Payments for Watershed Services: An Application to Irrigation Pricing in the El Angel Watershed, Carchi, Ecuador

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Introduction

Payment schemes for watershed and biodiversity conservation services are becoming more common in many developing countries (Pagiola et al., 2002). Recognition of the importance of environmental externalities, the valuation and assessment of relevant tradeoffs, and the incorporation of environmental service values in innovative strategies and policy interventions are highlighted in the Millenium Ecosystem Assessment (2005) and are the subject of numerous current efforts, including those of the World Bank, the Conservation Finance Alliance and the Katoomba Group. In practice, however, workable PES schemes are still are and often most successful in regions where large urban populations can be taxed – often through water or electricity charges – to generate the revenues necessary to provide environmental benefits. Situations in which the demanders and suppliers of PES services are both rural are relatively rare. Even the PSA (*Programa de Servicios Ambientales*) forest program in Costa Rica, the most frequently cited example of an existing developing country PES program, has been found to disproportionately benefit large, absentee, urban-based landowners (Zbinden and Lee, 2005).

As in much of Latin America, in Ecuador's El Angel watershed, water resource allocation to farm households differentiated by geography, farm size, income, and upstream versus downstream location has long been unequal and highly contentious. This watershed, located in Ecuador's northern highlands (Sierra) region close to the Colombian border and encompassing over 100,000 ha, is characterized by dramatic variations in elevation, topography, ethnicity, and water availability. At the highest altitudes of the watershed (3,600+ masl), the high humid Andean grassland ecosystem (or *páramo*) dominates. Water captured in this sponge-like ecosystem is released naturally for human and agricultural use at lower elevations in the watershed. Just below the *páramo*, dual-purpose cattle production and potatoes dominate in the watershed's Upper Zone (3,100-3,600 masl). Increasing population and demand are pushing production uphill into the remaining *páramo*, causing land use conflicts, decreasing biodiversity and the land's water-storing capacity. In the Middle Zone of the watershed (2,400-3,100 masl), the population density is higher and rain-fed production of crops like maize, potatoes, barley, peas and beans predominates, with growing demand for irrigation. In the watershed's dry Lower Zone (1,500-2,400 masl), the production of horticultural products dominates: maize, beans, peas, anise, and white carrots. This region however, is wholly dependent on irrigation, yet water supplies are erratic and unpredictable. Further details on the three zones are shown in Table 1.

The allocation and management of scarce water supplies in El Angel has long been characterized by social conflict between upper and lower zones due to seasonal water scarcities, chronic water theft, and inefficiency of water delivery in long, antiquated, and hard-to-maintain community irrigation systems. Water concessions have historically been allocated regardless of the amount of water actually available, leading to uncertainty, insecurity, and inefficient water use patterns. The situation is further complicated by a record of decreasing and irregular precipitation over the past 30 years, perhaps caused by climate change (Duveskog, 1999; Proaño and Poats, 2000). The legal and institutional framework governing water allocation in El Angel is weak: water rights are overallocated (given the water actually available) and overlapping; existing rights often go unenforced; government entities have typically failed to establish a clear allocation of scarce water resources (Evans, et al., 2003; Southgate and Whitaker, 1994). A multistakeholder watershed platform, the Carchi Consortium, has functioned in the El Angel since 1995, serving communities, local governments, NGOs, and *juntas de aguas* (water user associations) as a focal point for community conservation initiatives and negotiation over resource conflicts. One recent proposal has been to create a revised system of water use charges, building on the current system of minimal water charges, which would simultaneously 1) create greater rationality of water use; 2) discipline water use by imposing higher charges for this scarce resource; and 3) generate revenues to invest in water source protection and reforestation.

