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Achieving efficiency and equity in irrigation management: an optimization model of the El Angel watershed, Carchi, Ecuador

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Abstract

The objective of this paper is to address the problems of inefficiency and inequity in water allocation in the El Angel watershed, located in Ecuador's Sierra region. Water is captured in a high-altitude region of the watershed and distributed downstream to producers in four elevation-defined zones via a system of canals. Upstream and downstream producers face radically different conditions with respect to climate and terrain. A mathematical programming model was created to study the consequences of addressing chronic water scarcity problems in the watershed by shifting water resources between the four zones. The model captures the nature of water use by humans, crops and dual purpose cattle. Its objective function maximizes producer welfare as measured by aggregate gross margin, subject to limited supplies of land, labor and water. Five water allocation scenarios are evaluated with respect to efficiency in land and water use and equity in income distribution. Results reveal that although water is the primary constrained resource downstream, in the upstream zones, land is far more scarce. The current distribution of water rights does not consider these differences and therefore is neither efficient nor equitable. Improvements in efficiency (resource use) and equity (income distribution) are associated with (1) a shift of water to the lower zone, and (2) the use of lower levels of irrigation intensity upstream. Furthermore, the scenarios that result in the most

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efficient use of resources also bring the greatest degree of equity in income distribution, indicating that these may be complementary, not conflicting, goals.

Keywords: Mathematical programming; Water allocation; Watershed management; Efficiency; Equity

1. Introduction

Agriculture demands more water than any other single activity, requiring 69% of the world's water supply (Holden and Thobani, 1996). In many countries, efforts to raise levels of agricultural production through increases in cultivated land, cropping intensity and yields have led to a greater dependence on irrigation. This pressure has been most severe in developing nations, where water resources are often scarce and many irrigation systems are primitive.

Although Ecuador has estimated water resources of 38,372 m^3 per capita, nearly four times the worldwide average of 10,800 m^3 per capita, the distribution of water is uneven and is heavily concentrated in the country's Amazon and Coastal regions (Sotomayor, 1996). It is estimated that 95% of the country's irrigation structures utilize conventional canal technologies (Sotomayor, 1996). The upstream–downstream asymmetry in water availability and low levels of irrigation technology lead to an inequitable and inefficient allocation of water among users. Absent a strong institutional system of water management, there are few incentives for upstream producers to use water efficiently, which leads to uncertainty for downstream producers, and in many cases, conflict. This study examines the effects of alternative management scenarios aimed at improving efficiency and equity in water allocation. Although focused specifically on Ecuador's Sierra region, the study is illustrative of water management problems faced widely in the developing world.

The canals of the El Angel watershed in the highlands of Carchi, Ecuador were constructed over 100 years ago to provide water to the several large haciendas which then dominated the 100,000-ha region. Today, these canals transport water a distance of over 60 km, from altitudes of more than 4000 m above sea level (masl), to hotter, drier regions as low as 1500 masl. The primary source of water is the *páramo*, an area of humid alpine grasslands in the upper reaches of the watershed whose sponge-like terrain is well-suited to the capture, storage and transfer of water. The five canals that are the focus of this study are largely non-reinforced, open structures, highly susceptible to losses from evaporation, spillage, seepage and theft.[1]

The five canals are located in the eastern portion, or left margin of the watershed. As demonstrated by Prato and Wu (1996), the ''target-level'' of a resource management policy plays a significant role in determining its environmental and economic costs and benefits. Brooks et al. (1994) argue for policymaking at the watershed level, noting that most natural processes occur within watershed boundaries. Beau-

[1] The five canals studied are: (1) San Vicente de Pusir de los Baños, 2) San Vicente de Pusir del Voladero, (3) Cúnquer, (4) Chulunguaza, and (5) El Tambo.

lieu et al. (1998), however, caution that most farmers make decisions at the field level, and do not consider the watershed-level effects of their decisions. Furthermore, policymaking often comes down to a tradeoff between economic and environmental objectives due to the fact that watershed boundaries rarely coincide with political boundaries (Brooks et al., 1994; Okumu et al., 1999).

The study region is divided according to elevation into three primary zones: upper, middle and lower; the middle zone is further divided to account for the diversity in production systems found in the region.[2] As one travels downstream, temperatures, levels of solar radiation and rates of evapotranspiration rise, and soils are increasingly sandy and susceptible to erosion. While the upper zone is oriented primarily toward pasture (cattle) and potato production, a more diverse group of crops can be produced in the middle and lower zones. However, the degree of dependence on irrigation in these downstream zones is much greater. Table 1 summarizes key characteristics of each zone.

In the midst of Ecuador's agrarian reform, water rights or "concessions" were divided among new landowners along the canals. Although a number of regional water agencies were established to enforce the nation's 1972 Water Law, in reality, minimal control is exercised by the state, and in most cases, management occurs at the local level (Proaño, 2000). Community members form groups called *juntas* to enforce concessions and carry out maintenance tasks for a particular canal. The effectiveness of the *juntas* varies widely. Most failures can be attributed to a lack of resources, poor communication and farmers' unwillingness to participate.

Without effective enforcement of water rights, many producers base water use decisions on availability rather than actual crop water requirements, and as a result, regularly use canal water beyond their legal allocations. Downstream farmers are at a natural disadvantage, their access being limited to that portion of canal water that has not been used upstream. These circumstances have led to a number of water-

Table 1
Breakdown of the left margin of the El Angel Watershed by Zone

Zone	Elevation range (masl)	Land (ha)	Human population	Average farm size (ha)	Average precipitation (mm/year)	Average evaporation (mm/year)	Production system
Upper	4000–3100	552	6356	3.88	1046	722	Dual purpose cattle, potatoes, barley
Middle 1	3099–3000	910	4022[a]	3.37[a]	955	903	Dual purpose cattle, potatoes, barley, wheat
Middle 2	2999–2400	732			807	1100	Corn, black beans, peas
Lower	2399–1500	747	2244	3.15	416	1421	Anise, corn, sweet potato, white carrot

Sources: Montenegro (1998), Proaño and Paladines (1998), MANRECUR Project, CIP.
[a] Entire middle zone.

