II Conferencia Electrónica sobre Usos Sostenibles y Conservación del Ecosistema Páramo en los Andes: "Los Páramos como Fuente de Agua: Mitos, Realidades, Retos y Acciones"

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Esta contribución al Foro electrónico es un informe que no ha sido publicado. Publicaremos una versión condensada en una revista científica.

En el contexto del Foro quisiera añadir lo siguiente:

1. El trabajo presentado representa, desafortunadamente, uno de los primeros estudios cuantitativos sobre la hidrología del páramo. Creemos que esto hace el estudio muy valioso, pero al mismo tiempo queremos advertir que la extrapolación de las conclusiones del presente estudio a otras regiones o situaciones no es necesariamente válida. La cuenca del Río El Angel tiene características específicas. El clima, la vegetación, el suelo y el manejo de la tierra varían entre regiones, y causan diferencias significativas en la hidrología de las cuencas.

2. En este estudio, el efecto del uso de la tierra ha sido interpretado únicamente en el contexto hidrológico. Aunque el cultivo de papas no parece causar grandes cambios hidrológicos en la región estudiada, no hemos estudiado su influencia en la erosión, la biodiversidad, la fertilidad del suelo, la contaminación etc.

3. Este estudio demuestra que existe una gran necesidad de información. En primer lugar porque hay muy pocos datos de referencia para estas regiones altoandinas o inclusive para los suelos que predominan en estas regiones. En segundo lugar porque los resultados no están siempre de acuerdo con las creencias o la intuición. Esto se debe a la combinación única de caracteristicas de los páramos. La discusión sobre los páramos y la toma de decisiones sobre su futuro requieren muchos más datos y merecen la atención de muchos más científicos.

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The importance of high Andean native ecosystems for the water supply to a downstream region in Carchi, Ecuador, and the consequences of their replacement by agricultural fields

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Abstract Features of the climate and soils of the high Andean ecosystems are unique and determine the hydrological functioning of the watersheds. This paper assesses the importance of a high elevation natural ecosystem for water supply to lower elevation, drier areas. The area studied is the El Angel watershed in the northern Andes of Ecuador. Precipitation was measured at 7 sites, and soil and vegetation properties quantified for 9 sites, both natural ecosystems and agricultural lands. Landscape position, land-use history, and the management and composition of the vegetation were described. Field infiltration measurements were taken, and soil samples analyzed in the laboratory. Potential evapotranspiration rates were calculated. Our analysis shows that in the El Angel watershed rainfall intensities are generally sufficiently low to allow full infiltration into the soil despite low sorptivity. Variation in the amount of water stored is small because the vegetation transpires relatively little and occurrences of rain and fog ensure some input even in the dry season. Soil hydraulic parameters of potato fields are clearly different from those of the natural páramo ecosystem, but this is expected to have little impact on water balances, in this watershed, assuming continuation of current rotations, and wise soil management. Given the distinct hydrological behavior of forest ecosystems, massive deforestation in the past has probably had a greater effect on watershed processes than has the ongoing conversion of paramo to cropland and pastures. Reforestation of the most vulnerable and least productive lands should be considered. Recommendations for further investigations are given.

Keywords

Páramo – potato – pasture – precipitation – infiltration – water retention

INTRODUCTION

Frequent rains, low temperatures, and high atmospheric humidity are the causes of a considerable moisture surplus in most high-elevation ecosystems of the northern Andes. Many rivers, important for the water supply of the lower-lying, densely populated areas, have their origins in the upper montane landscape. Despite its importance, the hydrology of high-Andean ecosystems is little investigated. The need to conserve the water-supplying capacity of this landscape is generally acknowledged but seemingly based on popular assumptions like the capacity of forests to produce water, the sponge function of soils, and the contribution of fog to the water balance. Unfortunately, being aware of the importance of high-Andean ecosystems has not stopped the population from replacing forests and other native ecosystems with croplands and managed pastures.

Colonization of the high Andes has been going on for many centuries. Potato is a traditional crop, and remains the most important of the highest altitude agricultural zone. Potato cultivation is usually accompanied by the presence of cattle and grasslands because lands cropped with potato need to be left fallow after two cycles, and develop into grassland. Potato is grown up to altitudes that reach well into the páramo domain, which starts at about 3,300 m (Hofstede, 1997). Páramos are unique high-Andean ecosystems, typically dominated by tussock grasses, and often with characteristic stem rosette species (particularly *Espeletia* sp.). The natural limit between closed forest and páramo is thought to have been situated at elevations of 3,700 to 4,200 m, but was brought down by human influence, especially the use of fire (Hofstede, 1997).