A mathematical programming model was designed – with significant input from Carchi Consortium members – to determine the optimal allocation of water (and other) resources in the El Angel watershed. The model is based on the notion that if water were priced to reflect its true opportunity cost, most farmers would use less water; the widespread overuse of water in the Upper Zone would be curtailed, making more water available downstream where it is particularly scarce; and farmers' adaptive behavior would likely result in more efficient irrigation practices and changes in cropping patterns. After a summary of the model's objective function, activities and constraints, we examine potential water use under four water pricing scenarios, each of which have differing implications for farm incomes, resource use, income distribution, and employment. The final section summarizes the paper's conclusions.

Optimization Model: Objective Function, Activities and Constraints

A mathematical programming model was constructed whose objective function maximizes aggregate regional gross margin for the El Angel watershed. Revenues are generated from the sale of the crop and animal products given in Table 1, which differ by zone. The model is estimated over two periods, reflecting wet and dry seasons. Crop enterprise budgets were derived from primary data collected during fieldwork in the year 2003, as well as data available from the government Ministries, private sector sources, the International Potato Center and other published sources (Evans, 2001; Arce, 2003). Production costs were estimated for six cost categories: labor, equipment, seed, fertilizer, pest control and transportation. Costs and yields are each estimated under three levels of irrigation intensity.

Model activities and constraints are summarized in Table 2. Composite crop and pasture activities are defined for wet and dry seasons and encompass all crop production processes from planting to harvest. Activities were defined for labor, water, land, conservation, sales and home consumption activities. Details are provided in Anonymous (2004), however, given the importance of water resources, the treatment of irrigation requirements is briefly summarized here. Net crop irrigation requirements are estimated as a function of effective precipitation minus crop potential evapotranspiration, the latter estimated using the Penman-Monteith method, which captures the influence of climatic factors (temperature, relative humidity, wind speed, and solar radiation) on crop water requirements (Fipps, 2000). Inefficiencies in the El Angel irrigation system were also accounted for at conveyance, distribution and field application levels; overall estimated efficiencies ranged from 29.4% in the Lower Zone to 36.75% in the Upper Zone, so these losses are clearly highly significant. Crop yields were estimated using the simulation model originally developed by Doorenbos and Kassam (1979), which relates the ratio of actual to maximum yield to the accumulated evapotranspiration deficit for the entire growing season. Bernando et al.'s (1988) approach to estimating crop growth-stage effects was also used to simulate adjusted yield responses under the three levels of irrigation intensity.

Model constraints are divided into seven categories: human, crop, land, labor, water, food security, and market-related. Again, details are provided in Anonymous (2004) and we focus only on the water-related constraints here. Estimates of water balances for each zone were necessary to determine the magnitude and dispersion of water surplus and deficit areas, both temporally and spatially, in order to provide a calculation of the upper bounds of water supply for the watershed (and each zone therein). Using the methodology introduced by Thornthwaite and Mather (1957) and revised by Dunne and Leopold (1978), we estimated water balances given data available on precipitation, potential evapotranspiration, soil structure, soil depth, and soil cover for the El Angel watershed. This enabled estimation of monthly water surplus or deficits for each of the three altitudinal zones, in addition to the *páramo*, which is a net water supplier. The results show a net wet season water surplus in the *páramo* and Upper Zone of roughly 88.8 million m^3 and a net water deficit in the same season in the Middle and Lower Zones of -19.6 million m^3. In the dry season, the aggregate water surplus in the *páramo* and Upper Zone declines to about 32.8 million m^3 and the deficit in the two lower zones is -48.7 million m^3 . Even with high inefficiencies in the irrigation system, if storage were available (and located optimally), there would appear to be enough water to meet current crop requirements.

Water available for irrigation in each zone (Upper, Middle, Lower) and each margin (left (east) side, right (west) side) results from the water flows of all the canals serving each zone. Some canals deliver water all the way from the *páramo* via upper zones; in other cases, canals begin in the Middle Zone. Model water constraints are of two types: the first limits water use in each zone to be less than the total amount available in each season; the second aggregates the total amount of water available in each zone and allows for water transfers from Upper to Middle and Lower Zones, if the total use is less than that available in upper zones, given crop irrigation uses (net of water losses). Model constraints also impose limits on land and labor availability by zone and the land used by size of producer (large, medium, small). Food security constraints stipulate the amount of each produced commodity required to satisfy home consumption. Market constraints limit the amount of each crop available for sale in regional markets. Crop rotational constraints define the minimum number of hectares in each zone that must be devoted to pasture to accomplish appropriate rotation with crops. The final model included 323 columns representing activities and 223 rows for resource and accounting constraints, and was solved using GAMS (Brooke, et al., 1992).

