



Land-water linkages in rural watersheds

Case study series

Valuation of hydrological externalities of land use change: Lake Arenal case study, Costa Rica

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Introduction

Identification of offsite impacts of land use on hydrological regimes is of increasing interest for policy purposes, because provision of clean and sufficient water supplies is a service with direct market value. If and when these links can be clearly established, downstream water users might then, in principle, have an incentive to contribute towards the cost of implementing conservation practices upstream. Whether there is an actual incentive, will also depend on site-specific social, economic, and institutional factors.

In practice, the biophysical links are difficult to establish, because impacts of land use on hydrology depend on interactions among a large number of land uses, vegetation and geological characteristics that occur within heterogeneous landscapes over a range of spatial and temporal scales. For example, changes in water yield in the Arenal case study as presented below, depend on whether land use change has occurred in areas where forest has been cleared entirely or whether it is fragmented, whether that forest has a low or high canopy, and whether or not is it a cloud forest, which captures moisture from fog (“horizontal precipitation”). It also depends on management practices. Even when links between causes and effects can be established, such as between land use change and increased rates of erosion and sedimentation, whether or not this creates a financial incentive for conservation will depend on actual or perceived damages, and the time frame over which they occur. It will also depend on how costs and benefits are distributed among the various stakeholders, and either their relative ability to pay for ecosystem services or the extent of political will on the part of government to regulate land use practices.

This case study revisits previous work done by Aylward et al (1998; 1998; 1999) regarding the Rio Chiquito watershed of the Lake Arenal area in Costa Rica, which found that, in the aggregate, livestock production and the higher water yield from pasture would produce greater financial and economic returns than reforestation or natural regeneration. This was because of the relatively high aggregate value of livestock and dairy production, and also the value of the additional water for downstream hydroelectricity. The benefits of the increase in streamflow was found to outweigh the costs of the increase in sediment yield, which was less problematic in part due to the large amount of dead storage space in the reservoir. Sensitivity analysis found that even a strong dry season increase in baseflow under reforestation would be unlikely to reverse this conclusion. Although these conclusions challenge the conventional wisdom, that hydrological externalities provide the basis for financial incentives for reforestation, a disaggregated analysis did show that there were potential incentives for some of the smallholders to switch land uses, and that the greatest amount of water was captured in fragmented cloud forests, also found primarily in the small holdings.

Box 1: Summary of the Full Cost-Benefit Analysis study in Arenal

Conventional wisdom holds that the conversion of tropical rainforest to pasture leads to a rapid loss of soil fertility, a rise in the sedimentation of waterways and reservoirs, an increase in flooding and a decrease in dry season water supply. As a consequence, the establishment of large hydroelectric reservoirs in deforested watersheds often leads to proposals for curtailing agriculture and livestock production in favor of watershed protection and reforestation.

The Río Chiquito watershed in Costa Rica supplies water to Lake Arenal and a hydroelectric scheme that supplies 30% of the country's electricity. Over half the watershed is devoted to livestock and dairy production, with the remainder covered in cloud and premontane forest. Economic analysis of ranching and dairy production reveals that while some small producers are borderline profitable in economic terms, larger producers are generating significant returns to land in Río Chiquito (average returns per holding in net present value terms of \$500/ha). Meanwhile, available evidence fails to convincingly demonstrate that pasture use is leading to rapid and pervasive loss of soil productivity in the volcanic Arenal soils.

Analysis of hydrological function suggests increases in sedimentation for pasture areas and large gains in water yield from pasture in non-cloud forest areas. In the upper watershed area of Río Chiquito, the very "patchy" cloud forest landscape will lead to an increase in the capture of fog moisture over that in either pasture or forest alone. In physical terms, the increased volume of water yield that can be expected from pasture in Río Chiquito is one to two orders of magnitude greater than the corresponding increase in sediment. Productivity of the downstream hydroelectric scheme is lowered by an increase in sediment, but raised by the increase in water yield. Netting out the economic impact on power generation suggests that reforestation would lead to large losses in power generation, in the range of from \$250 to \$1,100 per hectare. Sensitivity analysis suggests that even if livestock production were to reduce infiltration rates so that all of the gain in water yield accumulated in the wet season (instead of being spread across dry and wet seasons), the magnitudes for these externalities would not change greatly.

As non-hydrological externalities are likely to be of minimal importance in Río Chiquito, the full cost-benefit study suggests that watershed management efforts should focus on how to maximize the complementary returns from livestock and water production. It must be emphasized that the analysis of these relationships is site-specific and that the particular results of this study should not be applied, or transferred, to other areas. Rather the paper seeks to highlight the need to revisit the conventional wisdom regarding land use-hydrology interactions and to estimate the changes in economic productivity associated with alternative land use choices and their downstream hydrological impacts. This is of particular importance in the case where resources, such as donor funds or government incentives, are to be invested in reforesting watersheds that feed large hydroelectric reservoirs in the humid tropics.

Source: Aylward and Echeverría (2001)

Although the study found that there is little incentive for the hydroelectric utility to cover costs of reforestation in the entire watershed as this would most likely reduce the water supply, it does not negate other stakeholder concerns with more localized consequences of land use practices within the watershed. Given that forest fragments in cloud forests appear to contribute disproportionately higher water yields, the option of partial reforestation or placing vegetative windbreaks in pasture found in cloud forest areas may provide more water in the dry season, while also limiting erosion and downstream sedimentation, and providing needed shelter to livestock. This type of measure may provide the electric utility (and smallholders in the upper watershed) with the incentive to take part in the development of a more localized participatory

monitoring system, which could provide a basis for identifying management practices most appropriate to the local context, and for more diversified and decentralized management approaches.

