67	51	98	53
6	31	37	78	68	59	99	55
7	33	38	84	69	73	100	57
8	39	39	90	70	81	101	62
9	44	40	96	71	87	102	64
10	45	41	102	72	93	103	67
11	46	42	108	73	99	104	69
12	58	43	2	74	105	105	71
13	65	44	18	75	111	106	75
14	72	45	21	76	115	107	77
15	80	46	28	77	122	108	79
16	86	47	36	78	1	109	83
17	92	48	48	79	3	110	85
18	98	49	52	80	5	111	89
19	104	50	60	81	7	112	91
20	110	51	66	82	9	113	95
21	114	52	74	83	11	114	97
22	119	53	82	84	13	115	101
23	20	54	88	85	15	116	103
24	25	55	94	86	17	117	107
25	27	56	100	87	19	118	109
26	35	57	106	88	24	119	113
27	49	58	112	89	26	120	116
28	54	59	117	90	29	121	118
29	61	60	120	91	32	122	121
30	68	61	10	92	34	123	123
31	76	62	22	93	37	124	124

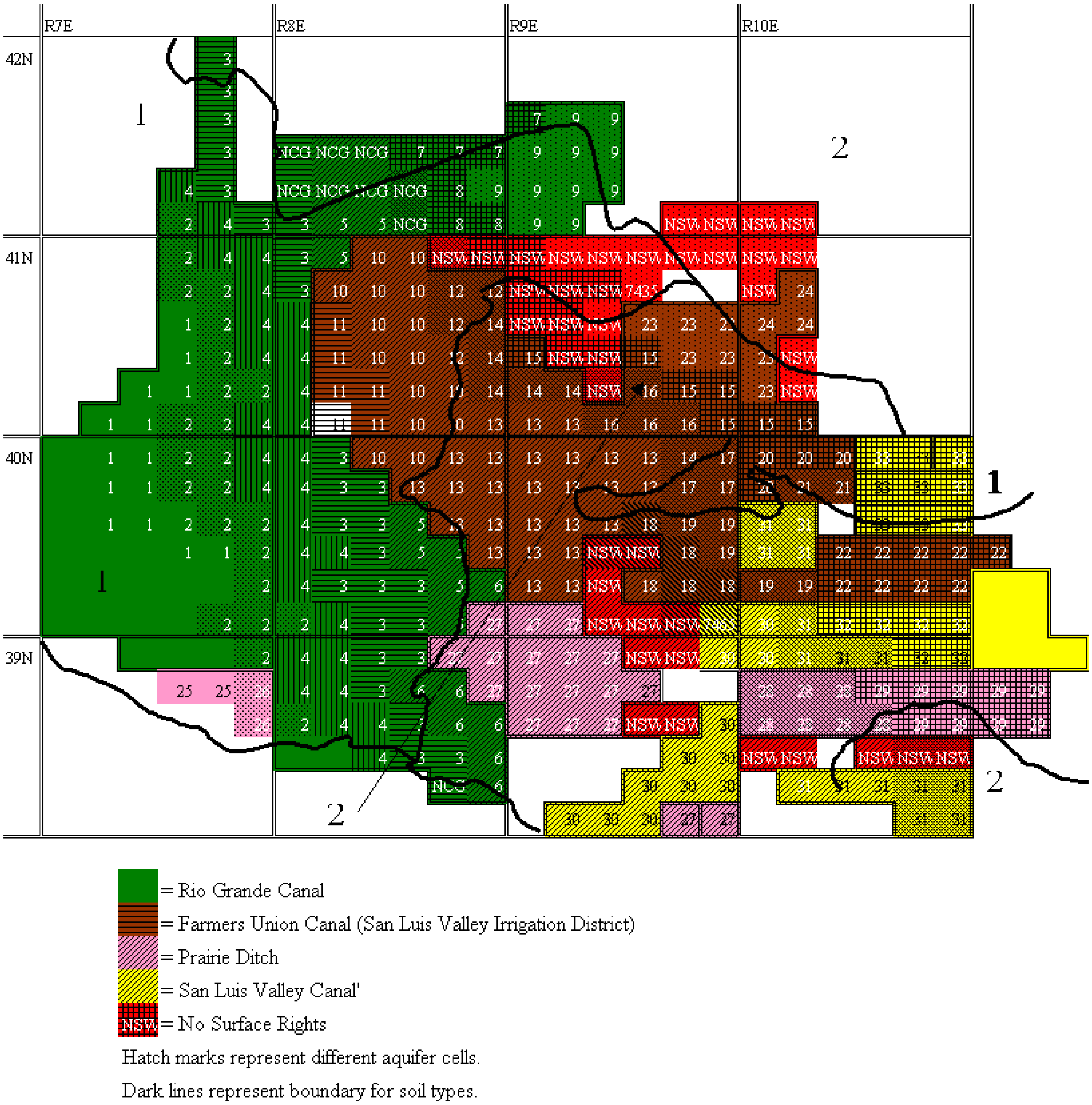
Appendix D: GAMS Model Input File, Water Right Priority By Ditch, San Luis Valley, Colorado