Policy Scenarios and Results

Several scenarios were modeled in order to examine the effects of introducing water prices under different assumptions. First, a *Current Scenario* was modeled in order to validate the model and compare estimated patterns of resource allocation against the actual current pattern. A second *Efficient Pricing* scenario was examined in which irrigation water is priced at its shadow price, unique for each season, zone, and margin of the watershed. In this scenario, water is treated as a global resource, able to move between zones to its most profitable use until its marginal value is equalized across zones. A third *Equitable Pricing Scenario* was examined in which water scarcity is equitably shared across the watershed by allocating to each altitudinal zone an equal proportion of actual water available relative to the maximum water demand resulting from the Maximum Water Scenario. After the model is solved, equitable shadow prices are introduced into the model and it is re-solved. This process allocates water such that all zones are able to use the same proportion of maximum water demand. Finally, a *Maximum Water Scenario* was estimated by removing the water constraints from the original model under the assumption that investments in new irrigation infrastructure – perhaps permitted by additional financial resources collected from higher water taxes – and/or the introduction of new crops, water storage facilities or agricultural technologies would permit the generation of additional production and income.

Table 3 shows selected results estimated for the four scenarios. Results were estimated separately for right and left margins of the watershed, although due to space limitations, only aggregated results are presented here; further details are available in Anonymous, 2004. Due to space limitations, only selected results are discussed here.

In the *Current Scenario*, producers in the Upper Zone are able to use water up to the point where the marginal productivity of water is zero. After that, the model allows for the transfer of excess water to the Middle Zone, which is complemented by water from other canals first entering the productive lands in the Middle Zone. The estimated maximum gross margin for the watershed is $3,328,527, of which 42.3% is generated in the Upper Zone, 38.5% in the Middle Zone, and 19.1% in the Lower Zone. Pastures and potatoes – the latter either rain-fed or irrigated at the lowest intensity – are the dominant crops in the Upper Zone. Cattle production is labor-extensive and water-intensive; since water is abundant and free of charge in this zone, labor requirements are reduced. In the Middle Zone, irrigation water is adequate in the right margin of the watershed, but only three-fourths of the land in the left margin is planted. The cropping pattern is a combination of grains, legumes, potatoes and pasture for livestock. In the Lower Zone, one-quarter of the land goes unplanted due to lack of irrigation water, but the remainder is planted to a number of crops including anise, corn, and beans.

In the *Efficient Pricing Scenario*, water is priced at its shadow price for each zone, season and margin. Given the conditions and assumptions under the Current Scenario and allowing water to move to its most profitable use, shadow prices can be calculated reflecting the highest value that producers would be willing to pay for water to maximize profits. We estimated shadow prices in the right margin of the watershed at $0.034/m^3 for the wet season and $0.057/ m^3 for the dry season; for the left margin, shadow prices were zero (e.g., water use was not constrained) for the wet season and $0.037/m^3 for the dry season. Using these estimates as the prices for irrigation water we recalculate the *Efficient Pricing Scenario* results. The results show that while the patterns of crop production, income and water use on the right margin of the watershed are largely unchanged, in the left margin, 22% of the Upper Zone is fallowed or retired from production (e.g., put into conservation uses). The extra water released to the Middle Zone permits a more intensive and wider planting of crops, especially corn and peas. Income in the left margin rises by 22%, and in the watershed overall, by 13%. Increased water use in the Middle Zone of the left margin comes at the expense of producers in the Lower Zone whose production and income levels decline. In sum, the introduction of water pricing at the levels of its shadow prices permits increased efficiency and income but worsens (slightly) the income distribution among zones and reduces (slightly) total employment levels in the region. On the other hand, water revenues amounting to an estimated $579,703 are generated which could be plowed back into infrastructure investment, water source protection, or other investments.