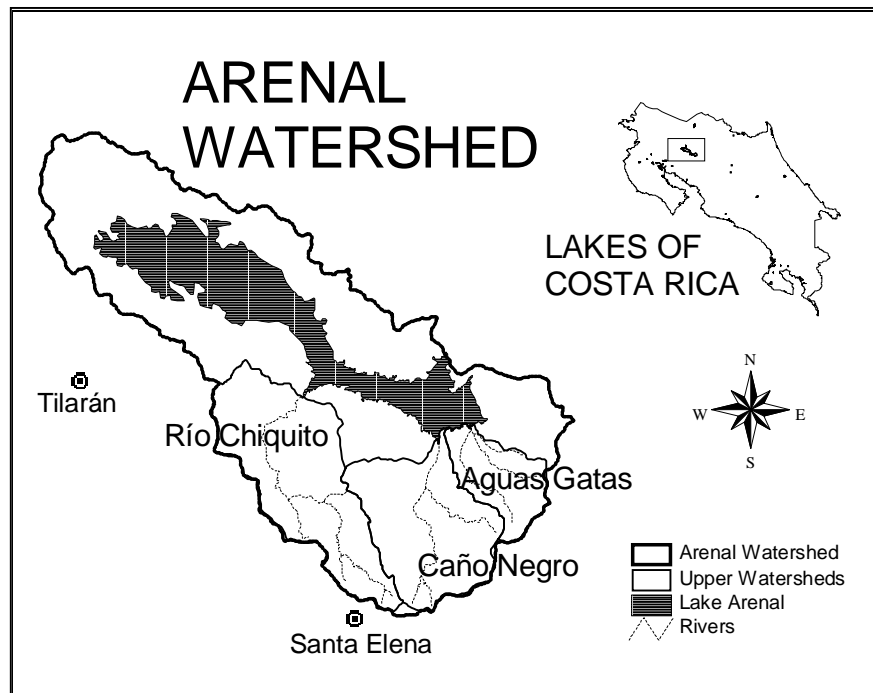
This paper examines the valuation of offsite externalities, upon which the above conclusions are based so as to better illustrate the uncertainties inherent in establishing cause and effect in a complex problem, and in managing a heterogeneous landscape for multiple and often conflicting uses. It concludes with a discussion of their implications for decision-making and presents some challenges for conservation in this broader landscape context.

As is evident from the discussion below, a single-minded focus on the valuation of one particular set of impacts – in this case the hydrological impacts – is not a sufficient basis for drawing conclusions and deriving policy recommendations. Mindful of this, the larger study of which this paper is a part also considered on-site economic returns to large and small ranching and dairy operations, soil conservation benefits and potential benefits of carbon sequestration, and water supply to irrigation although these are not the focus of this paper. For a summary of these aspects of the full cost-benefit analysis of land use undertaken by the study see Box 1. In addition, a review of the institutional issues associated with incentives for watershed management in Arenal can be found in Fernández González and Aylward (1999).

Background information on the study area

This case study examines the implication of land use practices in the Rio Chiquito watershed, for Lake Arenal, an enlarged natural lake found at the headwaters of the Arenal river that is of national importance to Costa Rica for the production of electricity (see Figure 1). Given that annual inflow is normally less than the live storage capacity, technical production levels are limited by water availability rather than by production capacity (362 MW) and the facility is operated as an inter-annual storage reservoir to buffer the national grid during dry years. Changes in water yield associated with land use practices in the Arenal watersheds are therefore a significant concern. Sedimentation is of lesser concern because of the large amount of dead storage capacity (the area below the outtake), where a large portion of the sediment is deposited, and that would need to be filled before sedimentation significantly impedes electricity production.

Figure 1. Map of the Arenal Watershed



Source: Aylward et al, 1998

Biophysical setting

The Río Chiquito watershed occupies 8,900 hectares and makes up approximately one fourth of the entire watershed for Lake Arenal (41,000 hectares), which is located on the Atlantic side of the continental divide and of the Guanacaste and Tilarán mountain ranges in Costa Rica. The lake was enlarged by constructing a dam at Sangregado, that was completed in 1979, and which led to a 34m rise in lake level. The total storage capacity of the lake is 2,416 million m³, when is it filled to the maximum height of 546 meters above sea level. Given that the minimum operational level is 520 meters, there is a live storage capacity of 2000 million m³, and 400 million m³ of dead storage capacity (Aylward et al. 1998).