[2] The four zones are referred to as "upper", "middle 1", "middle 2", and "lower" in this paper.

related conflicts between rural and urban communities, between producers at different altitudes and between small- and large-scale producers (Poats et al., 1998).

The objective of this paper is to address the problems of inefficiency and inequity in water allocation in the El Angel watershed. A comprehensive, crop-livestock mathematical programming model is described which allows the simulation of various water allocation scenarios. The current system of water management is then evaluated with respect to the achievement of efficiency and equity objectives. Next, a number of alternative water allocation strategies are examined. A comparison of these alternative strategies reveals the consequences of shifting water resources between the zones of the watershed. Finally, the relationships between efficiency and equity objectives demonstrated by the alternative strategies are discussed.

2. An optimization model of crop and livestock production

The mathematical programming model is designed to maximize aggregate gross margin from agricultural production in the El Angel watershed. The model includes activities and constraints that characterize the nature of water use for humans, crops and livestock over a 12-month period. The technical coefficients that quantify resource requirements were estimated for a representative farm in each zone.[3]

Mathematical programming models seek to determine the optimum allocation of constrained resources among competing activities (Hazell and Norton, 1986), and are widely utilized in studies of resource allocation in agriculture, including water allocation. Combining mathematical programming and simulation modeling techniques, Bernardo et al. (1988) find opportunities for improved water management in the Columbia River Basin, given that decreasing the water supply by 40% at the farm level results in only a 10% decrease in economic returns. Garg and Ali (1998) use a two-level mathematical programming model for the Lower Indus Basin in Pakistan to determine the optimal cropping pattern and sowing dates to efficiently use scarce water resources. Unlike these two studies, the focus of this model is not limited to water use for crops, nor to the analysis of resource use for livestock, as in Nicholson (1990) and Berger (1999). Rather, this study simultaneously incorporates both crop and livestock activities in evaluating water allocation.

2.1. Model objective function

The model's objective function maximizes aggregate gross margin (total revenue less variable costs) from crop and livestock production:

[3] Characterization of the representative farms is based on data collected in a joint survey, data obtained from the International Potato Center (CIP) and a number of secondary sources. The survey, conducted from January to September, 2000, was a collaboration between the MANRECUR Project, Cornell University and Universidad Central de Ecuador. The CIP data is from the project "Agricultural Chemical Use and the Sustainability of Potato Production in the Andean Zone", collected between April 1990 and December 1992 in a watershed directly adjacent to the El Angel watershed.

$$\text{MAX}\sum_{i=1}^{4}\sum_{j=1}^{J}\sum_{k=1}^{2}\left[\left(\text{GMCROP}_{ijk}\right)\left(\text{CROP}_{ijk}\right)\right]+\sum_{i=1}^{2}\sum_{k=1}^{2}\sum_{n=1}^{16}[(\text{GMA}_{ikn})(\text{A}_{ikn})]$$
$$+\sum_{i=1}^{2}\sum_{k=1}^{2}[(\text{RMILK}_{ik})(\text{MILK}_{ik})]-\sum_{i=1}^{2}\sum_{k=1}^{2}[(\text{SUPCOST}_{ik})(\text{SUP}_{ik})]$$
$$-\sum_{i=1}^{4}\sum_{k=1}^{2}[(\text{WCOST}_{ik})(\text{WUSE}_{ik})] \tag{1}$$

where activities are defined for the *i*th zone, the *j*th crop, the *n*th (of 16) herd category, and the *k*th season (wet or dry), and where GMCROP = per-hectare gross margin; CROP = number of hectares of each crop activity; GMA = per-animal gross margin, calculated using the revenue from animal sales only; A = number of cattle in each herd category; RMILK = per-liter price of milk; MILK = number of liters of milk sold; SUPCOST = per-kilogram cost of animal feed supplements; SUP = number of kilograms fed; WCOST = per-cubic meter tax on water use; and WUSE = total use of canal water.

2.2. Model activities

Four categories of activities are included in the model: human, crop, animal and water (Table 2). Human activities are included to quantify non-agricultural water requirements in each zone, based on population estimates and water consumption data in Montenegro (1998).

Composite crop activities are defined over a 12-month period, and include all of the processes that are involved with the production of a crop, including soil preparation, fertilization, irrigation and harvest. Activities are defined for each season to account for variations in irrigation requirements due to lower levels of precipitation in the dry season. Certain crop activities are defined at multiple levels of irrigation intensity to account for the fact that farmers often exhibit profit-maximizing rather than yield-maximizing behavior when allocating irrigation water among crops (Doyle, 1990; Santos, 1998). The exceptions are potatoes and improved pasture, for which reductions in irrigation showed little or no impact on yields.

The yield response to water is estimated for each crop using the relationship between relative yield (Y_a/Y_m) and relative evapotranspiration (ET_a/ET_p), established by Doorenbos and Kassam (1979):[4]

$$\frac{Y_a}{Y_m}=\prod_{i=1}^{4}\left[1-k_{y_i}\left(1-\frac{ET_{ai}}{ET_{pi}}\right)\right] \tag{2}$$

[4] Previous applications of this method include Bernardo et al. (1988) and Paudyal and Das Gupta (1990).

where "i" denotes each period (of four) in the plant's growth cycle; Y_a = actual yield; Y_m = maximum yield; k_{y_i} is the yield response factor for each stage i of the crop's growth cycle; ETa_i = total amount of actual evapotranspiration during period i; and ET_{p_i} = total amount of potential evapotranspiration during period i.

