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Attempts to determine the effects of forest cover on stream flow by direct hydrological measurements in Los Negros, Bolivia

Valentin Le Tellier [a,1], Alex Carrasco [b], Nigel Asquith [c,2,*]

[a] AgroParisTech-ENGREF, Campus d'Agropolis 648 rue Jean-François Breton, BP 7355, 34 086 Montpellier cedex 4, France
[b] Universidad Autónoma Gabriel René Moreno, Facultad de Ciencias Agrícolas, Carrera de Ingeniería Forestal, Programa de Investigaciones (PROINFOR), El Vallecito, Carretera al Norte Km 8.5, Casilla Postal 3051, Santa Cruz de la Sierra, Bolivia
[c] Property and Environment Research Center, Lone Mountain Fellows Program, 2048 Analysis Drive Suite A, Bozeman, MT 59718, USA

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ABSTRACT

Underlying many payments for watershed services (PWS) schemes in tropical montane forest contexts is the assumption of a direct positive relationship between forest cover and dry season stream flow. We developed a low cost research program to assess the forest cover-stream flow relationship in the Los Negros watershed in eastern Bolivia. We asked three questions: (1) can watersheds that are similar enough to undertake paired catchment studies be identified using only simple parameters such as size, aspect and geographic proximity; (2) can a functioning locally based hydrological monitoring system be set up for less than $10 000 by training local farmers to collect hydrological data, and (3) can such data be used to improve the functioning of a PWS initiative? A land use map of the upper Los Negros valley was created from a 2005 Landsat image and a digital elevation model used to calculate physical and hydrological properties of 10 sub-watersheds. Farmers measured stream flow rates in these sub-watersheds from 2005 to 2008 and maintained 10 automatic rain gauges. We found no relationship between forest cover and stream flow. This may indicate that no such relationship exists, but could also reflect the short period of the study, the low quality of the data, and the fact that the sub-watersheds had relatively similar forest coverage (54–76%). We conclude that (1) watersheds can be identified as "similar-enough-for-analysis" using the criteria of size, aspect and proximity without undertaking further research, (2) a useful hydrological monitoring system can be developed for <$10,000 and (3) although our local farmers did not collect sufficiently high quality data to fully explore the forest/water relationship in Los Negros, with improvements in methodologies, low cost, locally based monitoring has the potential to be an important component of future PWS initiatives. We recommend that stream discharge should be calculated directly; only the most locally relevant hydrological criteria, rather than scientifically complete criteria, should be monitored; locally based monitoring must be institutionalized to reduce staff turnover and hydrological monitoring must be embedded within a context that makes it socially acceptable.

1. Introduction

Payments for environmental services (PES) are increasingly common as an incentive-based form of natural resource management (Asquith and Wunder, 2008). PES can be defined as a voluntary, contingent transaction around a well-defined environmental service (or a service-producing land use) between at least one buyer and one seller (Wunder, 2005). Because hydrological services are valuable for most communities, these services are perhaps the best-suited environmental services for locally developed incentive-based management such as PES. Though many of the nascent payments for watershed services (PWS) systems in Latin America have been studied and analyzed by researchers (Robertson and Wunder, 2005), little attention has been paid to what is perhaps the most important basis of all such systems: the hydrological characteristics of the watersheds that are purportedly providing the environmental service. In most cases, there is simply an assumption that reducing forest degradation will maintain stream flow. In other words, most existing PWS systems have at their fundamental base an untested assumption of a direct forest/water relationship (Landell-Mills and Porras, 2002).

* Corresponding author at: Center for International Development, Kennedy School of Government, Harvard University, 79 JFK Street, Cambridge, MA 02138, USA. Tel.: +1 617 495 1417; fax: +1 617 496 8753.
E-mail address: nigelasquith@yahoo.com (N. Asquith).
[1] Present address: Beaulieu, 1730 Route de Saint Jean du Gard, 30140 Anduze, France.
[2] Present address: Sustainability Science Program, Center for International Development, Kennedy School of Government, Harvard University, 79 JFK Street, Cambridge, MA 02138, USA.

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Measuring the biophysical flow of any environmental service is complex (Cowling et al., 2008, Jack et al., 2008): quantifying the scale, scope and value of watershed services is especially time consuming and costly. A typical experimental approach, such as a paired catchment analysis, takes between 5 and 10 years for the response to treatment effects to be recorded across relatively dry, relatively wet and average conditions (Jeanes et al., 2006). Further, the results of such experiments cannot be directly extrapolated to other locations, as details of soil, vegetation and rainfall patterns will differ (Jeanes et al., 2006).

There is thus an urgent need to develop tools that can measure and monitor if forests are truly providing watershed services, and to quantify the effect of land use change on such provision. The World Agroforestry Centre (ICRAF) has led the way with development of a Rapid Hydrological Appraisal Model (RHA) (Jeanes et al., 2006) which has been tested in a number of Asian watersheds (e.g., the Singarak Lake Basin in west Sumatra). Designed to be completed in 6 months and for less than $10 000, the RHA is comprised primarily of modeling, consultations and discussions about the perceptions of various watershed stakeholders. The ICRAF RHA methodology relies minimally on actual hydrological data collected in the field.