This paper assesses the importance of a high-elevation ecosystem for water supply to lower elevation, drier areas. The El Angel watershed covers 300 km^2 in the northern Andes of Ecuador (Carchi province). The lower part of the watershed is dry and in many places degraded. The middle part (altitudes around 2,500 m) has irrigated agriculture. Between 3,000 and 3,500 m lies another agricultural zone where traditionally a variety of crops was grown, but which has increasingly become a pasture/potato belt. Above 3,500 m the landscape is covered by natural páramo vegetation. Soils in the upper part of the watershed are classified as Typic Hydrandepts (MAG-ORSTOM 1980). They developed in volcanic ashes, and are usually deep (about 1.5 m).

For over a century, water has been tapped from páramo streams, and led through small channels many kilometers down to irrigated fields. Water is a critical resource in the watershed, being abundant in the upper part and scarce in the lower. Annual precipitation in the higher parts is estimated to be more than twice that in the lower (Nouvelot *et al.*, 1994), and evapotranspiration is much lower because of lower temperatures, higher atmospheric humidity, and abundant cloudiness.

The watershed of the El Angel river is almost entirely deforested. Most of the páramo ecosystem, however, is in good state. This unique vegetation is found from about 3,500 m up to 4,150 m, the highest elevation in the watershed. Although no settlers live in this area, frequent fire and the presence of paths are evidence of human influence. Most plant species are fire-resistant and resprout immediately after fire. A more drastic impact is the conversion of páramo to cropland. The páramo is tilled, potatoes are planted, fertilized, and sometimes irrigated. Potato yields average 12 t ha^{-1} on the small farms at high elevations. After two cycles (1 year), the land is left fallow for about 3 years (Arce *et al*., 1996). Soon after harvest, the land develops into short grassland made up of native species, but lacking the typical structure of páramo. In some cases improved pastures are sown.

Advancing the agricultural frontier at the cost of natural páramo creates a potential conflict between agricultural production and hydrological and ecological services. Here we provide data on processes that determine the water balance of high-altitude ecosystems in the El Angel watershed, and preliminarily assess the impact of converting natural wet páramo to cropland.

METHODS

Precipitation was measured at seven sites in the watershed (Table 1). One location was the highest existing meteorological station of the region, at an altitude of 3,020 m. Four sites were chosen in the altitudinal zone where cropland and páramo meet (3,400-3,500 m), and two more sites above this zone. Rainfall was measured using plastic funnels of 19.5 cm diameter with a vertical rim, mounted on plastic bottles at a height of 0.5 m. The fog catchers consisted of cylinders of 1-mm mesh steel gauze, with a diameter of 10.3 cm and a height of 19.4 cm. This creates a 200 cm^2-intercepting surface in all horizontal directions. Cylinders were placed at 1 m above ground level. Funnels collected water dripping from these cylinders (Schemenauer and Cereceda, 1994). Roofs of 1 m^2 were placed above the fog catchers to prevent rain falling into them. Rain and fog were sampled daily at 8 a.m. from 1 March to 30 November 1997.

Soil and vegetation properties were quantified for nine sites representative of different land uses or stages therein (Table 2). Two sites represented natural páramo vegetation at different altitudes, two were potato crops at different stages of development, and three were pastures (fallows after potato crops) of different ages. We also sampled a forest relict site, and a site characterized as shrub páramo. The latter was probably an abandoned pasture site, heavily invaded by shrubs.

Landscape position, land-use history, and management and composition of the vegetation were described. Geographical coordinates were determined with a Global Positioning System, and altitude with an altimeter.

Soil pits were made for taking infiltration measurements and samples for laboratory analyses. Infiltration was measured using metal cylinders of 10 cm diameter, at depths of 0, 5, 20, and 40 cm. The soil surface was carefully prepared to avoid the sealing of pores. Cylinders were introduced into the soil to a depth of 10 cm, and filled to a height of 10 cm. The decrease of water level was then recorded after 1, 2, 5, 15, 30, 45, 60, 90, and 120 min. Cumulative infiltration, plotted against the square root of time, showed an initially linear relationship. Sorptivity was taken as the slope of this relation for the first 2 minutes of the experiment (Philip 1957). Field hydraulic conductivity was estimated as the mean infiltration rate between 45 and 120 min after starting the experiment. During that period, infiltration was about constant.