Ditch ID	Decree Amount (AF/Month)	Ditch ID	Decree	Ditch ID	Decree	Ditch ID	Decree Amount
1	666.3	32	7864.6	63	136.8	94	285.6
2	18941.6	33	7454.1	64	5473.1	95	559.2
3	1356.4	34	794.2	65	5551.6	96	1066.7
4	1350.4	35	1224.3	66	5526.6	97	1427.2
5	1546.7	36	561.6	67	9605.3	98	1191
6	1998.9	37	223.1	68	2633.6	99	332.5
7	1451.6	38	97.0	69	1859.1	100	944.1
8	987.5	39	619.9	70	619.9	101	935.2
9	2581.9	40	309.9	71	464.6	102	135.6
10	3093.5	41	852.5	72	1084.5	103	33.9
11	17472.2	42	271.3	73	1239.8	104	67.8
12	2677.1	43	178.5	74	1549.1	105	767.4
13	5054.3	44	6252.4	75	619.9	106	7.7
14	2914.4	45	44.6	76	1626.5	107	971.5
15	2304.6	46	44.6	77	2974.5	108	232.6
16	2459.3	47	169.5	78	2489.1	109	834
17	5243.4	48	658.6	79	20270.6	110	121.4
18	4860.9	49	2191.6	80	7328.0	111	264.7
19	10922.4	50	3563.5	81	3979.9	112	193.9
20	4918.6	51	1200.5	82	636.5	113	999.4
21	2672.3	52	1355.8	83	6133.4	114	38.7
22	2595	53	1239.8	84	119.0	115	333.7
23	14.9	54	1471.8	85	785.3	116	155.3
24	8257.2	55	963.7	86	6264.3	117	1560.4
25	14.9	56	929.8	87	1778.8	118	38.7
26	56.5	57	619.9	88	119.0	119	324.8
27	324.2	58	387.3	89	621.1	120	832.9
28	6270.8	59	406.9	90	178.5	121	338.5
29	16685.2	60	155.3	91	107.1	122	3391.5
30	9500.0	61	18578.7	92	615.7	123	23225.5
31	6554.6	62	356.9	93	41.6	124	100000.0

Appendix E: GAMS Model Input File Numeric Identifier for Irrigation Ditch San Luis Valley, Colorado

Right ID	Ditch	Right ID	Ditch	Right ID	Ditch	Right ID	Ditch
1	1	32	3	63	5	94	5
2	1	33	3	64	5	95	5
3	1	34	3	65	5	96	5
4	1	35	3	66	5	97	5
5	1	36	3	67	5	98	5
6	1	37	3	68	5	99	5
7	1	38	3	69	5	100	5
8	1	39	3	70	5	101	5
9	1	40	3	71	5	102	5
10	1	41	3	72	5	103	5
11	1	42	3	73	5	104	5
12	1	43	3	74	5	105	5
13	1	44	3	75	5	106	5
14	1	45	3	76	5	107	5
15	1	46	3	77	5	108	5
16	1	47	3	78	5	109	5
17	1	48	3	79	5	110	5
18	1	49	3	80	5	111	5
19	1	50	4	81	5	112	5
20	1	51	4	82	5	113	5
21	1	52	4	83	5	114	5
22	1	53	4	84	5	115	5
23	2	54	4	85	5	116	5
24	2	55	5	86	5	117	5
25	2	56	5	87	5	118	5
26	2	57	5	88	5	119	5
27	2	58	5	89	5	120	5
28	2	59	5	90	5	121	5
29	2	60	5	91	5	122	5
30	2	61	5	92	5	123	5
31	2	62	5	93	5	124	5

Appendix F: Map of Study Area with Irrigation Ditches, Aquifers, and Soil Type, San Luis Valley, Colorado



🟩 = Rio Grande Canal

🟫 = Farmers Union Canal (San Luis Valley Irrigation District)