Taking a different approach to ICRAF's RHA methodology, we hypothesized that local farmers could be trained to collect useful data on stream flow (depth and velocity) and rainfall. Our goal was to see if at low cost (<$10 000) and over a short time period (<3 years) local farmers could collect scientific data that would be useful and trustworthy enough to shed light on whether there was a forest cover-hydrology link. In order to try to quantify a temporal phenomenon (i.e., with continued deforestation, stream flow will reduce), we reformulated the question as a spatial hypothesis: within a larger watershed, sub-watersheds that are already partially deforested will produce less dry season water than sub-watersheds that have maintained more of their forest cover. Our research was based in Bolivia's Los Negros valley, where a locally managed PES system is developing (Asquith et al., 2008). Our primary interest was differences in water flow in the dry season, when lack of water is often a limiting factor for agricultural productivity in this region.

There are many challenges in involving local people to monitor natural resource management outcomes, but our research was predicated on the assumption that if payments for watershed services are to become a widespread management tool, then monitoring must be sustainable. Monitoring protocols must thus be simple to conduct, inexpensive and locally relevant (Evans and Guariguata, 2008). Because it is likely that relatively untrained workers will be required to set up and undertake locally based monitoring, we here describe the lessons we have learned in implementing a pilot protocol, and propose a series of recommendations for others involved in designing or implementing watershed compensation schemes.

Specifically, in this paper we ask:

(1) Can watersheds that are similar enough to undertake paired catchment studies be identified using only simple parameters such as size, aspect and proximity?
(2) Can a functioning locally based hydrological monitoring system be set up for less than $10 000 by training local farmers to collect hydrological data?
(3) Can such data be used to improve the functioning of a PWS initiative?

2. Study area description

Santa Rosa de Lima is a village that is situated in the upper Los Negros watershed (17°44'S, 63°26'W), in the Municipality of Pampagrande, Province of Florida, Department of Santa Cruz. Santa Rosa has a humid to sub-humid warm-temperate climate. The average annual temperature is 19 °C, with a range of between 13 °C and 23 °C. There are two distinct seasons: the October to April wet season with 63–78% of the annual rainfall input, and the May to September dry season (Prefecture of Santa Cruz, 2007).

The study sites were within the 5100 ha Santa Rosa watershed, and comprise the tributaries of two streams, the Pailón and the Agua Blanca, that join to form the Santa Rosa river (Fig. 1). The upper reaches of these sub-watersheds are frequently covered in cloud or mist. The particular climatic conditions of these tropical montane "cloud" forests give trees an unusual aspect: they are of reduced stature, gnarled and covered with many epiphytes such as bryophytes, bromeliads, lichens and ferns. Tropical montane forests play an important hydrological role by capturing atmospheric moisture (horizontal interception) and returning it to the soil as droplets, and providing climatic conditions that limit water loss through transpiration. Both effects contribute to increasing stream flow, especially in the dry season (Bruijnzeel, 2004, Bruijnzeel and Proctor, 1995).

Land use within the study site was determined through interpretation of a 2005 Landsat satellite image (Carrasco, 2008). Land use varies throughout the area, comprising 63% cloud forest, 18% wet forest, 3% secondary forest, 6% grassland and 10% cropland. We ground-truthed ~60% of the study site in June 2008 to confirm the accuracy of the 2005 data. We found that there had been very little deforestation between 2005 and 2008. Only three new areas of deforestation were found, ranging between 0.3 and 0.8 ha. Thus the 2005–2008 deforestation rate was 0.05% for the study area (Le Tellier, 2008). This is far less than general values for Bolivia: 0.4% for the 1990–2000 period and 0.5% for the 2000–2005 period (Food and Agriculture Organization, 2006). This is probably because the area of the study site is steep, inaccessible, and covered with stony soils. As the rate of land use change during the study was so low, and within the precision range of the satellite image used to create the map, we used the 2005 data for our analyses.

3. Methods and techniques

Our research was undertaken in three stages:

1. First, we identified 10 sub-watersheds using three simple criteria—geographic proximity, and similar apparent size and aspect. We then delimited the 10 micro-watersheds and generated their channel network through an ArcMap® treatment of a Digital Elevation Model (cell of 30 m × 30 m) derived from a NASA Radar Image. The broadly used principle consists of considering picture pixels draining an area greater than a threshold area S_0 (S_0 = 16 ha in our study) (Moussa, 2003). Once each sub-watershed had been mapped, we calculated a series of hydrological coefficients to assess whether the watersheds were indeed as similar as we had hypothesized.
2. Second, we trained local farmers to collect rainfall and stream flow data in each of these sub-watersheds from 2005 to 2008. We compared the stream flow data with land use patterns to assess if there was a relationship between forest cover and hydrology.
3. Finally, we assessed whether our research protocols had worked and if the data collected had aided the development of the local PWS scheme, and we identified the major lessons we had learned.