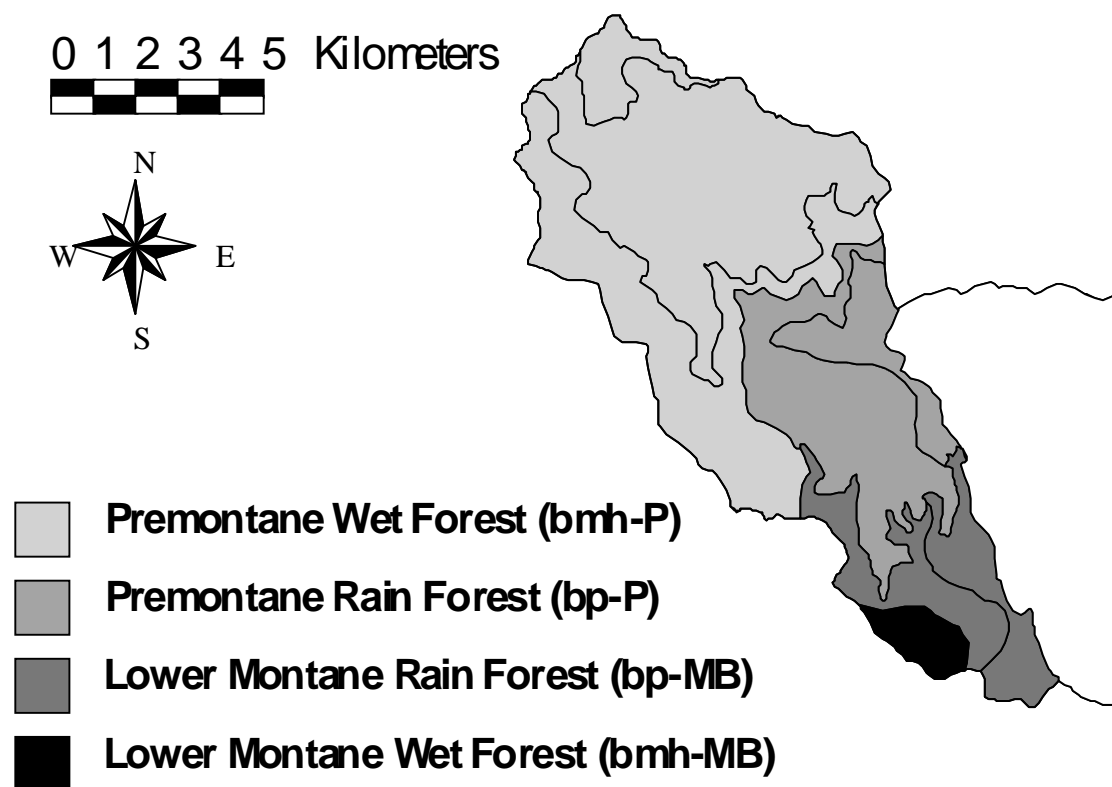
The dominant characteristics of the watershed are steep slopes with abrupt ridges and valleys – 90% of the area is on slopes greater than 25%. Elevation ranges from lake level at 545m up to 1800m. A land suitability analysis conducted by the Tropical Science Center based on topographic criteria, found that 75% was suitable only for forest protection, and the remaining 25% for production forestry (CCT 1980). However, the soils are volcanic and up to 4m deep, which may delay the on-site consequences of soil erosion, thereby reducing financial incentives to adopt conservation measures. Increased erosion rates in pasture areas as compared with forest areas may range as high as 207 tons/ha/yr but comparisons of the results of

models and field studies suggest that the expected increase in mean erosion rate in pasture areas is 40 tons/ha/yr. Sediment yield was estimated to be 90,000 m³ a year, of which approximately half is deposited to live, and half to dead storage areas of the lake (Saborío and Aylward 1997).

Four of the 12 Holdridge life zones are present in the Río Chiquito (see Figure 2):

1. The lower watershed is Wet Premontane Forest (bmh-P).
2. The middle section of the watershed on the east side and to the interior are Premontane Rainforest (bp-P).
3. The upper watershed is predominantly Lower Montane Rainforest (bp-MB).
4. A small section of the upper watershed that borders the continental divide (to the west) is Wet Lower Montane Forest (bmh-MB).

Figure 2. Map of Life Zones in Río Chiquito



Source: Tropical Science Center and Aylward *et al.* (1999)

A rough estimate of actual remaining forest as a percentage of pasture, used also as an indicator of forest fragmentation, is 15% in the lower watershed, and 60% in the upper.

Precipitation is estimated to range from 2000 to 8000 mm/yr depending on the life zone, as is shown in Table 1, of which approximately 75% is received during the rainy season, and 25% during the dry season. The table also shows ranges in temperature, potential evapotranspiration, and actual evapotranspiration as a percentage of precipitation. These are key variables used to estimate water balances and changes in average streamflow as a result of conversion to pasture. They are generally consistent with figures in Table 2, which shows an analysis of water balances based on rainfall and temperature data collected in life zones of the Arenal basin, that are similar in classification to those in Rio Chiquito, as indicated by precipitation levels (CCT 1980). They were also found to be generally consistent with figures from empirical studies reported in the literature for lowland tropical forests by Bruijnzeel (1990). Table 3 shows estimates of run-off under forest and pasture by life zones, also based on the Holdridge methodology, and suggests an increase in streamflow under pasture ranging from 160mm to 242mm/yr. Yearly fluctuations in rainfall amounts and cycling from wet to dry periods are also noticeable (see Table 1).

Table 1. Meteorological and Hydrological Variables of the Life Zones found in Rio Chiquito

Life Zone	Wet Premontane Forest (bmh-P)	Premontane Rainforest (bp-P)	Wet Lower Montane Forest (bmh-MB)	Lower Montane Rainforest (Bp-MB)
Precipitation (mm)	2000 - 4000	4000 - 8000	2000 - 4000	4000 - 8000
Biotemperature (°C)	17 - 24	17 - 24	12 - 17	12 - 17
ET, Potential (mm)	1000 - 1400	1000 - 1400	700 - 1000	700 - 1000
ET, Real/Precipitation	50% - 25%	12.5% - 25%	50% - 25%	12.5% - 25%

Source: Extracted from Holdridge (1967)