▨ = Prairie Ditch

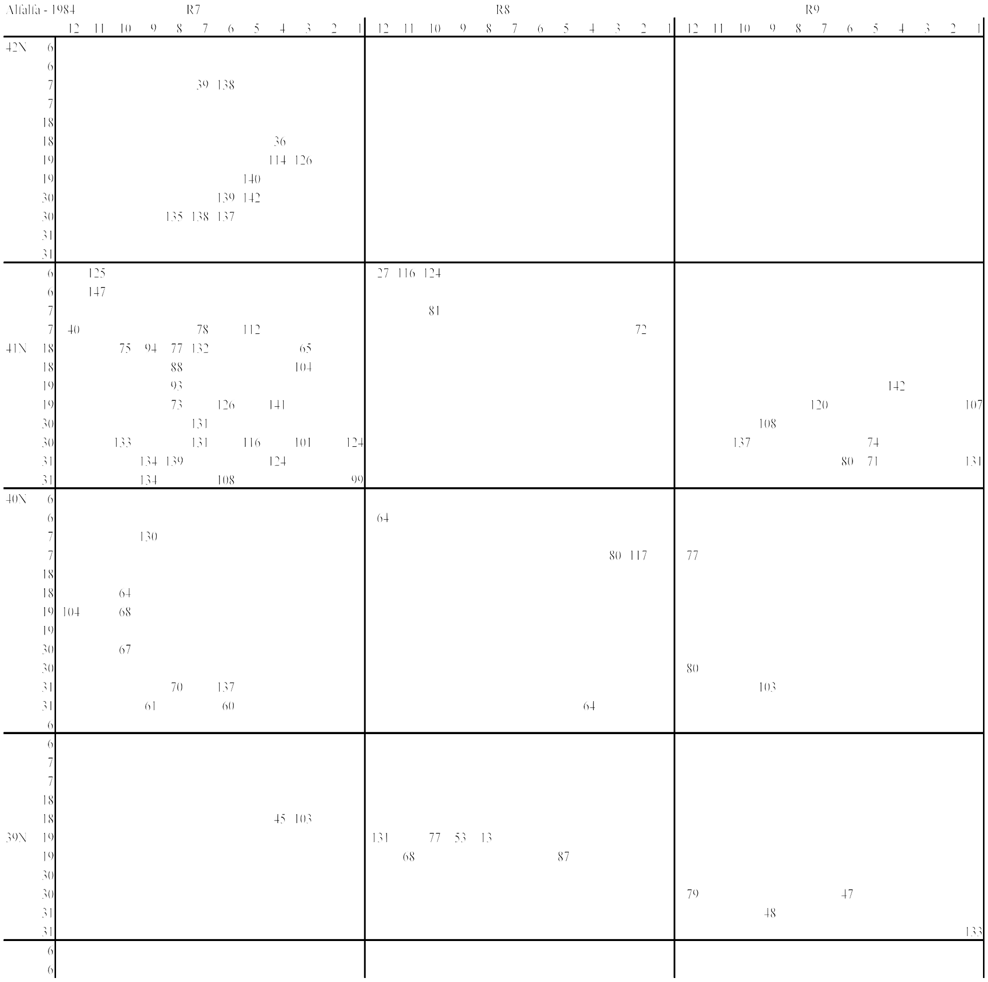
🟨 = San Luis Valley Canal'

NSW = No Surface Rights

Hatch marks represent different aquifer cells.

Dark lines represent boundary for soil types.

Appendix G: Typical Cropping Pattern Map, San Luis Valley, Colorado



Example cropping pattern map showing acres of alfalfa produced on each quarter section by Range, Township and Quarter Section of land in the study area.

Appendix H: GAMS Model Input File, Crop Acreage Limitations, San Luis Valley, Colorado

Farm	Alfalfa	Barley	Potatoes
1	1988	5784	5075
2	1575	4573	2851
3	1622	3930	3131
4	1793	4930	4247
5	251	1210	1080
6	393	1116	807
7	10	144	0
8	6	100	320
9	318	361	186
10	562	2789	2808
11	473	1067	520
12	68	782	877
13	572	5525	5458
14	287	1176	1068
15	407	1341	983
16	363	922	541
17	5	577	700
18	117	865	1339
19	207	756	965
20	335	504	536
21	128	397	266
22	602	731	758
23	195	1426	628
24	94	354	211
25	136	303	400
26	78	312	480
27	725	3854	3712
28	515	496	237
29	406	140	49
30	690	1820	1660
31	610	1216	1122
32	416	1100	460
33	177	850	1079

Appendix I: GAMS Model Input File, Total Acreage Limitation for Representative Agricultural Areas, San Luis Valley, Colorado