3.1. Watershed comparability

Many factors influence watershed hydrology including morphometric and hydrographic properties, soil and geology (Moussa,

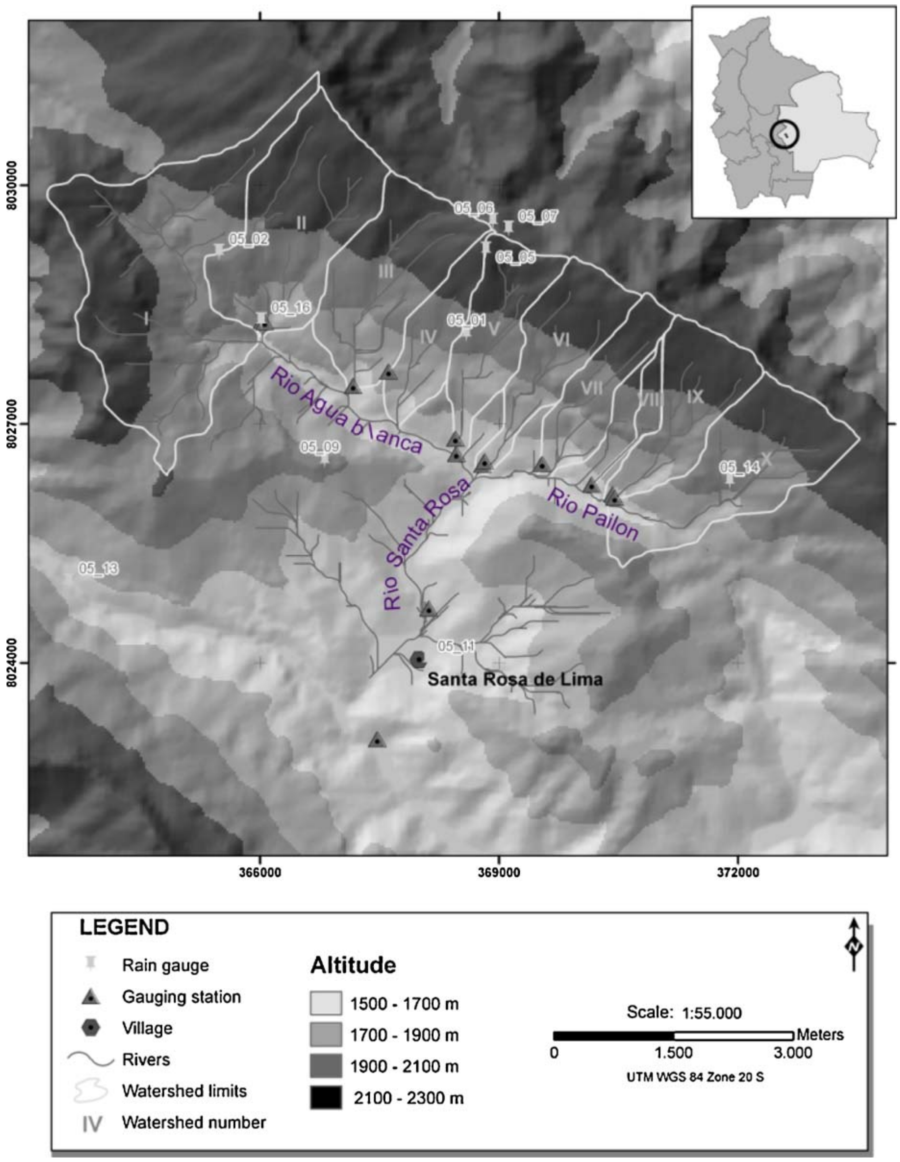

Fig. 1. Location of rain gauges, stream velocity gauging stations and study watersheds around Santa Rosa in the Los Negros valley, Bolivia.

2003). To isolate the effect of our variable of interest – land use – we chose 10 sub-watersheds that appeared to be of similar size and aspect, and were situated close to each other to try to factor out other effects, such as geology and geomorphology (Fig. 1). We hypothesized that this "quick-and-simple" identification based on easily understood criteria would be sufficient to identify sub-watersheds that could be experimentally "paired" based on their land cover. To assess whether the sub-watersheds we had chosen were indeed similar enough that they could be considered to come from the same population, we computed and compared the following watershed characteristics:

1. Drainage basin area, which constitutes the rainfall reception area and feed area for a given channel, and thus has an important influence on water yield.
2. Mean altitude, of great importance concerning rainfall inputs (see below).
3. Aspect and exposure to dominant wind (assessed through an aspect-derived index), which influences the quantity of rainfall collected by the watershed, depending on its relative position to the dominant wind (blowing from the north in the study zone).
4. Mean slope, which helps describe the watershed topography. Slope is related to the time necessary for water to reach the channel.
5. Shape of the watershed surface, quantified using the Gravelius index (K_c) (Te Chow et al., 1988).
6. Watershed length, the curvilinear distance measured along the mainstream from the outlet until a point representing the watershed gravity center projection (Musy, 2003). This length influences the rate at which water is released into channels.
7. Drainage density, the ratio of the length of channel segments to total watershed area.
8. Bifurcation ratio, the quantitative measure of stream networks, namely the number of stream segments of a given order in a river basin relative to the number of segments of the next higher order (Te Chow et al., 1988).