Table 2. Examples of the Water Balance Method in the Life Zones of Arenal

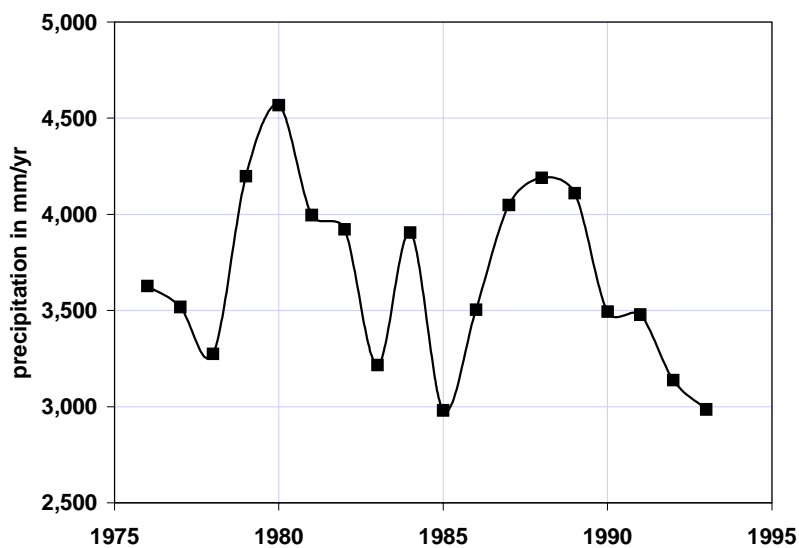
Life Zone	bmh-T to bmh-P	bmh-T to bmh-P	Bmh-P	bp-MB	bmh-MB
Biotemperature (°C)	23.6	22.3	20.7	18	17.2
ET, Potential (mm)	1393	1319	1219	1064	1016
Precipitation (mm)	2470	4440	3892	3599	3210
ET, Real (mm)	1374	1319	1219	1064	1016
Run-off (mm)	1096	3121	2673	2535	2194
ET/Precipitation	56%	30%	31%	30%	32%
Elevation (m.a.s.l)	530	720	1015	1400	1620
Station	Tronadora (Vieja)	Caño Negro	Los Andes	San Bosco	San Gerardo

Source: Tropical Science Center (CCT) (1980)

Table 3. Run-off under Forest and Pasture by Life Zone

Run-off (mm/yr)	bmh-P	bp-P	bmh-MB	bp-MB
Pasture	2274	5345	1982	4522
Forest	2032	5127	1808	4362
Gain from pasture	242	218	174	160
Gain in m ³ /ha/yr	2420	2180	1740	1600

Source: CCT and CINPE (1995)

Figure 3: Annual Precipitation in the Upper Watershed of Rio Chiquito, Arenal (1975/76 to 1993/94)

Source: Calvo (1996)

Socio-economic setting

The main categories of land use in the Rio Chiquito watershed are pasture, production forestry, and protection forestry, in addition to minimal amounts of cultivation. Between 1960 and 1992, pasture areas more than quadrupled, while the area under primary forest was cut in half, from almost 80% to just under 40% (see Table 4).

Table 4. Land Use in Arenal Watershed

	1960	1992
Primary Forest	77%	36%
Secondary/Intervened Forest	10%	7%
Pasture	13%	56%

Source: Aylward et al. (1998)

Key factors identified by Kauck and Tosi (1989) that have historically influenced land use in the Arenal watersheds are:

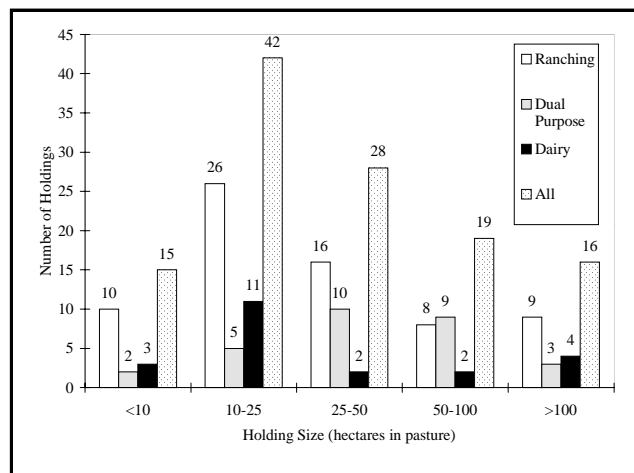
1. Expansion of coffee production in the valley that displaced agriculture and ranching to marginal areas between 1880 and the 1950s;
2. Expansion of commercial cattle ranching between the 1930s and 1970s, when Costa Rica became the 4th largest exporter of meat to United States;
3. The rise in the Arenal lake level upon completion of the dam in 1979, which displaced some residents to higher and steeper slopes; and
4. Creation of the Arenal Monteverde protected zone, which promoted land speculation.

Past policies that have shaped existing land uses include encouragement of land clearing by recognizing it as evidence of “use” that was required to establish land ownership, and the provision of subsidized credit to the ranching industry. Under the Costa Rican forestry law of 1996 (no. 7575), landowners gained access to financial incentives of \$220 per hectare (paid over five years) of conserved forest in payment for forest environmental services that include: mitigation of CO₂ emissions, biodiversity conservation, provision of scenic beauty, and hydrological services.

The dominant economic activities are livestock ranching and dairy production. At the time of the study, there were 156 land parcels in the Rio Chiquito watershed, of which useful information was gathered on 137 parcels. Of the 120 livestock holdings in the sample 69 were used exclusively for ranching, 22 for dairy production, and 29 for dairy and ranching combined. The holdings can be further distinguished between large and small producers, which of two major dairies they sell to, and, the dual purpose units, by whether they also produce cheese. The average holding is 60 ha, and contains approximately 1 animal unit/ha. However, land has become increasingly concentrated in larger holdings that average 150 ha, belonging to a smaller number of producers who mostly live outside the watershed (see Figure 4). Just over 200 people actually live in the watershed as many landholders prefer to live on the other side of the continental divide on the drier Pacific slopes where access to services is better. Other stakeholder groups present in the upstream area include small coffee growers, the local municipality, the Arenal Conservation Area (the government conservation agency responsible for the area), 2 FAO soil conservation projects, and the Monteverde Conservation League, which operates conservation programmes in the adjacent area.

Downstream, land use in the Rio Chiquito is of particular interest to the Costa Rican Electricity Institute (ICE), which operates the hydroelectric facilities that rely in water flows through Lake Arenal. It is also of national interest, because it provides 30% of the country’s electricity, and up to 50% during the dry season. Another source of national interest is its conservation value, indicated by the initiatives of two national level NGOs. In addition, it is a source of water for irrigation of 6,000 ha on the dry Pacific slope, to which additions of 54,000 hectares were originally planned. Thus it is also of potential interest to the national water and irrigation service (SENARA).