Farm	Acres
1	12847
2	8999
3	8683
4	10970
5	2541
6	2316
7	154
8	426
9	865
10	6159
11	2061
12	1727
13	11555
14	2530
15	2730
16	1826
17	1281
18	2321
19	1928
20	1375
21	791
22	2092
23	2250
24	659
25	840
26	870
27	8291
28	1249
29	594
30	4170
31	2948
32	1976
33	2105

Appendix J: GAMS Model Input File, Farm, Soil Type, Ditch, and Aquifer Identifiers, San Luis Valley, Colorado

Farm	Soil	Ditch	Aquifer	Farm	Soil	Ditch	Aquifer
1	1	1	1	18	2	2	9
2	1	1	2	19	2	2	6
3	1	1	4	20	1	2	7
4	1	1	3	21	1	2	6
5	1	1	5	22	2	2	7
6	2	1	2	23	2	2	8
7	2	1	7	24	2	2	8
8	1	1	7	25	1	3	1
9	1	1	8	26	1	3	2
10	1	2	5	27	2	4	9
11	1	2	4	28	2	4	5
12	1	2	6	29	2	4	6
13	2	2	5	30	2	5	5
14	2	2	6	31	2	5	6
15	2	2	7	32	2	5	7
16	2	2	6	33	1	5	7
17	1	2	6				

Appendix K: GAMS Model Input File, Representative Farm Proportionate Share of Diversions, San Luis Valley, Colorado

Farm	Irrigation Ditch Number Proportion of Ditch Water Assigned to Farm			
	1	2	3	4
1	0.25	0	0	0
2	0.19	0	0	0
3	0.18	0	0	0
4	0.23	0	0	0
5	0.05	0	0	0
6	0.05	0	0	0
7	0.01	0	0	0
8	0.02	0	0	0
9	0.02	0	0	0
10	0	0.055	0	0
11	0	0.055	0	0
12	0	0.15	0	0
13	0	0.05	0	0
14	0	0.055	0	0
15	0	0.1	0	0
16	0	0.055	0	0
17	0	0.1	0	0
18	0	0.055	0	0
19	0	0.055	0	0
20	0	0.055	0	0
21	0	0.055	0	0
22	0	0.055	0	0
23	0	0.055	0	0
24	0	0.05	0	0
25	0	0	0.15	0
26	0	0	0.07	0
27	0	0	0.63	0
28	0	0	0.1	0
29	0	0	0.05	0
30	0	0	0	0.25
31	0	0	0	0.25
32	0	0	0	0.25
33	0	0	0	0.25

Appendix L: GAMS Model Input File, Groundwater Decrees, San Luis Valley, Colorado

Farm	Decree Amount (AF/month)	Farm	Decree Amount (AF/month)
1	9028	17	0
2	13840	18	3730
3	28656	19	2523
4	43359	20	1547
5	9220	21	685
6	8374	22	2540
7	0	23	437
8	0	24	0
9	0	25	0
10	12099	26	520
11	6589	27	29425
12	0	28	2419
13	35402	29	952
14	5503	30	4782
15	2788	31	6301
16	3090	32	2046
		33	3148

Appendix M: GAMS Model Input File, Farm Share of Aquifer, San Luis Valley, Colorado

Farm Number	Aquifer Number and Proportion of Aquifer Assigned to Farm								
	1	2	3	4	5	6	7	8	9
1	0.94	0	0	0	0	0	0	0	0
2	0	0.74	0	0	0	0	0	0	0
3	0	0	0	0.81	0	0	0	0	0
4	0	0	1	0	0	0	0	0	0
5	0	0	0	0	0.07	0	0	0	0
6	0	0.19	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0.01	0	0
8	0	0	0	0	0	0	0.03	0	0
9	0	0	0	0	0	0	0	0.09	0
10	0	0	0	0	0.17	0	0	0	0
11	0	0	0	0.19	0	0	0	0	0
12	0	0	0	0	0	0.12	0	0	0
13	0	0	0	0	0.33	0	0	0	0
14	0	0	0	0	0	0.17	0	0	0
15	0	0	0	0	0	0	0.18	0	0
16	0	0	0	0	0	0.12	0	0	0
17	0	0	0	0	0	0.09	0	0	0
18	0	0	0	0	0	0	0	0	0.68
19	0	0	0	0	0	0.13	0	0	0
20	0	0	0	0	0	0	0.09	0	0
21	0	0	0	0	0	0.05	0	0	0
22	0	0	0	0	0	0	0.14	0	0
23	0	0	0	0	0	0	0	0.24	0
24	0	0	0	0	0	0	0	0.07	0
25	0.06	0	0	0	0	0	0	0	0
26	0	0.07	0	0	0	0	0	0	0
27	0	0	0	0	0.24	0	0	0	0
28	0	0	0	0	0	0.08	0	0	0
29	0	0	0	0	0	0	0.04	0	0
30	0	0	0	0	0.12	0	0	0	0
31	0	0	0	0	0	0.2	0	0	0
32	0	0	0	0	0	0	0.13	0	0
33	0	0	0	0	0	0	0.14	0	0