Once computed for all 10 sub-watersheds, we applied a statistical test on each of the variables to assess whether the study watersheds could be considered as belonging to one population (i.e., they really share similar values for each variable). We assumed the following theoretical logic: if X is a variable of interest, let us call x_i the X-value of watershed i. The population behavior can be summed up by a statistical distribution of mean value μ and standard deviation σ. Let us assume that this distribution were the $N(0,1)$ normal one ($\mu = 0, \sigma = 1$). Assuming a normal distribution, there is a 95% probability that a given point x_i of this population presented value in the [−2;2] confidence interval. It is thus quite improbable ($P = 5\%$) that a point would be outside this interval.

This theoretical approach was adapted to the data set. However, the real distribution is unknown and thus has to be approximated with a known theoretical one. We supposed first that the variable of interest followed a normal distribution as suggested by the central limit theorem, even though we were working with a small sample size (10 points).

The suitable watershed population distribution is only partially known via the 10 study site watersheds. As a consequence μ and σ were not known but only estimated through the data set mean and standard deviation values. We therefore used a Student distribution instead of a normal one. Given that the latter assumption can still be imprecise as variables can present asymmetric distributions, we used Box–Cox transformations to normalize the distributions (NIST/SEMATECH, 2003). Our analyses thus used statistical distributions with a smoothed data set where extreme values were minimized. This made the test more conservative, excluding values and watersheds only when it was improbable that they were from the same population.

Once one or more watersheds were excluded for being outside the confidence interval, the study sample size changed, and so a new round of estimates was made with the new sample size. Another test was undertaken with the new μ and σ estimates, and repeated until stabilization, i.e., until all points fell between the confidence interval.

3.2. Rainfall, stream flow and the forest cover-hydrology relationship

To analyze whether forest cover affects stream flow, we computed two variables: the rainfall entering, and the stream discharge exiting each sub-watershed. Rainfall was measured directly at 10 points, and average values calculated across each watershed. Stream depth and velocity were measured directly and used to calculate discharge. We then regressed dry season stream discharge on forest cover for each sub-watershed.

3.2.1. Rainfall

Ten 0.25 mm tipping bucket rain gauges (Rainwise, Bar Harbor, Maine, cost ∼$300 per gauge) were installed in 2005 to cover the altitudinal range of the study (1590–2381 m). The location of some of these rain gauges was not optimal because of difficulties accessing the cloud forest canopy. Rain gauges were serviced and downloaded by a trained technician at least every 4 months. Gauges were clustered, rather than being distributed randomly or evenly across the study area, because few access trails exist. Of the 10 rain gauges installed, one was destroyed mid-project by an unknown person while one (rain gauge 05_7) gave abnormally low annual data compared to other gauges set in the same altitudinal range. Data from both these gauges were excluded from the analysis. Conversely, rain gauge 05_13 was used for the regression analysis even though situated out of the study zone, because it showed results comparable to those obtained in the study site.

Several methods exist to extrapolate data from specific records: considering the number of gauges, the heterogeneity of the study area and the relative difficulty of each method, we regressed rainfall on a series of variables, namely altitude, distance from the summit and exposure to dominant wind (assessed through an aspect-derived index) to the rain gauge station (Musy, 2003).

Regressions were linear. Their hypotheses (normality, homoscedasticity and independence) were checked: particular attention was paid to the data set behavior for high values where dispersion was higher. The statistical analysis was carried out with S-PLUS 2000 Professional release 3 with a 5% significance threshold.

Our initial plan was to use rainfall data averaged on the whole 2005–2008 period as their statistical fittings with altitude were generally better. However, Bolivia is influenced by the El Niño Southern Oscillation phenomenon and for this reason can present highly distinct rainfall features from one year to another, which was the case between 2005 and 2008. As a consequence it was not appropriate to average values for different years, so we established month-by-month regression relations.

Thirty-four regressions (corresponding to the 34 months of record) were tested from which 15 were significant ($P < 0.05$) with these conditions. Another method was used for the 19 months when no significant linear regression could be found between altitude and monthly rainfall (mainly in the dry season when dispersion was higher). This method was inspired by CLAS (2006) and was based on the observation that for a given month, the monthly/annual rainfall ratio is relatively stable for all watersheds that then follow similar yearly patterns. Averaged ratio values enabled us to estimate the missing monthly rainfall data for each watershed.