Figure 4: Landholding Distribution by Size



Source: Aylward et al. (1998)

The main concerns of stakeholders, as indicated by consultations, were:

- erosion on landholdings caused by livestock leading to reductions in livestock stocking rates, productivity and holding profitability;
- ensuing sedimentation of the lake, affecting the live and dead storage volume of the reservoir with subsequent effects on hydroelectric productivity and the downstream irrigation scheme in the Tempisque province;
- sedimentation of the lake caused by geologic factors (including earthquakes and mass soil movements); and
- diminished supply of water from springs for productive and domestic uses within the watershed, perceived to be a consequence of deforestation.

There was also tension between ICE and upstream producers who felt that they had been excluded from the benefits of hydropower production for which their lands “produce“ water. Some of these concerns are questionable given the results of the research upon which this paper is based while others reflect broader concerns than were or could be addressed by the valuation exercise. There is also a lack of consensus on the nature of the problem. Main elements of the stakeholder developed Action Plan developed to address these are: forest conservation and regeneration, reforestation in marginal pasture areas, improving livestock technology, community development, development of local ecotourist projects, and inter-institutional coordination. These suggest that an underlying concern is to generate funding for the development of an economically marginalized upper watershed area, and to reconsider perhaps the equity of existing institutional arrangements that have provided the context for existing land uses.

Linkages between land use and water resources

In general, as discussed above, water yield appears to be greater from pasture in non-cloud forest areas, and from cloud forest areas, and in particular, from fragmented forest and cloud forest areas. This is because there is less water lost to evapotranspiration in pasture areas, the capture of moisture or “horizontal precipitation” by cloud forests, particularly in forest fragments. Together with the increase in streamflow also comes an increase in sedimentation eroded from pasture areas.

Although the data presented in the previous section appear sufficient to determine these general relationships, there are also significant sources of uncertainty, given the large amount of natural variability and landscape heterogeneity. The link between land use and water yield is difficult to establish unequivocally at the watershed scale for a number of reasons including the existence of a number of land uses and vegetation types: pasture, forest with different canopy heights and cloud forest of differing degrees of fragmentation, all of which are changing over time. This section provides an overview of some of the principal techniques and measurements used to assess and monitor the impacts of these changes, and highlights areas of uncertainty so as to make these more transparent to stakeholders.

Monitoring of land-use impacts

Inherent in the hydrological data are several sources of uncertainty that appear to be irresolvable absent more localized monitoring, as they reflect the complexity of the landscape. A statistical analysis of streamflow data from 24 rural watersheds (Calvo 1996), found a good correlation between estimates based on the Holdridge method and historical data for the Pacific watersheds. Runoff from Atlantic watersheds, which include those of Lake Arenal, was underestimated by the Holdridge method. One possible explanation was that the model did not account for horizontal precipitation captured by cloud forest on the upper Atlantic slopes; however, it was not possible to find a good correlation between the level of underestimation and the presence of cloud forests. A remaining source of uncertainty is the accuracy of the rainfall maps, which are based on data from a limited number of meteorological stations.

A study conducted on behalf of the project (Fallas 1996), did monitor actual interception rates in the Rio Chiquito watershed over the period of a year, in 4 different types of cloud forest – primary forests with low and high canopy heights, a primary forest fragment, and a secondary regrowth fragment – and compared these to precipitation received in adjacent pasture areas. As seen in Table 4, the highest amounts of precipitation were received in the primary forest fragment, which received 458 mm more than the pasture area because of the capture of horizontal precipitation. Only the high canopy primary forest area received a lower amount of rainfall than the pasture area. However, all received significantly higher amounts of precipitation than pasture areas during the dry season (January to March), demonstrating the importance

of horizontal precipitation captured by cloud forests to the overall hydrological regime.

Table 4. Capture of Horizontal Precipitation in the Cloud Forests of Rio Chiquito

Month	Precipitation in the open (mm)	Precipitation under Forest Cover (mm)			
		Primary Forest Fragment	Secondary Regrowth Fragment	Low Primary Forest	High Primary Forest
Dry: March 95	68	144	95	125	83
Wet: August 95	455	345	425	346	364
Wet: October 95	436	497	446	333	340
Dry: January 96	216	321	246	387	255
Yearly Totals	3,301	3,759	3,558	3,496	2,986
Gain/(Loss) as opposed to pasture		458	257	194	(315)

Source: Fallas, 1996

The water balance models also rely on average annual figures over an extended time horizon, on data reported in the literature, and on simplifying assumptions that soil water storage does not change. These assumptions are needed to make a study such as this manageable, but may obscure the outcome of interactions among site-specific factors resulting from natural variability.

Sedimentation was analyzed by calculating simulated surface erosion using the Universal Soil Loss Equation (USLE), the result of which was used in a sediment transport model (CALSITE) to estimate sediment delivered to mouth of watershed. The CALSITE model was calibrated with data from the Rio Chiquito and Cano Negro watersheds (Saborío and Aylward 1997), and is integrated with a GIS program, which allows it to consider differences in erosion rates in different areas of the watershed. A field study by Vásquez and Rodríguez (1995) found that average erosion rates were likely to be between 35 and 45 tons/ha/yr, which was more consistent with the results of simulations (39.7 tons/ha/yr) than previous estimates, which were treated as upper and lower bounds (11.6 to 109 tons/ha/yr) on mean estimates. Table 5 illustrates the range of estimates obtained in the various studies. What is important to keep in mind is that some areas are more erosion prone than others, and may have erosion rates closer to the extreme values. Conservation measures in these areas then may disproportionately decrease overall levels of sedimentation.