The objective of using this method was not to precisely calculate the relationship between water use and yields. This was not possible due to the high data requirements of econometric and simulation methods. Rather, as intended by Doorenbos and Kassam, the equation is used "to quantify the effect of water stress" on the studied crops in the watershed. The right-hand side of Eq. (2) is a number between zero and

Table 2
Model activities and constraints[a]

Activities	Constraints
Human	*Human*
Population in each zone	Define populations in each zone
Crop	*Crop*
Hectares of crop/pasture production	Equate seasonal production
-For each zone	-For each zone
-For each level of irrigation intensity	-For each level of irrigation intensity
Animal	*Animal*
Primary age groups	Divide age groups by sex and activity
Activity- and sex-based subgroups	Relate sizes of age groups
-Male/female calves	Convert herd to animal units (AUs)
-Replacement/sold heifers	Define aggregate nutrient reqts.
-Steers	Ensure nutrient reqts. are met
-Lactating/dry cows	Determine cattle canal water reqt.
-Culled cows	Restrict stocking rate
Animal units	Define milk use
Aggregate nutrient intake	-Production
-Dry matter	-Consumption
-Crude protein	-Sale
-Metabolizable energy	*Land and Labor*
-Water	Restrict land use based on supply
Canal water requirement	Restrict labor use based on supply
Purchased supplemental feeds	*Water*
Milk activities	Define aggregate water supplies[b]
-Production	Define total water use in each zone
-Consumption	Restrict water use $\leqslant$ water supply
-Sale	Restrict water use in each zone[c]
Water	
Levels of water use	
-From each source of water supply[b]	
-For each zone	

[a] Most activities and constraints are defined for both the dry and wet seasons. The complete algebraic formulation of the model, including over 200 individual activities and constraints, is reported in Evans (2001).

[b] Water supplies enter at the top of the watershed and at the end of middle zone 1.

[c] For certain water allocation scenarios.

one, often referred to as the crop's water stress index (WSI). A WSI closer to one indicates a lower level of water stress.

ET_p data are taken from the comprehensive study by Montenegro (1998) of the use, management and distribution of irrigation and potable water in the El Angel watershed. These data were calculated using the FAO software CROPWAT.[5] Based on average levels of precipitation in each zone as well as soil moisture observations, ET_a is calculated using the method described in Thornthwaite and Mather (1957) and later in Dunne and Leopold (1978). This method was chosen primarily due to the instrumentation and data limitations associated with working in the remote study area.

Doorenbos and Kassam define Y_m as "the harvested yield of a high-producing variety, well-adapted to the given growing environment, including the time available to reach maturity, under conditions where water, nutrients and pests and diseases do not limit yields." Y_m values are most accurately estimated with the use of experimental data that account for the effects of a number of variables, including crop variety, temperature and length of the growing season. These experimental values must then be adjusted to according to actual farming conditions (Doorenbos and Kassam, 1979). Due to a lack of experimental field data, Y_m values used in this study were obtained from interviews with local farmers and from secondary sources such as Proaño and Paladines (1998) and Espinosa et al. (1996) that are specific to the region or to a comparable region. These maximum yield values compare conservatively with those presented by Doorenbos and Kassam for tropical climatic regions.

To solve for yield levels for the various irrigation-defined crop activities, the difference between ET_{a_i} and ET_{p_i} during each period of a crop's growth cycle is decreased by a percentage that represents the extent to which irrigation is used to fill any evapotranspiration deficit. Y_a is then calculated according to Eq. (2).

In the case of dual purpose cattle production, activities are included for the upper zone and middle zone 1 only. Herd category and nutrient requirement activities are subdivided to account for differences in animal age, sex, weight, weight gain and activity. The model solves for the number of animals in each of the seven cattle age groups, which are further subdivided by sex and activity. Activities are also included to quantify herd size in animal units (AUs), used later in stocking rate restrictions. Based on the total herd size, the model calculates aggregate nutrient requirements,[6] the amount of canal water required to supplement animal feeds to meet water requirements, the kilograms of feed supplements purchased to meet nutritional requirements, and levels of milk production.

Finally, the model solves for the levels of water use in each zone. Like all other activities, water use activities are included for the dry and wet seasons separately.

[5] CROPWAT version 5.7, issued in 1992 is a decision support system developed by the Land and Water Development Division of FAO. It is commonly used to calculate reference evapotranspiration, as well as crop water and irrigation requirements.

[6] Required quantities of dry matter, crude protein, metabolizable energy and water.

2.3. Model constraints

The model's constraints can be divided into five categories: human, crop, animal, land and labor, and water (Table 2). Human constraints are included to define the human population in each zone, in each season, which is fixed throughout the year.

Although a shift of resources to the production of high-valued crops such as potatoes and anise could result in significant income growth, such a dramatic change is unlikely in the short run, given the potential problems associated with resource bottlenecks, nutritional deficits and price variability. To be consistent with the short-run nature of the model and historical production patterns in the region, constraints are included for each zone to ensure minimum levels of crop diversity.

Similar to animal activities, animal constraints are driven by the nutritional requirements of the various herd categories. The first of six types of animal-related constraints divide the herd into age-, sex- and activity-based categories. These constraints establish relationships between the sizes of age groups, the numbers of males and females, the numbers of sale and replacement heifers and the numbers of lactating and dry cows. Herd size is converted to AUs in the second group of animal constraints. The third and fourth types of animal constraints respectively define aggregate herd nutrient requirements and ensure that these nutrient requirements are met. These constraints determine the levels of canal water and nutritional supplements consumed by the herd. The fifth set of constraints limits the herd size according to maximum stocking rates typical to the region. Finally, a set of milk constraints defines the liters of milk that are produced, consumed and sold.

Land and labor constraints limit the total supply of these resources in each zone, in each season. The land supply consists of sectors that are or could be irrigated by the canals, as identified by Montenegro (1998). Labor supply is limited based on estimates of the total population active in agriculture and the number of days worked per month. It is assumed that labor is non-transferable between zones.