3.2.2. Water velocity and stream depth measurements

Stream flow gauging stations were installed at 14 locations along the streams of the area: six in Río Agua Blanca area, six in Río Pailon area, and two on Río Santa Rosa. Ten of the 14 stations were used in this study, being located at the outlets of the sub-watersheds. The four others were designed to control the other gauging stations or to measure changes in the channel of the valley's principal river.

Local farmers were identified as potential data collectors by word of mouth: we contracted those individuals who expressed an interest in the position and hired them until they voluntarily left the job. Training was minimal: a technician who had been trained in stream flow data collection by one of the authors (AC or NMA) then trained the farmers. AC occasionally accompanied the technician and farmers during data collection and suggested improvements to the methodologies.

We investigated two different methods for standardizing measurement locations. In five streams farmers simply attempted to measure at the same locations. In the five other streams we constructed a concrete platform (watersheds I, II, IV, V and VIII) to facilitate stream depth and velocity measurement. Construction took place in the dry season, when we laid a ∼2 m platform of concrete along the length of the stream bed, and at the downstream end built two 1 m × 0.2 m concrete walls to constrain channel width. These structures were not designed to restrict flows, but rather to standardize data collection by ensuring a constant stream width across a smooth stream floor. However, wet season stream flows in Santa Rosa are so powerful that these concrete structures did not last long: four were destroyed by water in February 2007 and the fifth in March 2008.

Measurements were taken from June 2005 until July 2008. For most of the year (including all of the dry season), measurements were taken two times per week for stream depth and four times per month for both stream depth and flow velocity. In the wet season (e.g., in February) dangerously high stream flows sometimes made taking measurements impossible. Measurement points were taken every 50 cm in a perpendicular line across the river. In the streams that did not have the standardized gauging stations, the riverbed was cleared of big stones prior to measurements. Depth measurements were made with a graduated rule (precision:

Table 1
Watershed morphometric and hydrographic characteristics.

Watershed	I	II	III	IV	V	VI	VII	VIII	IX	X
Area (ha)	647[b]	383	298	126	181	194	143	29[b]	195	325
Mean altitude (m)	2105	2121	2047	1955[a]	2043	2084	2020	2063	2086	2009
Aspect Index	0.45[b]	0.11	0.13	0.09	0.10	0.10	0.10	0.02[b]	0.11	0.27[c]
Mean slope (%)	23	25	25	27	28	29	31[a]	25	27	23
Gravelius Index	1.67	1.25	1.26	1.52	1.51	1.52	1.47	2.49[a]	1.39	1.39
Watershed length (m)	1760	1856	1687	1285	1621	2184	1519	1439	1813	2198
Drainage density (km km^{-2})	2.55	2.58	3.31	2.60	3.18	3.62	3.34	5.01[a]	2.80	2.65
Bifurcation ratio of order 1	2.4	1.4	3.0[a]	1.3	2.0	1.7	1.2	1.5	1.6	1.9

[a] Rough value outside the 90% confidence interval.
[b] Box–Cox value outside the 90% confidence interval.
[c] Second round Box–Cox value outside the 90% confidence interval.

0.5 cm). Water velocity was measured with the current meter Flow Probe FP101 (Global Water Instrumentation Inc., Gold River, California) (cost ~$750).

The variable actually measured was mean velocity, i.e., the velocity representative for a vertical section of water. We followed the US Geological Survey methodology (Te Chow et al., 1988) for shallow rivers less than 60 cm, taking one point of measurement at 60% of total depth from the surface. This point presents a velocity representative for the whole vertical section (Te Chow et al., 1988). As streams were shallow (generally less than 50 cm), measurement could be taken easily moving across the channel. Each measurement lasted the time necessary to get a stabilized velocity, generally about 1 min.

The actual discharge Q (m^3 s^{-1}) at a cross section of area A (m^2) is given by

$$Q = \iint_A v \cdot dA$$

where v is the flow velocity in m s^{-1}.

This integral can be approximated by measurements realized in n vertical sections, the approximated discharge being (Te Chow et al., 1988):

$$Q = \sum_{i=1}^{n} v_i d_i \Delta w$$

where v_i is the mean velocity of each section (m s^{-1}), d_i is the water depth of each section (m), Δw is the distance between each point of measurement (m).

By measuring partial discharge of each section and then summing them, we computed the stream's total discharge. We expected that regression analysis of the data points from the days on which both depth and velocity were measured would allow extrapolation to calculate total flow (Q) on the days when only depth were taken.