Using the "shared scarcity" approach to equity mentioned above, a third *Equitable Pricing Scenario* was estimated in which an equal proportion of actual water demand relative to maximum water demand (under the Maximum Water Scenario) was allocated to each zone in each margin of the watershed. Shadow prices were then derived and introduced again into the model to solve for optimal outputs and input use. The results again show that changes in crop mix and incomes are small in the right margin of the watershed. The most dramatic changes occur in the Lower Zone which benefits from greater water availability made possible by more efficient water use in the upper zones. In the watershed's left margin, however, changes are more pronounced. The introduction of equitable prices for water raises income by 15%, or almost $300,000. Like the *Efficient Pricing Scenario*, more water is allocated to the Lower Zone under this scenario, which is permitted by less intensive pasture production and increased land fallowing in the Upper Zone of the left margin. In the Middle Zone, the area planted to maize increases by over 1,100 hectares compared to the *Current Scenario*, while in the Lower Zone, additional water availability permits an increase in cultivated land by 15%. Revenues from the revised system of "equitable" water pricing increase significantly above the levels generated in the Efficient Pricing Scenario to an estimated $1,243,067.

Finally, a *Maximum Water Scenario* was estimated in which existing water constraints were removed and all other model components are unchanged. Although this scenario is arguably not realistic since increasing water supplies would likely significantly affect planting patterns, the opportunity cost of land and many other watershed activities, this does become an additional baseline point of comparison for evaluating the other scenarios and provides a ceiling on estimated incomes achievable. In this scenario, the major change in the right margin is a significant increase in cultivated area in the Lower Zone; a major shift from maize to the more highly valued, though water-intensive, anise occurs. In the left margin, overall household income increases by 41% as crop cultivation expand widely in the Middle and Lower Zones. With maximum levels of irrigation available, potato, corn and peas are pushed to market sales constraint boundaries in the Middle Zone, and in the Lower Zone, anise production triples while other more low-valued crops decline. All the cultivable land in the left margin is used in production under this scenario. Employment increases significantly.

Introducing a differentiated system of water prices based on the shadow prices estimated above (or a similar type of system) some might argue is unrealistic and is unlikely to be operational. Alternatively, a single price of water might be introduced which increases aggregate income (while not maximizing it) and generates revenues for watershed infrastructure investments. A parametric series of single seasonal price combinations was modeled to identify efficient pricing alternatives. Figure 1 demonstrates the results of several pricing options and the additional regional income they would generate. One option would be a combination of $0.034/m^3 in the wet season and $0.0437/ m^3 in the dry season. This would generate an estimated increase of $376,397 in regional income and an equitable distribution to the Lower Zone of both margins, though it would necessitate a roughly 20% decrease in water use in the Upper Zone.

Conclusions

Several conclusions are possible from this analysis of water pricing in the El Angel watershed. First, adequate water resources clearly exist in the watershed to permit a reallocation of water within the watershed, which in turn would generate higher regional production and incomes. Second, several pricing alternatives – including but not limited to the 'efficient' and 'equitable' pricing alternatives examined here – are available which would discipline water use in the Upper Zone where water is currently free, overused and unregulated. Although producers in the Upper Zone might resist such changes, our results show that income in that zone would be reduced only about $100,000, while permitting increased incomes in the Middle and Lower Zones of several times that. A third and related conclusion is that while tradeoffs exist in achieving resource conservation, efficiency and equity goals, significant net gains are clearly achievable. The *Equitable Pricing Scenario*, for example, generates a 5% lower regional income gain than the *Efficient Pricing Scenario*, but still increases regional income by over $250,000, generates an estimated $1.24 million in water revenues for watershed infrastructure investments, and reduces employment by only 2.5%. Third, even if a differentiated system of water prices is deemed to be impracticable, a politically more realistic system of single seasonal prices similar to that depicted in Figure 1 would generate many of the benefits of the differentiated system. Introducing a system of comprehensive water charges would appear to have many benefits, not only in El Angel, but in many other developing country watersheds facing similar resource constraints.