The last category of constraints defines water constraints. Although efforts are currently underway to systematically measure water volume at multiple points along several of the canals, for the purposes of this analysis, it was impossible to identify how much water is taken from the *individual* canals in each zone. Thus, in the model, canal water is considered to be a global resource among the five canals. Of the five canals, four begin in the *páramo*, above the upper zone, and one begins at an altitude of 3200 masl and is used only by residents of middle zone 2 and the lower zone. To allow for multiple intakes of water along the canals, the first set of constraints defines water use in each zone, with water use from each source defined separately. The second set limits total water use from each source to be less than or equal to the estimated supply.[7] In addition, for certain allocation scenarios, constraints are included that limit water use from both sources at the zone-level. Given their

[7] The estimated supply from each source is calculated by varying average canal volume (Proyecto DRI, 1991) according to assumed monthly fluctuations, and summing the monthly values over the dry and wet seasons. These fluctuations are calculated from weekly volume data collected by the local MANRECUR Project from November, 1999 to October, 2000 in the canal San Vicente de Pusir de los Baños.

importance to the allocation of water solved for by the model, water constraints are explained in greater detail in the Appendix.

3. Development of model technical coefficients

The study of resource allocation on a farm requires empirical specification of relationships between underlying biological and economic processes (Nicholson, 1990). This section describes the calculation of technical coefficients to quantify the resource requirements for humans,[8] crops and animals. To account for differential resource availability by season, total requirements of a resource or input are disaggregated by wet and dry season when necessary.

Although farmers in the watershed often utilize a single hectare for the production of multiple crops, for ease of measurement, technical coefficients for crops are calculated on a per-hectare basis. Crop irrigation requirements, which account for the majority of demand for canal water, are calculated using the FAO Penman-Monteith method (Allen et al., 1998). The crop's total water requirement during month t (REQ_t) is calculated using the formula:

$$\mathrm{REQ}_t = \mathrm{ET}_{\mathrm{o}_t} \times kc_t \tag{3}$$

where $\mathrm{ET}_{\mathrm{o}_t}$ is the total amount of reference evapotranspiration during month t and $k\mathrm{c}_t$ is the crop coefficient corresponding to the appropriate month of crop growth. The formula for a crop's total irrigation requirement (IREQ) during its growth cycle is:

$$\mathrm{IREQ} = \sum_{t=1}^{T} \frac{\mathrm{REQ}_t\text{-}\mathrm{EP}_t}{\mathrm{IE}} \tag{4}$$

where T is the total months in the plant's growth cycle; REQ_t is the crop's water requirement during month t; EP_t is the amount of effective precipitation during month t; and IE is indicative of the level of inefficiency in the system of water distribution.

A number of sources of data were relied upon for the calculation of irrigation requirements. Precipitation data were obtained from Ecuador's National Center for Hydrologic Resources (CNRH)[9] and from the International Potato Center.[10] Reference evapotranspiration data were from Montenegro (1998). Effective precipitation was calculated using the method described in Brouwer and Heibloem

[8] Based on data reported in Montenegro (1998), a fixed quantity of 3.75 m^3 of water per month is allocated per human for such uses as drinking, washing, cooking and watering small gardens. The net amounts of human water use in each zone are then adjusted for the effects of conveyance inefficiencies.

[9] As reported by Montenegro (1998) and collected from the meteorological station at El Angel.

[10] Data are monthly measures of rainfall (mm) at four representative meteorological stations: Chalpatán (3360 masl); El Angel (3055 masl); Bolívar (2640 masl); and San Vicente de Pusir (1870 masl).

(1986). Monthly k_c values specific to the region were obtained for most crops from Apollin and Eberhart (1998). Finally, factors reported in Montenegro (1998), reflecting the degree of efficiency in the capture, conduction and application of irrigation water in the watershed's system of canals, were used to determine gross irrigation requirements.

Data used in the derivation of crop enterprise budgets were for the most part collected by B. Arce during the course of fieldwork in the year 2000. Costs were broken down into six major categories: labor, equipment, seed, fertilizer, pest control and transportation. Levels of investment vary widely between the crops that are produced for commercial sale (potatoes, corn, anise), and those which are largely produced for home consumption (wheat, sweet potato, white carrot). Costs and yields are adjusted for crop activities where lower irrigation intensities are assumed (Table 3).[11]

Table 3
Summary of assumed crop input costs, yields and prices

Zone/Crop	Price[a] ($/mt)	100% Irrigation Cost[a] ($/ha)	100% Irrigation Yield (mt/ha)	67% Irrigation Cost[a] ($/ha)	67% Irrigation Yield (mt/ha)	33% Irrigation Cost[a] ($/ha)	33% Irrigation Yield (mt/ha)
Upper							
Potatoes[b]	120.00	824.84	15.91				
Improved pasture[b,c]	n/a	175.31	19,247				
Barley	195.00	248.45	2.27	242.25	2.19	236.05	2.10
Middle 1							
Potatoes[b]	120.00	824.84	15.91				
Barley	195.00	248.45	2.27	227.17	1.83	207.91	1.43
Wheat	211.00	263.73	2.27	246.36	1.94	230.01	1.64
Middle 2							
Corn	243.18	345.10	3.86	334.55	3.65	324.10	3.44
Beans	440.00	222.41	1.00	217.04	0.92	211.72	0.84
Peas	580.00	214.89	1.11	200.23	0.78	187.43	0.49
Lower							
Corn	243.18	345.10	3.86	282.39	2.46	237.05	1.46
Anise	1585.58	250.34	0.90	231.24	0.54	217.97	0.30
Sweet Potato	102.94	318.01	9.00	272.77	5.10	242.48	2.53
White Carrot	100.00	318.01	9.00	273.46	5.16	243.33	2.60

Data sources: Arce, fieldwork (2000), Proaño and Paladines (1998), CIP (1990–1992).
[a] Prices and costs effective as of June 2000.
[b] Potatoes and improved pasture are assumed fully irrigated.
[c] Yield data for improved pasture are annual values of kg DM/ha. Cost data for improved pasture are totals for a 3-year period.

[11] Although not identical, this formulation is similar to a separable programming formulation to approximate diminishing marginal productivity of an input (Hazell and Norton, 1986).

Enterprise budgets for dual purpose cattle production include the costs of labor, vaccines, vitamins and minerals that are directly attributed to each animal. Costs of producing improved pasture are counted as a cost of crop production in the objective function. Costs are identified separately for lactating and non-lactating animals, primarily due to the differences in labor requirements.