3.2.3. Land cover-hydrological relationship

Once the stream flow and land use cover data were collected for each sub-watershed, we used regression analysis to assess if these variables were related. Because stream flow is still highly correlated to watershed area (correlation coefficient of 90%), the regression analysis was made with *specific discharge* (that is the discharge per unit area) expressed as a depth (in mm of water per month). We then calculated the *runoff coefficient* (ratio of runoff depth to precipitation depth – calculated from the rainfall regression analysis described above, and highly dependent on watershed land use). Given that local farmers were interested in maximizing dry season flows, we tested for a relationship between % cloud forest cover and (1) dry season stream flow in L/s/ha; and (2) the dry season (May–September) runoff coefficient.

3.3. Evaluation of protocols and relevance to the local PWS scheme

Upon completion, each component of the project was evaluated in the context of two primary questions: (1) how could protocols be improved, and (2) how had each project component affected the concurrent development of a local PWS scheme? To answer these questions we interviewed the farmer participants and other upstream and downstream residents.

4. Results

The watersheds we had chosen using the "quick-and-simple" approach were between 29 and 647 ha. Table 1 represents the results of the Box–Cox transformed analyses. Sub-watersheds II–VII, IX and X can be considered from the same population, i.e., they were similar in all their variables. In contrast, watershed I was large, with an east-southeast exposure that enabled it to capture more clouds from the northern winds. Watershed VIII was small, protected from the northern winds (with its almost due south exposure), and was long and narrow (high Gravelius index), with relatively few channel segments higher than first order. Thus, while watershed I was different from the other watersheds in size and aspect, watershed VIII differed in size, aspect, shape and drainage density: we therefore excluded both from the land use-hydrology analysis.

Annual rainfall measured by rain gauges ranged from 1063 to 2294 mm (Table 2). Monthly rainfall showed high variability between years (as signaled by Bruijnzeel, 1990). The only significant variable in the regression was altitude (explaining up to 95% of the rainfall variability). The distance from summit variable was also significant but was abandoned as it was redundant with the altitude variable: the correlation coefficient was −0.79 between these variables.

In this dynamic hydrological system natural and artificial variability is high: depth was measured in slightly different places each time, and stream morphology changes frequently. Indeed, wet season floods destroyed all five of the concrete platforms. In dynamic streams such as those in Santa Rosa, hydrological measuring platforms clearly do not work.

Table 2
Annual rainfall data in the Los Negros valley.

Rain gauge	X	Y	Altitude (m)	Annual rainfall (mm)
05_01	368,593	8,028,139	1965	1999
05_02	365,489	8,029,161	2064	1803
05_05	368,838	8,029,189	2283	2294
05_06	368,924	8,029,549	2381	1927
05_11	368,107	8,024,045	1590	1120
05_13	363,603	8,025,019	1711	1156
05_14	371,897	8,026,289	1901	1457
05_16	366,016	8,028,299	1649	1063

Table 3
Monthly specific discharge and runoff coefficients in eight sub-watersheds of the Los Negros River.

Watershed	II	III	IV	V	VI	VII	IX	X
% Cloud forest	76	68	54	65	76	62	70	57
Size (ha)	383	298	126	181	194	143	189	325
Monthly average (L/s/ha, runoff coefficient)	0.22 (0.41)	0.17 (0.44)	0.09 (0.18)	0.25 (0.53)	0.16 (0.29)	0.22 (0.51)	0.20 (0.44)	0.20 (0.45)
Dry season (L/s/ha, runoff coefficient)	0.09 (0.32)	0.11 (0.42	0.05 (0.14)	0.13 (0.45)	0.07 (0.23)	0.11 (0.46)	0.14 (0.46	0.12 (0.43)
Wet season (L/s/ha, runoff coefficient)	0.32 (0.49)	0.23 (0.45)	0.13 (0.22)	0.35 (0.59)	0.24 (0.36)	0.32 (0.56)	0.26 (0.43)	0.27 (0.47)

We did not usually take both depth (d) and velocity (v) measurements together: only 28% of stream flow measurements were realized with both depths and flow velocity. The regression analyses that attempted to extrapolate flow (Q) when only d was taken were not significant: we found a statistical relationship between d and v in only three of the streams. Given that we could not calculate stream flow Q on the occasions when we had only collected depth values, we were thus unable to use more than 70% of our data in the stream flow/land use regressions.

Our regression analyses only used data from the dates when we collected d and v and directly calculated Q (Table 3) and found relationship neither between dry season stream flow and cloud forest cover (Fig. 2) nor between the dry season runoff coefficient and cloud forest cover (Fig. 3).

Interviews with farmers confirmed that the local PWS scheme is gaining traction both usptream and downstream. However, downstream buy-in seems to be based primarily on the precautionary principle rather than the results of the hydrological monitoring. Downstream farmers are now contributing stakeholders in the maintenance of upstream water supplies. A crucial catalyst for this interest was the presentation of a hydrological modeling analysis (CLAS, 2006) that predicted potentially catastrophic effects on dry season flows of continued deforestation around Santa Rosa.