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Table 1. Descriptive Statistics for the El Angel Watershed, Carchi, Ecuador

	Upper Zone	Middle Zone	Lower Zone
Elevation (masl)	3,100-3,600	2,400-3,100	1,500-2,400
Land area (hectares)	10,910	7,852	2,952
Population	14,157	8,000	3,600
Average Farm Size (hectares)	3.9	3.4	3.2
Average Precipitation (mm/year)	1,046	881	416
Average evapotranspiration (mm/year)	722	1,001	1,421
Major Production Systems	Dual purpose cattle, potatoes, barley	Dual purpose cattle, potatoes, maize, barley, peas, wheat, beans	Maize, beans, peas, anise, sweet potato, white carrots

Source: Anonymous, 2004; Evans, et al., 2003, Proaño and Palidines, 1998.

Table 2. Model Activities and Constraints

Activities	Constraints
<u>Human</u> Population in each zone	<u>Human</u> Define population in each zone
<u>Cropland</u> Hectares of crop/pasture production - For each zone - For each level of irrigation intensity (3) - For each farm size (3) Production process components: - land preparation - planting - weeding - pest control - fertilizer application - harvesting	<u>Crop Seasonal Constraints</u> All activities defined for wet and/or dry seasons <u>Land</u> Restrict total land available in each zone (3), in each season (2), by producer group (3) <u>Water</u>* Define aggregate water supply Define total water use in each zone Restrict water use ≤ water supply Restrict water use in each zone
<u>Labor</u> Man-days for each crop and livestock activity	<u>Labor</u> Restrict labor use ≤ labor supply in each zone
<u>Water</u> Levels of water use - from each source of water supply - for each zone	<u>Food Security</u> Home consumption requirements for small and medium-sized producers
<u>Conservation</u> Land retired or fallowed	<u>Market</u> Restrict upper and middle zone production due to regional market capacity
<u>Home Consumption</u>	
<u>Sales</u>	

* Water constraints by zone are defined by estimated water balances.

Source: Anonymous, 2004.

Table 3. Estimated Resource Use by Scenario and Zone, El Angel Watershed

	Current Scenario	Efficient Pricing	Equitable Pricing	Maximum Water Use
Land Use (hectares)				
Upper Zone				
Potatoes	1,253	1,253	1,253	1,253
Pasture	3,286	*2,392	*3,165	3,286
Peas	227	227	*227	227
Barley	68	144	94	68
Conservation	--	818	95	--
Middle Zone				
Wheat	78	71	50	81
Maize	362	1,373	*1,484	1,460
Beans	450	419	402	402
Peas	*526	525	481	525
Potatoes	619	619	619	619
Pasture	*2,644	*2,665	*2,606	2,585
Lower Zone				
Anise	519	498	785	1,050
Maize	530	318	231	7
Beans	97	97	97	56
S. Potato	4	4	4	4
W. Carrot	2	2	2	2
Water Use (m^3)				
Upper Zone				
Wet	3,568,150	1,871,060	1,790,000	3,568,150
Dry	3,754,650	2,080,125	1,983,790	3,754,650
Middle Zone				
Wet	5,648,400	7,578,020	6,380,701	12,569,552
Dry	4,595,600	6,625,520	4,413,940	7,614,960
Lower Zone				
Wet	7,690,600	7,680,510	6,818,760	5,736,140
Dry	8,247,970	7,872,730	9,386,250	15,508,300
Maximum Gross Margin ($)	$3,328,527	$2,801,693	$2,342,436	$4,305,173
Water Revenue ($)	0	$945,093	$1,243,067	0
Employment (Man-days/yr.)	587,618	562,541	572,509	615,329

*Aggregated estimated production levels using multiple levels of irrigation intensity.