The herd's energy, protein and water requirements determine the amount of pasture, concentrate and canal water needed for dual purpose cattle production. Utilizing assumptions regarding the quantity and quality of daily milk production per cow, as well as average weights and weight gains, the daily feed requirements of each type of cattle were determined.[12]

Both native and improved pasture are common in the upper zone; in middle zone 1, however, native pasture dominates. Although the use of improved pasture has been shown to allow gains in herd size and production per cow (Brockington et al., 1992), due to the costs of labor, seed and fertilizer, cultivation of improved pasture involves a greater investment for the producer. Because the nutritional content of both native and improved pasture varies between seasons and between years, average levels of nutritional content are calculated and used as technical coefficients in the model.[13]

Grain concentrates fed in the watershed generally consist of wheat bran and corn grain. In the model both are assumed to be available for purchase in unlimited quantities, and because they are manufactured, content is assumed to not vary significantly between seasons or years.

4. Model validation and water allocation scenarios

The process of model validation includes a comparison of the results of an Initial solution to historical production patterns. Generally, the similarity between the model's solution and historical land use is greatest in the upper zone, and decreases as one moves downstream. Based on historical data, the average percentage of cultivated land utilized for the representative crops in the left margin is greatest in the upper zone (83%), decreases in middle zone 1 (64%) and middle zone 2 (49%), and is at its minimum in the lower zone (30%).[14] This result is expected, given the greater diversity in production made possible by the higher temperatures and levels of solar radiation characteristic of downstream areas. Historical land use patterns for the entire watershed show that the percentage of cultivable land left fallow is also

[12] Equations for calculating the requirements of heifers and cows are taken primarily from Berger (1999); they are based largely on the published requirements of the National Research Council (1989). Requirements for steers are based on the National Research Council's (1996) requirements for beef cattle.

[13] Average nutritional contents of native and improved pasture for each season over a period of three years are determined from data provided by Instituto Nacional Autónomo de Investigaciones Agropecuarias (INIAP).

[14] Average percentages of cultivated area in the representative crops in each zone from 1996–1999, are based on survey data collected in 2000.

greatest in the lower zone (33%), which might partially account for the relatively low percentage of land sown in the representative crops (Proaño and Paladines, 1998).

The initial solution, in which herd size is endogenous, includes no cattle activities. This result supports the contention by Nicholson et al. (1994), that in most Latin American countries, "highland areas typically provide greater net returns when dedicated to agricultural enterprises other than livestock" (p. 312). For the small and medium-sized producers who dominate the watershed, it is likely that cattle are raised for reasons other than the monetary income they generate. The dual purpose production system is considered to be especially suited to tropical regions, given its sustainability with respect to resource use and consistency with the demand for milk and meat (Restrepo et al., 1991). Furthermore, in comparison to crop production, dual purpose cattle production provides a steady income, which mitigates the risk inherent in variable crop prices and the effects of between-harvest periods when savings are low.

For these reasons, constraints are added to ensure minimum acceptable herd sizes for the upper zone and middle zone 1, where minimum herd size is based on cattle population estimates by Arce et al. (1993) and Proaño and Paladines (1998). The validated model is used in all subsequent scenarios for the study of water allocation.

In an attempt to address the concerns of policymakers, five scenarios are modeled to reveal the effects of water allocation on the use of resources and the distribution of income among producers. First, in the Enforced Rights Allocation scenario, water is allocated from the canals strictly according to the pattern of ownership of water concessions between the four zones. This provides a starting point for policymakers, as it represents the possible consequences of enforcing the set of laws that currently govern water use.

Although this analysis reveals flaws in the current system, in reality, concessions are not enforced. Because much of the responsibility of water management is left to local residents, actual water use is driven by the laws of nature, rather than by the system of concessions. Thus, relative allocation is largely a function of location; upper zone farmers require less than their legal allocation, and the surplus water flows downstream. Middle zone producers are therefore in a position to use water beyond their legal allocation. The Actual Allocation scenario, designed to represent reality and used as a baseline of comparison for further analysis, portrays the distribution of water that results when illegal water use is allowed by middle zone producers.

Assuming the goal of policymakers goes beyond the identification of current system failures, it is useful to study alternatives to the Enforced Rights and Actual Allocation scenarios. Three additional scenarios are analyzed that specifically address the concepts of efficiency and equity. In the Efficient Allocation scenario, water is allocated by the basic economic criterion that the value of its marginal product is equal among all uses. This scenario is an efficiency "ceiling" for policymakers, representing the highest level of aggregate income that can be achieved, given current resource availability and relative price levels.

If policymakers instead seek to give some priority to equity considerations through resource (re)allocation, they must first clearly define their equity goal. In the Land-based Allocation scenario, equity is defined in terms of water allocation—an equal amount of water is allocated per hectare of land throughout the watershed. In contrast, when the goal is defined in terms of an equitable income distribution, a preferable standard for water allocation is that given by the Irrigation-based Allocation scenario, in which water is allocated in proportions that reflect the differences in average per-hectare irrigation requirements.[15]

5. Model results

Table 4 reports the activity levels for the five modeled scenarios. Water use in each zone is reported separately for the dry and wet seasons. Crop production activities are differentiated according to the levels of irrigation intensity. Herd size in animal units and the volume of milk produced in the upper zone and middle zone 1 are also presented. Table 5 displays total income and income distribution, represented by various measures, between the four zones in each case.

5.1. Key results

The results of the Enforced Rights Allocation scenario demonstrate that if water were allocated strictly according to the legal concessions in the watershed, resource use and income distribution would be neither efficient nor equitable. Although irrigation requirements are relatively low in the upper zone, producers there own more than 71 percent of the total volume of assigned water.[16] Water is used in a manner that maximizes agricultural income in the upper zone, until land restrictions become binding and significant surplus water results. If downstream farmers are restricted from using this excess water, more than 50% of the area's total water supply, and 40% of total land supply, go unused. Middle zone 1 producers respond by shifting resources to the production of dual purpose cattle fed by native pasture, activities that require much less water. The restrictions in resource use and resulting shifts to less profitable activities have a severe impact on income generated. As shown in Table 5, total income in the Enforced Rights Allocation scenario is limited, and its distribution is highly inequitable, heavily favoring upper zone producers.