5. Discussion

Our study was designed to answer three questions: (1) can paired watersheds for study be identified using simple parameters; (2) can a hydrological monitoring system be developed at low cost, and (3) can such data be used to improve the functioning of a PWS initiative? In addition to answering these questions, we here assess our results through the lens of Danielsen et al. (2005), who identified six factors as important in locally based monitoring systems: cost, sustainability, ability to detect true trends, decision-making and action, local constituencies, and tracking larger scale trends.

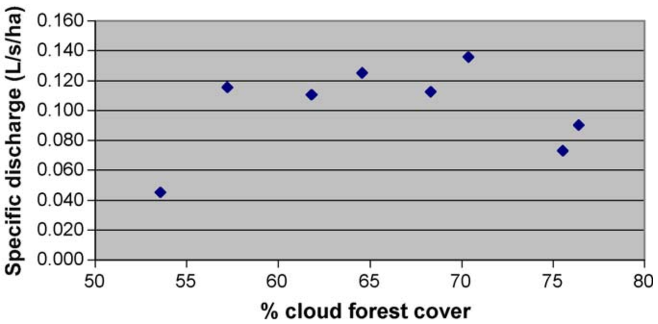

Fig. 2. Dry season specific discharge as a function of cloud forest cover.

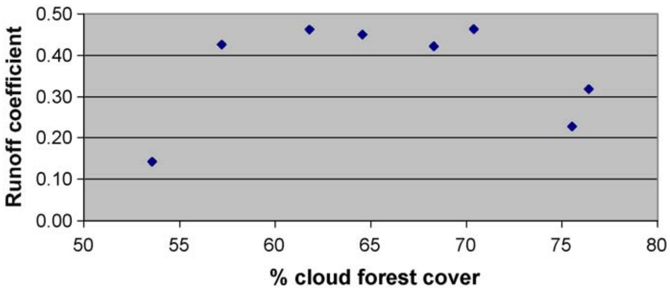

Fig. 3. Mean dry season runoff coefficient as a function of cloud forest cover.

5.1. Can watersheds that are similar enough to undertake paired catchment studies be identified using only simple parameters such as size, aspect and proximity?

When we designed the study, we chose watersheds using three basic criteria: size, aspect and proximity. These choices were made simply by visiting the field sites and not through evaluation of maps or satellite images. This quick-and-simple approach proved sufficient. We conclude that for future schemes, local decision-makers could similarly choose study watersheds to analyze the affects of forest cover on the hydrological cycle.

5.2. Can a functioning locally based hydrological monitoring system be set up for less than $10 000 by training local farmers to collect hydrological data?

5.2.1. Cost

In order to be sustainable, locally based monitoring must be inexpensive (Evans and Guariguata, 2008). We achieved our goal of setting up and running a monitoring system for less than $10 000, but we also identified a series of ways we could reduce costs. In the Los Negros valley, the only outcome of interest to downstream stakeholders is dry season base flow. Future monitoring could be made more efficient just by focusing on this variable, simultaneously removing the need to attempt measurements when water levels are dangerously high. An NGO, Fundación Natura Bolivia covered all monitoring costs associated with this study, but as the Los Negros PWS scheme becomes increasingly locally self-sufficient (Asquith et al., 2008), we expect that downstream users will cover such costs.

5.2.2. Sustainability

For locally based monitoring to become sustainable, the key is to keep it as simple as possible (Danielsen et al., 2005). In requiring that farmers only record stream depth, we tried to avoid giving them the more complex task of velocity measurement.

Our protocol therefore required that the farmers only collect depth measurements and had our better-trained NGO staff technicians periodically take velocity and depth measurements.We expected to regress velocity (v) and depth (d) to allow extrapolation of v and hence calculate discharge (Q) when only d was collected by the farmers. In addition, we constructed concrete platforms to try to standardize measurements and thus improve the probability of robust egressions of d and v. This strategy failed completely. The concrete platforms were destroyed and meaningful regressions proved impossible, requiring that we discard more than 70% of our data points. We propose that future hydrological monitoring systems should not depend on attempts to calculate regressions based on measurements made on other days. Rather, researchers should simplify their protocols by measuring both velocity and depth (and from them directly calculate discharge) every time, and do so using either a flat stone or a portable wooden structure to make flow measurements more uniform.

5.2.3. Ability to detect true trends

Although prior studies have noted a strong relationship between cloud forest cover and dry season stream flow (Bruijnzeel, 2004), our study did not. Several explanations can be proposed. The most obvious is that in our study site cloud forests do not have any effect upon stream flow (c.f. Bruijnzeel, 2004). This could be because Santa Rosa forests might not present marked cloud forests features such as horizontal interception and low evapotranspiration. An alternative explanation could be that the difference between watersheds with high (76% in watershed VI) and low (54% in watershed IV) cover rates of cloud forests is not high enough to detect any difference in hydrological responses (Bruijnzeel, 2004). A third, and perhaps most likely explanation is that our data series is too short – 3 years whereas hydrological studies usually take decades – and that we made a series of errors during collection.