Source: Anonymous, 2004.

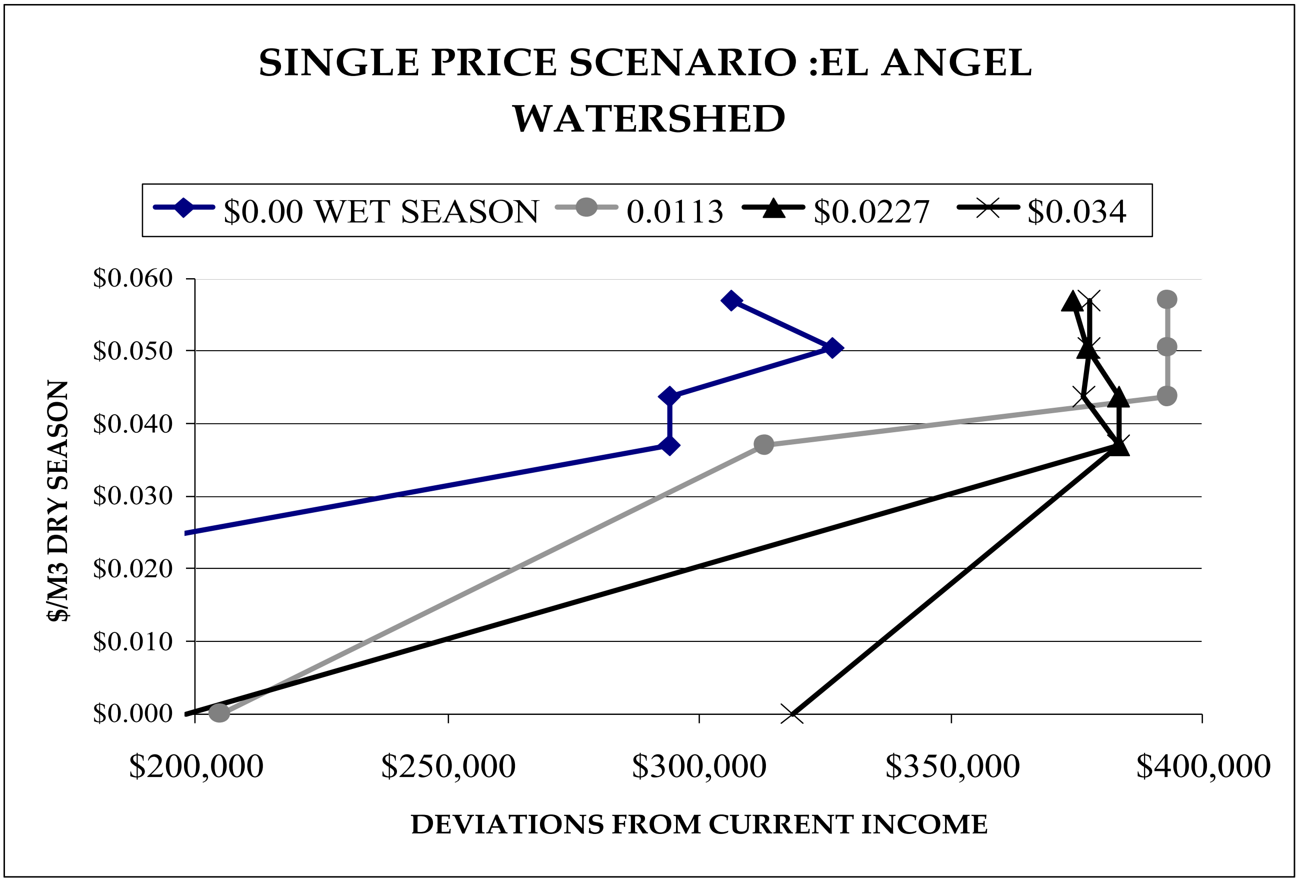

Figure 1. Single Price Scenario for the El Angel Watershed