Table 5. Comparison of Erosion Rates under Pasture and Forest

Study	Area	Forest Mean	Forest Range	Pasture Mean	Pasture Range
Duisberg (1980)*	Arenal	3.7	-	65.0	-
Duisberg (1980)**	Arenal	1.4	-	109.0	-
Calvo and Quirós (1996)	Arenal	3.7	0 a 4.8	11.6	6.2 a 22.95
Vásquez and Rodríguez (1995)	Río Chiquito	3.1	0.07 a 5.08	35.2	0.89 a 66.05
Saborío and Aylward (1997)***	Río Chiquito	0.24	0 a 1.55	39.7	0 a 206.64

Source: Aylward et al (1998)

Notes: All figures in tons/ha/yr. *Extrapolated from plot estimates in Colombia. **USLE derived estimates. ***In this study a distinction was made between primary forest and disturbed primary forest. For disturbed forest the mean for Río Chiquito is 0.49 and the range is 0 to 2.34 tons/ha/yr.

Valuation of upstream land use on downstream water resources

Impacts of land use on water resources depend on both biophysical changes, and on how these affect welfare. For example, the extent of damages from a flood depends on land uses in flooded areas – damages will be most expensive where there is urban infrastructure. In some cases however, regular flooding is considered beneficial, because floodwaters bring nutrients needed by farmers, and also to undeveloped riparian areas and wetlands. In this case study, the land use impacts valued were increases in sedimentation and changes in water yield associated with land use change, because of their potential implications for hydropower production. The seasonal timing of changes in water yield were included through a sensitivity analysis. Changes in peakflows during storm events were not a concern because the reservoir in effect buffers these events and their effect on hydropower or downstream flooding. Given the characteristics of the study area, other hydrological impacts that were not addressed in the Arenal study were the transport of nutrients and groundwater recharge.

For purposes of hydroelectric production, the increased volume of streamflow is a potential benefit if it can be productively used, instead of merely being spilled. The type of facility, amongst other factors, determines the importance of the timing of changes in streamflow. Changes in flow characteristics during a storm event and effects on dry season baseflow may be of particular consequence for small storage run-of-river facilities operated on a daily fill and release regime. For annual reservoirs additional water obtained during the dry and wet seasons may be of prime interest, particularly the dry season inputs as during normal or wet years additional inputs during the wet season may well be spilled instead of used to produce power. For inter-annual reservoirs, such as Arenal where the reservoir fills and is drawn down only over a number of years (instead of each year) the benefits of changes in annual water yield are likely to be the dominant factor as the distinction between wet and dry season inputs is reduced in importance when wet season water can, in effect, be carried over into the succeeding dry season, and so on.

In general, the increased deposition of sediment has the potential to be problematic if it replaces usable water in the live storage (volume above the outtake) lowering productive storage capacity or fills up the dead storage (volume below the outtake) thus cutting short the useful life of a reservoir. Again, however, the type of facility and its characteristics will determine the importance of these effects. The effect of sediment on live storage depends on the dry/wet season effect: that the presence of sediment results in the spilling of water at the end of the wet season – water that would have been used in the following dry season. In the case of Arenal, a large interannual reservoir this effect occurs only periodically, instead of with annual regularity, thus limited somewhat its effect on production. Meanwhile, the large dead storage capacity relative to the land area in the watershed and sedimentation rates suggest that it would require well in excess of 100 years for deposited sediment to fill the dead storage volume of the lake. As a result, sediment going to the dead storage does not have a significant cost in present value terms in terms of cutting project life short. Instead, the study suggests that there is a small benefit that is gained from the displacement upwards of stored water by sediment deposited in the dead storage. This water, which would otherwise have been stored below the outtake is instead stored in the live storage and available to use for power production during dry periods.

The values of these impacts were estimated based on the marginal opportunity costs to the electric power grid system, of failing to meet demand for electric power or the cost of meeting demand through the use of alternatives for power generation. For example, if a gain in power generation capacity pushes back by one year the need to build a gas turbine plant there is a corresponding benefit in terms of the costs foregone of meeting demand from existing supplies and postponing construction of the new facility. The estimates are derived based on relationships between land use and hydrology, between hydrology and reservoir operation, and between hydroelectric power generation and costs of power system operation. The model distinguishes between wet and dry seasons and wet and dry hydrological periods in order to explore the effect of changes in seasonal flows, differing assumptions regarding hydrological conditions, and differing marginal opportunity costs to the grid as these conditions vary. The valuation employs a 70-year time horizon, which coincides with the longest rotation scenario for the forestry production scenario under natural regeneration. The long time horizon also ensures that discount rate sensitivity analysis is provided ample room to express the effect of a lower rate. The discount rate used in the base case analysis is 9% as per a companion analysis of social discount rates in Costa Rica (Aylward and Porras 1998).

Below the base case results are presented briefly before turning to the sensitivity analysis which provide a richer feel for the determinants of these hydrological externalities.

Base Case Results

Table 6 shows the results for the base case scenario. The first column in the table lists the different simulations undertaken as explained in the preceding sections of this chapter. The results under each scenario are organized in rows corresponding to the externalities associated with water yield gain, sedimentation of dead storage, sedimentation of live storage and total externalities. Reading across the table, the first column of results indicates the outcome for a change of a single cubic meter of the respective hydrological output. In other words, under the first scenario the present value of the externalities caused by an increase in water yield of one cubic meter is \$0.403. An increase in live storage sedimentation of one cubic meter causes negative externalities of \$5.74. Succeeding columns present the results for each of the seven land units that result from the overlay of the three maps: forest type, location and life zone.