While our studies ability to detect true trends is thus still unknown (data collection is continuing), it is clear that we can improve our performance. Between July 2005 and June 2008, 10 different farmers took measurements, each working a median 115 days. Precision tests showed that in controlled conditions measurement results are highly comparable between farmers for a given location at a given moment: a 0.8% difference only was observed in stream flow values. However the quality of measurement might be different in routine conditions, as farmers did not always look for the same level of quality. We even suspect that data may sometimes have been invented. We tried to minimize this risk by simultaneously employing two farmers, one collected data on Sunday while the other collected data on Wednesday: extensive data invention would have thus required collusion between two independent workers. The collection of metadata (technician name, date, hour, and condition of the day) helped check data reliability.

5.3. Can these data be used to improve the functioning of a PWS initiative?

5.3.1. Decision-making and action

A water fund, financed by the Los Negros Water Cooperative and the Municipal Government, is now investing in upstream conservation though direct payments for watershed services. It appears that monitoring will continue using locally generated funds. However, the PWS scheme and the water fund are based on the precautionary principle rather than data. At first glance therefore, the monitoring described here has not yet provided results to aid local decision-making. However, development of the PWS scheme, a modeling analysis (CLAS, 2006), and perhaps our data collection have together catalyzed greater local awareness about the potential links between land use and hydrology, leading to the conservation of more than 3000 ha of upstream forests (Asquith et al., 2008, see Becker et al., 2005 for a similar result in Ecuador). The lessons we have learned from implementing our pilot monitoring protocols will likely aid downstream water users as they develop a sustainable hydrological monitoring system.

5.3.2. Local constituencies

Surprisingly, we found that employing local community members has advantages and disadvantages. We expected a greater acceptance of the validity of the data as it was locally "created" (Danielsen et al., 2005), but in reality other community members questioned the motives of the local workers. For example, one landowner suspected a technician of robbery and refused to let him take further measurements on his land. However, as the local PWS initiative approaches a tipping point – more people in the village of Santa Rosa will soon be in the scheme than are out of it – we expect that there will be concomitant upsurge in interest in improving the hydrological monitoring.

5.3.3. Tracking larger scale trends

Fundación Natura Bolivia has recently facilitated the creation of a series of other PWS funds in neighboring municipalities. The protocol described here has the potential to be adapted and applied in these watersheds. Our approach, which focuses on actual data collection, is a complementary alternative to ICRAF's Rapid Hydrological Appraisal Model that relies more on perceptions and modeling. The following improvements would allow our data collection protocol to be used more efficiently and effectively:

- *Given high natural and measurement variability, stream discharge should always be calculated directly.* This means that both stream depth and the more complex velocity should be measured every time. This will also obviate the need for building the easily destroyed gauging structures.
- *Only the most locally relevant hydrological criteria, as opposed to the scientifically complete criteria, should be monitored* (see Reed et al., 2008 for a discussion of the complementarity of using ecologically scientific and locally derived indicators). Given the interests of farmers in downstream Los Negros, we could likely just monitor dry season flows rather than measuring all flows all year.
- *Locally based monitoring must be institutionalized to reduce staff turnover.* Inherent measurement variation is exacerbated with more than one data collector.
- *Hydrological monitoring must be embedded within a context that makes it socially acceptable.* Without a functioning PWS system that is already financially helping community members, outsider-initiated collection of hydrological data may be viewed with suspicion and hostility. Once compensation payments are being received, it is easier for locals to accept that data need to be collected. In most contexts, it will not be known if a PWS scheme makes biophysical sense until after a few years of monitoring that assesses whether or not there really is a hydrological service. The experience of Fundación Natura Bolivia in Los Negros thus seems an appropriate model: an NGO "fronts" PWS payments for the first few years to generate goodwill and protect forest using the precautionary principle, while data collection and hydrological monitoring is initiated, the results of which can be later used to fine tune, or cancel the PWS system.

6. Conclusion

This project attempted to develop a monitoring protocol for data collection by minimally trained local farmers that would provide useful and usable hydrological data that could be used to calibrate and justify (or negate) the wisdom of developing local payments for watershed services initiative. Our work did neither involve extensive participative discussions about perceptions about water and forests (Jeanes et al., 2006), nor did we participatively develop a series of perceived indicators of water quality (Deutsch et al., 2004). Rather, we tried to keep our protocol simple, short, and data-driven.

We found that sub-watersheds could be identified as "similar-enough-for-analysis" using the simple criteria of size, aspect and proximity, without undertaking further research, suggesting that future experiments can chose study sites equally quickly. Further, we conclude that a locally based hydrological monitoring system can be developed for <$10 000. Even though our local farmers, in their first iteration, did not collect sufficiently high quality data to fully explore the forest/water relationship in the Los Negros valley, it appears that such data collection may be possible. With further refinements of the methodology, we believe that low cost locally based monitoring has the potential to be an important component of future PWS initiatives.

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