Appendix N: Crop Budget, Alfalfa, San Luis Valley, Colorado

	Unit	Price or cost/unit	Quantity	Value or cost/acre	Cost/unit of production
Gross Receipts	Ton	80.00	5	400.00	
Total Receipts				400.00	80.00
Direct Costs:					
Operating - Preharvest					
Fertilizer (Appl)	Acre	4.00	1	4.00	0.80
Irrigation Water	Ac. In	1.20	35	42.00	8.40
Irrigation Labor	Hr.	6.00	4	24.00	4.80
Herbicide (Sencor)	Pt.	16.06	1	16.06	3.21
Insecticide (Furidan)	Pt.	8.63	1	8.63	1.73
Aerial Spraying	Acre	4.00	1	4.00	0.80
Mach Fuel & Lube	Acre	4.50		1.36	0.27
Mach Repairs	Acre				0.00
Interest on Cap	Dollars	0.10			0.00
Amort. Est. Costs (5 years)	Dollars	28.98		28.98	
Total Preharvest:	Dollars			129.03	20.01
Operating - Harvest					
Baler Twine-Wire	Ton	1.25	5.5	6.88	1.38
Swath	Acre	8.00	1	8.00	1.60
Rake	Acre	2.00	1	2.00	0.40
Bale	Ton	13.00	5	65.00	13.00
Haul	Ton	10.00	5	50.00	10.00
Interest On Capital	Dollars	0.10			0.00
Total Harvest:				131.88	26.38
Total Operating Costs				260.91	46.39
Property/Ownership Costs	Dollars				
Machinery Replacement	Dollars				
Machinery Taxes/Insurance	Dollars				
General Farm Overhead	Dollars			15.00	2.73
Real Estate Taxes	Dollars			8.63	1.57
Total Property/Ownership	Dollars			23.63	9.12
Total Direct Costs	Dollars			284.54	55.51
Net Receipts	Dollars			115.47	24.50

Appendix O: Crop Budget, Feed Barley, San Luis Valley, Colorado

	Unit	Price or cost/unit	Quantity	Value or cost/acre	Cost/unit of production
Gross Receipts	Bu	3.26	135	440.10	
Total Receipts				440.10	3.26
Direct Costs:					
Operating - Preharvest					
Chisel Plow	Acre	8.00	1	8.00	0.06
Rotary Mow	Acre	4.00	1	4.00	0.03
Ridge	Acre	4.00	1	4.00	0.03
Roller Pack	Acre	4.00	1	4.00	0.03
Seed	Lbs.	0.14	100	14.00	0.10
Phosphate (0-45-0)	Lbs.	0.44	40	17.60	0.13
Nitrogen	Acre	0.21	150	31.50	0.23
Herbicide (Bronate)	Pts.	9.62	1.5	14.43	0.11
Custom Herb. Appl.	Acre	5.00	1	5.00	0.04
Irrigation Energy	AcIn	1.00	40	40.00	0.30
Irrigation Labor	Hr.	10.00	2	20.00	0.15
Mach Fuel & Lube	Acre		1	5.11	0.04
Mach Repairs	Acre		1	2.80	0.02
Interest on Cap	Dollars	0.10		8.31	0.06
Total Preharvest:	Dollars			178.75	
Operating - Harvest					
Custom Harvest	Bu	0.34	135	45.90	0.34
Mach Fuel & Lube	Acre			0.00	0.00
Mach Repairs	Acre			0.00	0.00
Interest On Capital	Dollars	0.10	13.95	1.33	0.01
Total Harvest:				47.23	0.35
Total Operating Costs				225.98	1.67
Property/Ownership Costs	Dollars				
Machinery Replacement	Dollars				
Irrigation Equipment	Dollars	30.00		30.00	0.22
General Farm Overhead	Dollars	97.30		97.30	0.72
Real Estate Taxes	Dollars	4.17		4.17	0.03
Total	Dollars			131.47	0.97
Total Direct Costs	Dollars				
Net Receipts	Dollars			82.65	0.61