The results show that water yield from pasture has greater value for hydroelectric production than the concurrent losses due to the expected increase in sedimentation with positive net external hydrological impacts recorded for all of the different land units of between \$250 and \$1,100 per hectare. While sediment has a much larger impact per cubic meter than does water yield, the superiority of water yield changes in terms of volume swamps the effect of sedimentation when converted to a per hectare basis. The cost of live storage sedimentation does not exceed \$100/ha under any of the land units, while the benefit of water yield gains range from \$275 to \$1,150/ha. The positive impact on production from the sedimentation of dead storage is, as expected, fairly marginal in comparison to the other impacts, never exceeding \$6/ha in total.

In the case of non-cloud forest areas, the externalities from \$1,100 to \$700/ha). Sedimentation is more costly in the mid-watershed (due to steeper slopes and higher erosion rates), but regardless the expected increase in water yield generates large, positive externalities. The size of the hydrological externalities increases moving from the lower to the upper watershed. This primarily reflects the greater level of fragmentation assumed for the cloud forest in the upper watershed. The variation in the total value of hydrological externalities in cloud forest areas runs from \$250 to \$1,100/ha.

Table 6. Hydrological Externalities: Results of Simulations for Pasture (as opposed to reforestation)

Land Unit Location Life Zone	Non-Cloud Forest Areas				Cloud Forest		
	A Lower bmh-P	B Middle bmh-P	C Middle bp-P	D Middle bp-MB	E Lower bmh-P	F Middle bmh-P	G Upper bmh-MB
Increase in Sedimentation	13	28	28	28	13	28	16
Water Yield Gain (\$ per m ³)	2,850 (\$/ha)	2,850 (\$/ha)	2,580 (\$/ha)	1,870 (\$/ha)	690 (\$/ha)	2,760 (\$/ha)	2,760 (\$/ha)
Base Case (wet period first, wet periods of 10 years and dry periods of 5 years, discount rate of 9%)							
Water Yield Gain 0.403	1,149	1,149	1,040	754	278	1,112	1,112
Dead Storage Gain 0.403	3	6	6	6	3	6	3
Live Storage Loss -5.74	-37	-80	-80	-80	-37	-80	-46
Total	1,114	1,074	965	679	243	1,038	1,070
Sensitivity 1: Switch order of hydrological periods so that dry period comes first							
Water Yield Gain 2.07	5,900	5,900	5,341	3,871	1,428	5,713	5,713
Dead Storage Gain 2.07	13	29	29	29	13	29	17
Live Storage Loss -5.63	-37	-79	-79	-79	-37	-79	-45
Total	5,876	5,850	5,291	3,821	1,405	5,663	5,685
Sensitivity 2: Switch length of wet period and dry period to seven and three years respectively							
Water Yield Gain 0.991	2,824	2,824	2,557	1,853	684	2,735	2,735
Dead Storage Gain 0.991	6	14	14	14	6	14	8
Live Storage Loss -11.5	-75	-161	-161	-161	-75	-161	-92
Total	2,756	2,677	2,410	1,706	615	2,588	2,651
Sensitivity 3: Switch length of wet period and dry period to five years each							
Water Yield Gain 1.55	4,418	4,418	3,999	2,899	1,070	4,278	4,278
Dead Storage Gain 1.55	10	22	22	22	10	22	12
Live Storage Loss -8.92	-58	-125	-125	-125	-58	-125	-71
Total	4,370	4,314	3,896	2,795	1,022	4,175	4,219
Sensitivity 4: Change percent of inflow accruing in dry season set to 0% (i.e. 100% in wet season)							
Water Yield Gain 0.283	807	807	730	529	195	781	781
Dead Storage Gain 0.283	2	4	4	4	2	4	2
Live Storage Loss -5.74	-37	-80	-80	-80	-37	-80	-46
Total	771	730	654	453	160	705	737
Sensitivity 5: Total externalities go to zero when percent of change in inflow gain accruing in the dry season is -56% and -48% for Land Units A and E respectively.							
Sensitivity 6: Discount rate set to 7%							
Water Yield Gain 0.580	1,653	1,653	1,496	1,085	400	1,601	1,601
Dead Storage Gain 0.580	4	8	8	8	4	8	5
Live Storage Loss -9.64	-63	-135	-135	-135	-63	-135	-77
Total	1,594	1,526	1,370	958	341	1,474	1,528
Sensitivity 7: Discount rate set to 11%							
Water Yield Gain 0.296	844	844	764	554	204	817	817
Dead Storage Gain 0.296	2	4	4	4	2	4	2
Live Storage Loss -3.75	-24	-53	-53	-53	-24	-53	-30
Total	821	795	715	505	182	769	789

Notes: All figures are present values over the seventy-year planning horizon.

Source: Aylward et al. (1999)

Sensitivity Analysis

The sensitivity analysis begins with an examination of the responsiveness of the results to the hydrological/meteorological assumptions regarding the order and length of the wet and dry periods used in the analysis. The effect of switching the first hydrological period to a dry period, but maintaining a five-year dry and ten-year wet

period cycle, increases the hydrological externalities by a factor of five or more. In the base case, power shortfall costs are not incurred as the first dry period occurs only in the long run. However, by switching the order of the periods around, shortfall costs are incurred. In addition, as the shortfalls are incurred in the first few years they are not heavily discounted. The sensitivity analysis then highlights the importance of water yield gains during dry periods to an inter-annual reservoir.

In the second sensitivity analysis the length of the full wet and dry period cycle is shortened to ten years, consisting of a seven-year wet period followed by a three-year dry cycle. Externalities are more than doubled as shortfall costs are incurred again in the short run. The increase in externalities is less in this case, however, as shortfalls are incurred for a shorter period of time and further into the planning horizon. Switching the cycle to a five-year wet period followed by a five-year dry period leads to even higher externalities, although not as pronounced as those observed by switching the order in which these periods occur.