Soil samples were taken with rings (diameter 5 cm, height 2.5 cm) in two pits per site, at depths of 0, 5, 10, 20, and 40 cm and for one páramo site also at 80, 120, 150, and 180 cm. The surfaces were protected and samples were kept at field moisture content until processed in the laboratory. Saturated hydraulic conductivity was determined on these samples using the saturated flux method (Klute & Dirksen 1986). Moisture contents were determined after saturation and equilibration at a tension of 75 cm water (7.5 kPa; pF 1.9). Higher tensions could not be applied because of equipment problems. Finally, dry weights were determined, and bulk density calculated. Organic matter contents were measured using the Walkley-Black method, assuming a 58% carbon content of organic matter.

Potential evapotranspiration rates were calculated for altitudes between 3,000 and 4,000 m using the Penman formula (Nokes, 1995). Unfortunately, no meteorological stations exist in the region at these elevations. A number of parameters had to be estimated by extrapolation using data from seven stations in northern Ecuador located at altitudes between 2,230 and 3,055 m (Jones, 1991). Altitudinal variation was estimated by regression and monthly variation by deviations of monthly means from annual means. Parameters thus estimated were mean maximum, minimum and dew point temperature (used to calculate vapor pressure deficit, latent heat of vaporization, and the slope of the vapor pressure-temperature curve), and wind speed. The mean global radiation of the northern Ecuadorian stations is 16.6 MJ m^{-2} d^{-1} (Jones, 1991), and

16.8 MJ m^{-2} d^{-1} according to Frère *et al*. (1975), with no evidence of an altitudinal trend. Frère *et al*. (1975) showed that net radiation is about 50% of global radiation for equatorial high-altitude sites at 3,000-m altitude. These estimates were used without modification for higher altitudes. Monthly values were adjusted for the trends observed in the stations from the CIAT database.

RESULTS

Precipitation

Rainfall decreased from March to August and increased from August to November (Figure 1). This pattern represents part of the typical bimodal pattern known for this region (Nouvelot *et al*., 1994). Another dry period normally occurs in December-January. Rainfall increased with altitude, as Nouvelot *et al*. (1994) demonstrated, although the rainfall in the measured period was below the long-term average (Figure 2). The difference is even slightly underestimated, because our rain gauge yielded 9% higher values than the standard rain gauge at 3,020 m. Rainfall at altitudes around 3,500 m was much better distributed than at 3,000 m. Although months with low rainfall occurred at all altitudes, the number of raindays per month remained high (>20) above 3,500 m, whereas it fell to 5 at 3,000 m (Figure 3). The rainfall per rainday was consistently lower at altitudes above 3000 m (data not shown).

The fog-catching devices measured significant horizontal precipitation (Figure 4) at all stations except at 3,000 m. Quantities were low and did not follow the same seasonal trend as for rainfall. Fog precipitation was highest in May for most stations. Variability was higher than for rain. Records from three stations forming an altitudinal transect showed an increase of fog precipitation with elevation. Totals for the period May-September were 150 ml at altitudes of 3,500 m, 885 ml at 3,610 m, and 1464 ml at 3,650 m (note that fog catches are given as volumes, not depths – see Discussion).

Even when protected by roofs, fog-catchers may catch some light rain moving at a sharp angle to the ground surface because of miniscule drop size or high wind speed. However, we found no indications that high fog catches coincided with windy conditions (wind records from the meteorological station at 3,020 m).

Evapotranspiration

Estimated potential evapotranspiration ranges from about 86 to 74 mm mo^{-1} at altitudes between 3,000 and 4,000 m (Figure 5). The altitudinal decrease is mainly caused by a decrease in vapor pressure deficit. The relatively small seasonal differences are mainly caused by differences in radiation. The greatest uncertainty in the estimates is due to the uncertainty about the radiation values, to which the result is highly sensitive. Radiation loads at these altitudes are likely to be significantly below those expected from linear extrapolation of observations from lower altitudes, because of orographic cloud formation. In a cloud belt in northern Colombia, Cavelier and Mejia (1990) measured a 50% reduction of solar radiation compared to a nearby location outside the cloud belt. If such a reduction were applied to our case, potential evapotranspiration would be around 50 mm mo^{-1}.

Infiltration

Sorptivity of páramo soils, measured in the field, was low at about 4 mm min$^{-0.5}$ (Figure 6). Preparing the land for potato cultivation caused a rise of an order of magnitude, but during fallowing sorptivity returned to "natural" levels within 2 years. Forest soils had by far the greatest ability to absorb water.

Hydraulic conductivity measured *in situ* at different depths showed a similar pattern to sorptivity (Figure 7). Except for forest soils and the loose top layer of one potato field, conductivity was low throughout the profile. Typical values were less than 10 mm h^{-1}. Unmanaged páramo soils (including shrub páramo) tended to have the lowest conductivity at all depths.