Appendix P: Crop Budget, Potatoes, San Luis Valley, Colorado

	Unit	Price or cost/unit	Quantity	Value or cost/acre	Cost/unit of production
Gross Receipts	CWT	5.50	310	1705.00	
Total Receipts				1705.00	5.50
Direct Costs:					
Operating - Preharvest					
Nitrogen	Lbs.	0.21	150	31.50	0.10
Phosphate	Lbs.	0.44	150	66.00	0.21
Potassium	Lbs.	0.18	100	18.00	0.06
Sulfur	Lbs.	0.45	50	22.50	0.07
Seed	CWT	5.50	20	110.00	0.35
Herbicide	Acre	10.50	1	10.50	0.03
Insecticide	Acre	10.00	1	10.00	0.03
Fungicide	Acre	27.00	1	27.00	0.09
Irrigation Energy	Acre	67.50	1	67.50	0.22
Irrigation Labor	Hr.	10.00	5	50.00	0.16
Cultivation (Custom)	Acre	5.00	2	10.00	0.03
Custom Apply Pesticides	Acre	5.00	4	20.00	0.06
Mach Fuel & Lube	Acre			8.11	0.03
Mach Repairs	Acre			55.05	0.18
Interest on Cap	Dollars	0.10	293.6	27.89	0.09
Total Preharvest:	Dollars			534.05	1.72
Operating - Harvest					
Labor	Acre	1.00	50.00	50.00	0.16
Storage - 6 Months	CWT	0.05	310.00	15.50	0.05
Sprout Inhibitor	CWT	0.07	350.00	24.50	0.08
Mach Fuel and Lube	Acre			5.57	0.02
Machine Repairs	Acre			51.47	0.17
Interest On Capital	Dollars	0.10	48.12	4.57	0.01
Total Harvest:				151.61	0.49
Total Operating Costs	Dollars			685.66	2.21
Property/Ownership Costs	Dollars				
Machinery Replacement	Dollars			133.96	0.43
Machinery Taxes/Insur	Dollars			25.74	0.08
General Farm Overhead	Dollars			50.00	0.16
Real Estate Taxes	Dollars			20.00	0.06
Total Property/Ownership	Dollars			229.70	0.74
Total Direct Costs	Dollars			915.36	2.95
Net Receipts	Dollars			789.64	2.55

Appendix Q: Data for Calculating Matric Potential and Hydraulic Conductivity for Sandy Loam Soils, San Luis Valley, Colorado

Φ	Φ_s	Φ/Φ_s	Unsaturated Hydraulic Conductivity (cm/hr)	Matric Potential (cm)
0.00	0.45	0	1.4E-12	
0.02	0.45	0.0444	1.5E-09	1631720
0.04	0.45	0.0889	9.0E-08	144225
0.06	0.45	0.1333	1.7E-06	34892
0.08	0.45	0.1778	1.6E-05	12748
0.10	0.45	0.2222	9.9E-05	5838
0.12	0.45	0.2667	4.7E-04	3084
0.14	0.45	0.3111	1.8E-03	1798
0.16	0.45	0.3556	6.0E-03	1127
0.18	0.45	0.4000	1.7E-02	746
0.20	0.45	0.4444	4.5E-02	516
0.22	0.45	0.4889	1.1E-01	370
0.24	0.45	0.5333	2.4E-01	273
0.26	0.45	0.5778	5.2E-01	206
0.28	0.45	0.6222	1.0E+00	159
0.30	0.45	0.6667	2.0E+00	125
0.32	0.45	0.7111	3.7E+00	100
0.34	0.45	0.7556	6.5E+00	81
0.36	0.45	0.8000	1.1E+01	66
0.38	0.45	0.8444	1.9E+01	55
0.40	0.45	0.8889	3.1E+01	46
0.42	0.45	0.9333	5.0E+01	38
0.44	0.45	0.9778	7.8E+01	33
0.46	0.45	1.0222	1.2E+02	0
0.48	0.45	1.0667	1.8E+02	100000
0.50	0.45	1.1111		100000

Where: Φ = soil water content
Φ_s = saturated water content

Appendix R: Data for Calculating Matric Potential and Hydraulic Conductivity for Sandy Soils, San Luis Valley, Colorado