The results of these analyses suggest that by putting a long wet period as the initial hydrological period, the base case provides fairly conservative estimates of the positive externalities. Altering this assumption raises the externalities significantly. The costs of sedimentation rise, but such small increases are overwhelmed by the large returns from avoiding power shortfalls in the short run.

The next two sensitivity analyses assess how responsive the results are to the assumption made regarding seasonal flows. Historical data show that 25% of water yield in Río Chiquito enters Lake Arenal during the dry season. The water yield gain is thus apportioned 25% to the dry season and 75% to the wet season in the base case scenario. This data, however, reflects the effect of existing land use patterns in the watershed. Were the effect of having forest in place of pasture to shift water from the wet season to the dry season this might lessen the positive externalities observed under pasture in the base case. In order to simulate the potential effects of such a change in the seasonal timing of run-off the simulation is run assuming that 100% of the water yield gain accrues in the wet season under pasture. That is, none of this gain arrives during the season when it would be most valuable. Because of this change, the value of the positive externalities is reduced by 35% to 50% from the base case depending on the land use unit. Nonetheless, pasture still produces significant positive externalities.

Of course, in the extreme case, having pasture in place of forest may result in a net shift of run-off from the dry season to the rainy season as dry season baseflow diminishes. In a second sensitivity analysis, it was assumed that the entire increment in water yield accrued in the wet season under pasture. An iterative process was then followed to find out how much more of the dry season run-off would need to be switched to the wet season (under pasture) in order to arrive at externalities of zero. In the case of land unit A the results suggested that this switchover point occurs at -56% of the water yield gain, or roughly 1,600 m³/ha/yr (of the original 2,850 m³/ha/yr gain). Recalling from Table 3 that average yearly run-off totals for Río Chiquito are around 2,500 mm/yr suggests that such a redistribution is significant, representing

one-quarter of existing dry season run-off (160 of roughly 625 mm/yr). This analysis is then repeated using land unit E, the one that showed the lowest initial externalities. The results suggest that total externalities go to zero with only a shift of 330 m³/ha/yr in dry season run-off (-48% on a water yield gain of 690 m³/ha/yr).

Thus, while the size of the shift required will vary, in most cases an exceedingly strong seasonal shift would be necessary in order for the net hydrological effect of the land use change to be ambiguous.

The results show considerable responsiveness to the use of different discount rates. An increase of from 40% in the externalities is observed by lowering the discount rate to 7%. Although an intuitive result, it is still of interest to note that the lower discount rate increases the positive externality associated with pasture. Note that due to the limited nature of the sediment impact, the externalities over the planning horizon continue to increase as successively lower discount rates are applied. A reduction in the externalities observed for the different land units of 26% of their original value results from raising the discount rate to 11%. This primarily reflects the lowered present values for the externalities associated with water yield gains.

Several potential benefits associated with forest land use options but not directly addressed in the study are: locally-consumed non-timber products, biodiversity prospecting, tourism, recreation, option and existence values. However, due to the close proximity of other primary forests and conservation areas of national and global significance, biodiversity, existence and ecotourism values associated with reforestation are expected to be minimal. Carbon fixation values are expected to range from \$200 to \$300 ha, which is not sufficient to justify land use conversion from pasture to forest, when compared to returns from ranching and hydropower generation.

The valuation methodology, which consisted of calculating the marginal opportunity costs of obtaining power from alternative sources, does not consider non-priced externalities associated with these other sources. Similarly, it does not include social and environmental costs of dislocation and habitat loss associated with the initial construction of hydroelectric dams, such as Lake Arenal.

Conclusion

Although the results show that there is little financial incentive for the hydroelectric facility to pay landowners for implementing reforestation practices across the board, or for all landowners to adopt conservation practices, there are opportunities to increase the production of water and reduce erosion in site-specific instances not reflected in these aggregate figures. For example, the analysis shows that water production is significantly increased in forest fragments, which are disproportionately found in small holdings for which economic returns are marginal. It is also likely that sedimentation could be significantly reduced by identifying the areas with erosion

values at the high extreme of the range. It is possible that these frequently overlap but more localized site-specific information is needed to identify these target areas.

In sum, the valuation reveals existing incentives, which can inform a process of mutual learning and deliberation among stakeholders, and provide the basis for developing mechanisms of cooperation. The companion Arenal study on incentives proceeds to recommend a specific mechanism – a 2-way sealed bid auction in which landowners may bid on contracts to provide ecosystem services, which could potentially lead to a more equitable sharing of benefits and costs (Aylward and Fernández González 1998). Some specific measures that were identified for increasing off-site benefits of land use practices, i.e., that would increase streamflow and reduce sedimentation, were:

- Reforestation of erosion-prone marginal pasture areas in all forest types;
- Natural regeneration of stream buffers in all forest types;
- Conversion of forest in non-erosion prone areas in non-cloud forest types;
- Cut and or convert to patchy forest coverage within contiguous cloud-forest areas;
- Natural regeneration in large pasture areas and placement of windbreaks in cloud-forest areas.

However, identifying optimal arrangements will also require more localized information than can be identified in aggregated figures provided in this type of analysis, which was nonetheless extensive. Development of a participatory monitoring system would complement existing research and also allow consideration of broader stakeholder concerns such as drying up of springs within the watershed.

This study suggests there is no single optimal response. Rather, there are many contributing factors that will require an equally complex set of responses grounded in local knowledge. These responses can be identified through a process of mutual learning, negotiation and conflict resolution among stakeholders that is inherent in the implementation process. In addition to showing the existing financial incentives, an implicit objective of this paper has been to also show what is obscured in the more aggregate kinds of analysis that could be addressed by obtaining more site-specific information, through the development of such a process.

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