From these results it appears that the illegal use of water by middle zone farmers is in fact consistent with the goals of efficiency and equity. The Actual Allocation scenario, which relaxes the restrictions on middle zone water use, clarifies the importance of location along the canals to water use and income distribution. Although lower zone farmers receive their full legal allocation (approximately 25% of total supply in both seasons), they earn only 11% of aggregate income (Tables 4 and 5). Despite the fact that the majority of water is used in middle zone 2 and the lower zone, it is not enough to offset the limitations imposed on downstream producers by

[15] In both the Land-based and Irrigation-based Allocation scenarios, human water use is subtracted from the total water supply prior to establishing the proportions of water allocated for agricultural use in each zone.

[16] Water concession information was obtained from Ecuador's National Center for Hydrologic Resources (CNRH), and is based on information recorded by this agency between 1973 and 1996.

Table 4
Zone level water use, crop production and cattle production for the modeled scenarios

Zone/ Water use (m^3)	Enforced Rights		Actual		Efficient		Land-based		Irrigation-based	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Upper	1,143,833	773,807	1,143,828	773,806	474,824	630,065	1,143,833	773,807	406,295	538,982
Middle 1	240,770	241,118	1,416,278	867,522	1,184,950	788,766	1,416,278	867,522	697,307	622,748
Middle 2	240,768	254,072	2,212,597	2,578,976	652,422	1,278,029	1,514,288	1,699,156	1,162,979	1,479,559
Lower	1,585,635	1,776,103	1,585,635	1,776,103	4,073,128	4,404,215	1,572,107	1,760,767	3,286,868	4,459,792
Zone/Crop production	Irrig. (%)	Hectares	Irrig. (%)	Hectares	Irrig. (%)	Hectares	Irrig. (%)	Hectares	Irrig. (%)	Hectares
Upper										
Potatoes	100	353.49	100	353.49	100	318.24	100	353.49	100	203.56
Barley	100	35.70	100	35.70	100	32.14	100	35.70	33	109.65
I. Pasture	100	162.81	100	162.81	100	15.36	100	162.81	100	0.00
N. Pasture	0	0.00	0	0.00	0	186.25	0	0.00	0	238.80
Middle 1										
Potatoes	100	35.22	100	35.22	100	240.68	100	240.68	100	240.68
Barley	100	0.00	100	0.00	100	336.25	100	336.25	100	67.66
Barley	33	49.20	33	49.20	33	0.00	33	0.00	33	268.59
Wheat	33	18.65	100	18.65	33	127.42	100	127.42	33	127.42
N. Pasture	0	806.93	0	806.93	0	205.66	0	205.66	0	205.66
Middle 2										
Corn	100	0.00	100	0.00	100	0.00	100	159.41	100	80.84
Corn	33	24.85	33	24.85	33	262.74	33	57.99	33	154.48
Beans	33	38.45	100	38.45	33	406.54	33	336.38	33	364.11
Peas	100	12.73	100	12.73	100	62.72	100	178.22	100	132.57
Lower										
Corn	100	68.09	100	68.09	100	173.55	100	67.44	100	205.81
Anise	100	66.93	100	66.93	100	185.88	100	66.29	100	143.22
S. Potato	100	14.74	100	14.74	100	40.93	100	14.60	100	31.54
W. Carrot	100	7.64	100	7.64	100	21.21	100	7.56	100	16.34
Cattle production	AUs	Milk (1)	AUs	Milk (1)	AUs	Milk (1)	AUs	Milk (1)	AUs	Milk (1)
Upper	391	139,080	391	139,080	391	139,080	391	139,080	391	139,080
Middle 1	1,320	469,980	391	139,080	391	139,080	391	139,080	391	139,080

differences in per hectare irrigation requirements. Both income per capita and income per hectare decrease as one travels downstream.

One alternative to the current system of water management is to allocate water according to a standard of economic efficiency. Water is allocated to the uses that bring the greatest return; hence, total income in the Efficient Allocation scenario is the greatest of the five studied scenarios. Not surprisingly, maximizing the efficiency of water use also brings the most efficient use of land resources; the percentage of land supply that is cultivated in the lower zone is at its maximum, 56%. Similar to the results of Bernardo et al. (1988), the scenario demonstrates the potential for efficiency gains due to water reallocation. In comparison to the Actual Allocation scenario, although water use in the upstream zones decreases by an average of 49% in the dry season, the average decrease in income in these three zones is less than 11% due to more efficient water use.

Results from the model reveal that policies designed to achieve equity as defined by water use versus income distribution criteria will have quite different effects on both resource use and income distribution, and are not likely to be supported by the same groups in the watershed. The Land-based Allocation scenario, which incor-

Table 5
Breakdown of income distribution by scenario by scenario and zone

	Enforced rights	Actual	Efficient	Land-based	Irrigation-based
Upper					
Zone income ($)	392,159	392,159	361,869	392,159	251,235
Percent of total (%)	62.09	33.55	27.95	34.47	22.29
Income per hectare[a]	710	710	656	710	455
Income per capita[b]	493	493	455	493	316
Middle 1					
Zone income ($)	82,533	359,656	347,041	359,656	314,181
Percent of total (%)	13.07	30.77	26.81	31.61	27.87
Income per hectare[a]	91	395	381	395	345
Income per capita[b]	69	303	292	303	264
Middle 2					
Zone income ($)	24,358	284,456	226,694	254,599	242,316
Percent of total (%)	3.86	24.34	17.51	22.38	21.50
Income per hectare[a]	33	389	310	248	331
Income per capita[b]	24	285	227	255	243
Lower					
Zone income ($)	132,581	132,581	358,985	131,312	319,383
Percent of total (%)	20.99	11.34	27.73	11.54	28.34
Income per hectare[a]	177	177	481	176	428
Income per capita[b]	121	121	329	120	292
Total income ($)	631,159	1,168,852	1,294,589	1,137,726	1,127,115

[a] Calculated based on total land supply.
[b] Based on total population dependent upon agriculture.

porates the standard of equity in water use, makes available an equal amount of water, at the water's source, to each hectare of land in the watershed, ignoring the differences in conveyance inefficiencies and irrigation requirements between zones. Due to these technological and climatological factors, the value of this water is much greater to upstream producers than downstream producers, and income distribution favors the upper zone and middle zone 1. An examination of Table 4 reveals a similarity between the results of the Land-based Allocation scenario and the Actual Allocation scenario. This suggests that, in reality, per-hectare agricultural water allocation is relatively equitable among zones. This does not imply that per hectare water *use* is equal between zones, as more water is required per hectare downstream, resulting in more land being left fallow.