Φ	Φ_s	Φ/Φ_s	Unsaturated Hydraulic Conductivity (cm/hr)	Matric Potential (cm)
0.00	0.35	0.00	5E-05	
0.02	0.35	0.06	1E-03	59033.2
0.04	0.35	0.11	7E-03	8075.0
0.06	0.35	0.17	3E-02	2522.1
0.08	0.35	0.23	7E-02	1104.5
0.10	0.35	0.29	2E-01	582.2
0.12	0.35	0.34	3E-01	345.0
0.14	0.35	0.40	6E-01	221.6
0.16	0.35	0.46	1E+00	151.1
0.18	0.35	0.51	2E+00	107.8
0.20	0.35	0.57	2E+00	79.6
0.22	0.35	0.63	4E+00	60.6
0.24	0.35	0.69	5E+00	47.2
0.26	0.35	0.74	7E+00	37.5
0.28	0.35	0.80	1E+01	30.3
0.30	0.35	0.86	1E+01	24.9
0.32	0.35	0.91	2E+01	20.7
0.34	0.35	0.97	2E+01	17.4
0.36	0.35	1.03	3E+01	14.7
0.38	0.35	1.09	4E+01	12.6
0.40	0.35	1.14	4E+01	10.9
0.42	0.35	1.20	5E+01	0.0
0.44	0.35	1.26	7E+01	100000.0
0.46	0.35	1.31	8E+01	100000.0
0.48	0.35	1.37	1E+02	100000.0
0.50	0.35	1.43		100000.0

Where:
Φ = soil water content
Φ_s = saturated water content

Appendix S: Planting, Harvest, Irrigation, and Rainfall Dates and Amounts, Alfalfa, San Luis Valley, Colorado

# days	Total irrig/rain (in)	Dates	Total time (hrs) at .5 cm/hr	# days	Total irrig/rain (in)	Dates	Total time (hrs) at .5 cm/hr
45	1.25	4/15 to 5/29	6.35	3	1.25	7/23 to 7/25	6.35
1	0.66	>>> 5/30	3.35	1	0.00	>>>7/26	0.00
3	1.25	5/31 to- 6/2	6.35	3	1.25	7/27 to 7/29	6.35
1	0.00	>>> 6/3	0.00	1	0.48	>>>7/30	2.44
3	1.25	6/4 to 6/6	6.35	16	1.25	7/31 to 8/15	6.35
1	0.00	>>> 6/7	0.00	1	0.51	>>>8/16	2.59
3	1.25	6/8 to 6/10	6.35	3	1.25	8/17 to 8/19	6.35
1	0.00	>>> 6/11	0.00	1	0.00	>>>8/20	0.00
3	1.25	6/12 to 6/14	6.35	3	1.25	8/21 to 8/23	6.35
1	0.21	>>> 6/15	1.07	1	0.00	>>>8/24	0.00
16	1.25	6/16 to 7/1	6.35	3	1.25	8/25 to 8/27	6.35
1	0.21	>>> 7/2	1.07	1	0.00	>>>8/28	0.00
3	1.25	7/3 to 7/5	6.35	3	1.25	8/29 to 8/31	6.35
1	0.00	>>> 7/6	0.00	1	0.51	>>>9/1	2.59
3	1.25	7/7 to 7/9	6.35	3	1.25	9/2 to 9/4	6.35
1	0.00	>>> 7/10	0.00	1	0.00	>>>9/5	0.00
3	1.25	7/11 to 7/13	6.35	3	1.25	9/6 to 9/8	6.35
1	0.48	>>> 7/14	2.44	1	0.26	>>>9/9	1.32
3	1.25	7/15 to 7/17	6.35	3	1.25	9/10 to 9/12	6.35
1	0.00	>>> 7/18	0.00	1	0.00	>>>9/13	0.00
3	1.25	7/19 to 7/21	6.35	33	0.00	9/14 to 10/15	0
1	0.00	>>> 7/22	0.00				

Appendix T: Planting, Harvest, Irrigation, and Rainfall Dates and Amounts, Barley, San Luis Valley, Colorado

# days	Total irrig/rain (in)	Dates	Total time (hrs) at .5 cm/hr	# days	Total irrig/rain (in)	Dates	Total time (hrs) at .5 cm/hr
25	1.50	4/15-5/10	7.62	3	1.00	6/21-6/24	5.08
1	0.29	5/11	1.47	1	0.00	6/25	0.00
3	1.50	5/15-5/18	7.62	3	1.00	6/26-6/29	5.08
1	0.00	5/19	0.00	1	0.00	6/30	0.00
3	1.00	5/20-5/22	5.08	3	1.00	7/1-7/4	5.08
1	0.37	5/23	1.88	1	0.00	7/5	0.00
3	1.00	5/24-5/27	5.08	3	1.00	7/6-7/9	5.08
1	0.00	5/28	0.00	1	0.32	7/10	1.63
3	1.00	5/29-5/30	5.08	3	1.00	7/11-7/14	5.08
1	0.00	5/31	0.00	1	0.32	7/15	1.63
3	1.00	6/1-6/4	5.08	4	1.00	7/19-7/23	5.08
1	0.00	6/5	0.00	1	0.32	7/24	1.63
3	1.00	6/6-6/9	5.08	4	1.00	7/25-7/29	5.08
1	0.21	6/10	1.07	1	0.00	7/30	0.00
3	1.00	6/11-6/14	5.08	75	0.00	8/1-10/15	0.00