In the Irrigation-based Allocation scenario, which attempts to achieve equity in income distribution, the average seasonal irrigation requirements in each zone are summed and the proportion of the total average requirement attributed to each zone in each season is used as a basis for limiting agricultural water use. These proportions naturally increase as one travels downstream, and the scenario allocates more water and more income to the lower zone, in comparison to the Land-based Allocation scenario. Lower zone farmers respond by increasing production of all crops, with greatest increases in high-value crops such as corn and anise. As is the case with the Efficient Allocation scenario, the shift of water to the lower zone is partly achieved by reducing the levels of irrigation intensity in the upper zone and middle zone 1. Of the five scenarios, the Irrigation-based Allocation scenario does in fact result in the most equitable distribution of income.[17]

The combined results of the five water allocation scenarios clarify important relationships between water allocation and the achievement of efficiency and equity objectives. The Actual and Land-based Allocation scenarios demonstrate that an equitable distribution of water will not maximize efficiency in resource use nor equity in income distribution. In contrast, the Efficient and Irrigation-based Allocation scenarios result in the most efficient use of water and land resources, as well as the most equitable distribution of income, indicating that these two goals can be consistent with one another. Summarizing the results, improvements in efficiency (in resource use) and equity (in income distribution) are generally associated with (1) a shift of water to the lower zone, and (2) the use of lower levels of irrigation intensity upstream.

It is important to note, however, that even if policymakers were to take action to redistribute water use according to these standards, it is highly unlikely that all residents of the watershed would support such an initiative. Although a water management policy may potentially improve the efficiency of resource use and increase total income in the watershed, it may not be implemented because a majority of farmers are better off without the policy (Ray, 1997). This is true of

[17] As a percentage of per capita income in the highest-income zone, the difference in per capita income between the highest-income zone and the lowest-income zone is 23% in this scenario, compared to 95, 75, 50 and 76% in the Enforced Rights, Actual, Efficient and Land-based Allocation scenarios, respectively.

upper zone farmers in the El Angel watershed, who are currently favored with respect to the ownership of water rights as well as position along the canals, and who have no incentive to support such a change.

5.2. Resource valuation

A comparison of shadow prices (reported in Evans, 2001) reveals a relationship between the allocation of water and the value of land.[18] In the water allocation scenarios which favor the upper zone (the Enforced Rights Allocation scenario and the Land-based Allocation scenario), the shadow price of land is greatest in the upper zone, and decreases as one goes downstream. Conversely, with respect to water allocation, the Irrigation-based Allocation scenario favors downstream producers. In this scenario, the value of land is greater in middle zone 1 and middle zone 2 than in the upper zone. Thus, changes in water allocation would not only influence farmers' annual incomes earned from crop and cattle production, but could also simultaneously influence producers' wealth by either increasing or decreasing the value of their land assets.

5.3. Taxation strategies

The shadow price of water in the Efficient Allocation scenario, \$0.053/m^3 in the dry season and \$0.036/m^3 in the wet season, is an estimate of the value generated per cubic meter of water when the marginal value of water is equal among uses. These dry and wet season values are used as a basis for the study of water use taxation strategies. Water use is taxed at these levels; the tax is then gradually increased in the upper zone and middle zone 1 and gradually decreased in middle zone 2 and the lower zone.

The series of tax strategies studied using the model demonstrate that taxation can be used as a tool for shifting water resources and altering levels of efficiency and equity. As the tax on upstream water use is increased and the tax on downstream water use is decreased, the marginal value of water to downstream producers increases relative to upstream producers, and water and income therefore flow to the lower zone. At the same time, aggregate income increases and aggregate tax revenue decreases, due to the simultaneous increase in water use and decrease in tax rates downstream. Levels of production, and therefore income, in the upper zone, middle zone 1 and middle zone 2 prove to be quite insensitive to the imposition of taxes on water use, with primary changes occurring in production of the same crops at lower irrigation levels and the shift of land from improved to native pasture.

[18] Labor is never a limiting resource in any scenario, and therefore its shadow price is always zero. The same can be said for the shadow price of land in the lower zone. In all modeled scenarios, water limitations restrict land use in this zone to less than 60% of the total available land supply.

6. Conclusions and policy implications

Results from this study indicate that the actual allocation of water from the five studied canals, characterized by middle zone water use beyond the legal allotment, is more consistent with the goals of economic efficiency and income equity than the allocation of water that would result if current water rights were strictly enforced. Water rights are not strictly enforced, as local water user groups are hindered by a lack of government involvement, limited access to monetary and technological resources and poor communication. Under these circumstances, a producer's ability to obtain and utilize water resources to earn income is largely dependent upon his or her proximity to the water's source. Upstream farmers have no incentive to use water efficiently, and in the face of uncertainty, downstream farmers have an incentive to use water illegally.

By examining alternative standards for water allocation, this study provides guidelines for policymakers who seek to change these incentives. On one end of the policy spectrum is the strict enforcement of current concessions, which results in an underuse of both water and land. At the other end is an economically efficient allocation of water that maximizes the value of agricultural output. Although this standard results in the greatest level of total income, it also requires the most dramatic shift of water resources to the lower zone.

Water can be used more efficiently in the lower zone for a number of reasons. First, the sensitivity of income to changes in water use is relatively small in the three upstream zones, due to the fact that crops in these zones may be produced at lower levels of irrigation intensity without severely reducing yields. Second, yield losses associated with reduced irrigation intensities in the lower zone offset the gains that could be made from using this water elsewhere, given relative price levels. This is largely the result of the third factor driving water downstream, the limited upstream land supply. Much of the water flows to the lower zone because the land constraints become binding in the three upstream zones.

Given the differences in the relative values of land and water resources, allocating an equal amount of water to each hectare of land will not provide the necessary incentives for improvement. If agricultural water could be allocated in proportions that reflect these differences, upstream farmers would have an incentive to utilize water more efficiently, and downstream farmers would have a sufficient supply to ensure a more equitable distribution of income.

The existence of a market for water rights might provide the necessary incentives to alter water use patterns. Unfortunately, due to a lack of communication between water user groups and government organizations, current water rights are not reliably recorded and local water organizations have neither the tools nor the authority to make and enforce decisions with respect to water use. Furthermore, water ownership is tied to land, which seriously inhibits the transferability of water in accordance with differences in its marginal value product among uses.

Results from this analysis also show that, if effectively implemented and enforced, a water use tax could be used to redistribute water as well as raise funds for canal improvements. Given the minimal impact of the tax on cropping patterns, tax revenue could also be used to equalize income distribution without significantly changing production levels through direct payments to targeted taxpayers.

In conclusion, achieving efficiency in resource use and equity in income distribution requires a significant transfer of water resources to the lower zone, largely accomplished through a shift to lower irrigation intensity crop activities upstream. However, at this time, the design and implementation of a policy to stimulate such a shift would be a difficult task, given the vastly different conditions faced by upstream and downstream users and the resulting incentives for water use. An alternative would be to make a one-time investment in technology to modernize the canals and improve levels of efficiency, thereby reducing the locational discrepancies between zones.

The implications and conclusions of this study are of relevance not only to the Andean Sierra, but could be applied to any region or watershed facing the challenges of increasing agricultural production, food security and achieving greater efficiency and/or equity in the allocation of irrigation resources. Using the terminology of Omezzine and Zaibet (1998), for those watersheds where the "horizontal" expansion of agricultural areas is not possible due to limitations in land and water supply, methods must be determined to "vertically" expand yields by increasing land and water efficiency and productivity. The mathematical programming model could be modified to reflect the meteorological and agricultural characteristics of other watersheds to determine the relative value of constrained resources and to provide guidelines for policymakers with respect to resource allocation.

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Appendix. Water constraints

Water in the five canals is a global resource in the model. Four of the five canals originate in the *páramo* at more than 4000 masl; one has its source in the Bobo River at an altitude of 3200 masl. The water entering at the top of the watershed is available to users in all zones, but that which enters from the second source is available in middle zone 2 and the lower zone only. Water constraints limit water use on an aggregate level, and for certain scenarios, at the zone level, in each season, and from each source.

The first set of constraints defines the total water use in each zone of the watershed. For the upper zone and middle zone 1, the water use constraints are of the following form:

$$-(\mathrm{HUMW}_{ik})(\mathrm{HUM}_{ik}) - \sum_{j=1}^{J}\left[\left(\mathrm{IREQ}_{ijk}\right)\left(\mathrm{CROP}_{ijk}\right)\right] - (\mathrm{WCANAL}_{ik}) + \mathrm{WUSE0}_{ik} = 0; (i = 1, 2 \text{ and } k = 1, 2)$$

where HUMW = per capita (human) water use; HUM = human population in each zone; IREQ = per hectare irrigation water requirement by each crop; CROP = number of hectares of each crop; WCANAL = total canal water required for cattle, as determined by the model; and WUSE0 = aggregate water from the supply at the top of the watershed used in zone i during season k. All subscripts are as previously described. For each zone during each season, per-crop water use is summed over the representative cropping activities. All water use values are stated in units of cubic meters. Water use technical coefficients for humans, crops and animals are gross requirements which account for the decreasing levels of efficiency in water distribution as one travels downstream. For middle zone 2 and the lower zone, the water use constraints are slightly different:

$$(\mathrm{HUMW}_{ik})(\mathrm{HUM}_{ik}) + \sum_{j=1}^{J}\left[\left(\mathrm{IREQ}_{ijk}\right)\left(\mathrm{CROP}_{ijk}\right)\right] - \mathrm{WUSE0}_{ik} - \mathrm{WUSE1}_{ik} = 0; (i = 3, 4 \text{ and } k = 1, 2)$$

where all variables are as previously defined. Now, water may come from the supply at the top of the watershed, WUSE0, or may enter from a lower altitude, WUSE1.

The second set of constraints ensures that water use does not surpass the availability of the resource. Since water enters the study area at two different points, there are two constraints restricting water use. The first constraint limits the water used from the supply at the top of the watershed, available for use in all zones:

$$\sum_{i=1}^{4}\mathrm{WUSE0}_{ik} \leqslant \mathrm{BAL0}_{k}; (k = 1, 2)$$

where $\mathrm{WUSE0}_{ik}$ = total water used in zone i during season k, and $\mathrm{BAL0}_{k}$ = total supply of water at the top of the watershed during season k. The constraint limiting water use from the lower-altitude supply is:

$$\sum_{i=3}^{4}\mathrm{WUSE1}_{ik} \leqslant \mathrm{BAL1}_{k}; (k = 1, 2)$$

where $\mathrm{WUSE1}_{ik}$ = water from the lower-altitude supply used in zone i during season k, and $\mathrm{BAL1}_{k}$ = total supply of water from this source during season k.

For certain water allocation policy scenarios, additional water use constraints limit the water which can be used in each zone. For the upper zone and middle zone 1:

$$\mathrm{WUSE0}_{ik} \leqslant \mathrm{b}_{ik}; (i = 1, 2 \text{ and } k = 1, 2)$$

and for middle zone 2 and the lower zone:

$$\mathrm{WUSE0}_{ik} + \mathrm{WUSE1}_{ik} \leqslant \mathrm{b}_{ik}; (i = 3, 4 \text{ and } k = 1, 2)$$

where all variables are as previously defined and b_{ik} = maximum water use in zone i during season k.

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