Appendix U: Planting, Harvest, Irrigation, and Rainfall Dates and Amounts, Potatoes, San Luis Valley, Colorado

# days	Total irrig/rain (in)	Dates	Total time (hrs) at .5 cm/hr	# days	Total irrig/rain (in)	Dates	Total time (hrs) at .5 cm/hr
46	1.50	4/15-5/30	7.62	3	0.90	7/26-729	4.57
1	0.37	5/31	1.88	1	0.00	7/30	0.00
3	1.50	6/1-6/4	7.62	3	0.90	7/31-8/2	4.57
1	0.00	6/5	0.00	1	0.26	8/3	1.32
3	1.50	6/6-6/9	7.62	3	0.90	8/4-8/7	4.57
1	0.00	6/10	0.00	1	0.26	8/8	1.32
3	0.90	6/11-6/14	4.57	3	0.90	8/9-8/11	4.57
1	0.21	6/15	1.07	1	0.00	8/12	0.00
3	0.90	6/16-6/19	4.57	4	0.90	8/13-8/17	4.57
1	0.00	6/20	0.00	1	0.26	8/18	1.32
3	0.90	6/21-6/24	4.57	4	0.90	8/19-8/23	4.57
1	0.21	6/25	1.07	1	0.26	8/24	1.32
3	0.90	6/26-6/29	4.57	4	0.90	8/25-8/29	4.57
1	0.00	6/30	0.00	1	0.00	8/30	0.00
3	0.90	7/1-7/4	4.57	4	0.90	8/31-9/3	4.57
1	0.32	7/5	1.63	1	0.00	9/4	0.00
3	0.90	7/6-7/9	4.57	7	0.90	9/5-9/12	4.57
1	0.00	7/10	0.00	1	0.26	9/13	1.32
3	0.90	7/11-7/14	4.57	7	0.90	9/14-9/21	4.57
1	0.32	7/15	1.63	1	0.26	9/22	1.32
3	0.90	7/16-7/19	4.57	7	0.90	9/23-9/30	4.57
1	0.00	7/20	0.00	1	0.35	10/1	1.78
3	0.90	7/21-7/24	4.57	15	0.00	36084	0.00
1	0.32	7/25	1.63				

Appendix V: Crop Growth Simulation Model Partial Input File, San Luis Valley, Colorado

```
   0.0    0.0010 .0000001     1.0       0.0      5.0        -
   0.0    0.005      0.40     0.0     100.0     90.0        -
 468.0    0.4370   -25.34  0.3410    -15.98     2.87     4.48
  45.0      45.0    0.900   0.235    200.00  -6400.0  -6400.0
   1.0       1.0    0.900   0.255    200.00  -6400.0  -6400.0
   3.0       3.0    0.900   0.385    200.00  -6400.0  -6400.0
   1.0       1.0    0.900   0.451    200.00  -6400.0  -6400.0
   3.0       3.0    0.900   0.451    200.00  -6400.0  -6400.0
   1.0       1.0    0.900   0.451    200.00  -6400.0  -6400.0
   3.0       3.0    0.900   0.451    200.00  -6400.0  -6400.0
   1.0       1.0    0.900   0.451    200.00  -6400.0  -6400.0
   3.0       3.0    0.900   0.451    200.00  -6400.0  -6400.0
   1.0       1.0    0.900   0.451    200.00  -6400.0  -6400.0
  16.0      16.0    0.650   0.465    200.00  -6400.0  -6400.0
   1.0       1.0    0.800   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    0.800   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.478    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.478    200.00  -6400.0  -6400.0
  16.0      16.0    0.650   0.405    200.00  -6400.0  -6400.0
   1.0       1.0    0.800   0.401    200.00  -6400.0  -6400.0
   3.0       3.0    0.800   0.401    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.401    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.401    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.401    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.401    200.00  -6400.0  -6400.0
   1.0       1.0    1.000   0.401    200.00  -6400.0  -6400.0
   3.0       3.0    1.000   0.401    200.00  -6400.0  -6400.0
```

1.The ditch does not use shares, but services 388 quarter-sections. Owners of land serviced by the ditch get an equal share of the water if they call for it.