Saturated hydraulic conductivity as determined in the laboratory was typically between 10 and 60 mm h^{-1}, except for potato fields, which had high conductivities in the top layer (0-10 cm), and the forest soil, which had high conductivities throughout the profile (Figure 8). The results shown for potato fields are means taking into account the variability within potato fields. The potatoes are often grown in raised beds of mixed and loosened soil. Under and between these beds, the soil is undisturbed and infiltration there is as slow as under páramo and pasture.

Water retention capacity, bulk density, and organic matter content

Volumetric soil moisture content at saturation was above 80% in all soils except the forest soil, which had values of 70-80% (Figure 9). Water retention was highest in unmanaged páramo soils, slightly lower in potato fields and pastures, and lowest in forest. Overall, water retention showed a small decrease with increasing depth.

At a tension of 7.5 kPa (pF 1.9), moisture contents were still as high as 70-80%, with the exception of the forest soil (50% moisture) and the top 10 cm of potato fields (50-60% moisture)(Figure 10).

Bulk densities were very low (0.35-0.65 g cm^{-3} in 0-5 cm) and increased gradually with depth (Figure 11). Soils of potato fields showed a more sudden increase from the loose top layer to the undisturbed soil underneath. Soil organic matter content was high (30-60% in 0-5 cm), decreased with depth, but was still 20-30% at 40-80 cm (Figure 12). Páramo soils had the lowest bulk density and the highest organic matter content.

Rooting was dense and reached great depth (usually >1 m) in all profiles, except in potato fields where roots were more superficial.

Bog ecosystems, found in depressions in the landscape, are distinct elements of the El Angel watershed, but no measurements of infiltration were made. Bogs and a few lakes cover a large, flat area at 3,750 m. These boggy areas contain important water reserves. At one site we sampled the organic top layer of the soil, which apparently floated on a water body. This soil contained the equivalent of six times its dry weight in water. Layers like this may be several meters deep (Cleef, 1981).

DISCUSSION

Water balance

Rainfall records confirm the altitudinal trend reported for the region (Nouvelot *et al*., 1994). Moreover, the number of raindays is higher and the average amount of rain per rainday is lower, indicating that rainfall is better distributed at high altitude. This contributes to the maintenance of high soil and atmospheric humidity, and facilitates infiltration. In a study of rainfall intensity and duration in Ecuador, Nouvelot *et al*. (1994) found that for intervals between 5 minutes and 1 day, the Andean sites had consistently lower rainfall intensity than other regions of the country.

Fog precipitation does occur in the watershed, and does not show the seasonal trend of rainfall (Figure 4). Therefore, fog precipitation may be beneficial for the water balance during rainless periods. Nonetheless, the total amount deposited is probably small. Actual deposition rates depend on the amount, structure, and texture of the vegetation, amount and sizes of fog droplets, and wind speed (Unsworth and Crossley, 1987). The amounts measured with the fog-catching device can be used for between-site comparisons, but the effectiveness of the vegetation in intercepting fog remains unknown. The collector (200 cm^2 vertical area) captured fog on a horizontal surface area of about 85 cm^2. If we simply assume that a vegetation could intercept similar amounts of water on similar surface areas, a fog catch of 8.5 ml would equal 1 mm of precipitation. Thus, catches of 200 ml mo^{-1}, which were common (Figure 4) would imply over 20 mm mo^{-1} of precipitation. This is a significant amount, especially in the dry season. However, it is difficult to imagine that the relatively smooth canopies of the watershed could be as efficient as a freestanding device designed to intercept fog water. In contrast, forests with high and rough canopies may be able to intercept greater amounts. At similar altitudes in Colombian Andean forests, Veneklaas and Van Ek (1990) found no evidence of fog precipitation, despite frequent fog. The droplet-size distribution of the fog may explain these observations. Cavelier and Goldstein (1989) suggested that small droplet size was responsible for much lower fog precipitation in an Andean forest compared to coastal forests in Colombia and Venezuela. The amounts of fog precipitation differ considerably between areas that are frequently immersed in cloud (Clark *et al.,* 1998), and the El Angel watershed seems to be an area with relatively low amounts.

Our estimate of potential evapotranspiration (monthly means at 3,000 m of 86 mm mo^{-1}) is similar to that of Ducrot (1993) (92 mm mo^{-1}) Penman's evapotranspiration estimate (Figure 5) applies to well-watered grassland. The vegetation in the El Angel watershed, with the exception of forest, is all short-statured and unlikely to experience soil water deficits (except perhaps due to low temperatures; Smith and Young 1987). However, páramo vegetation may not behave quite like a well-watered grassland. A páramo may have a reasonably high leaf area index (2-3 m^2 green leaf area per m^2 ground area; Hofstede *et al.* 1995) but the green leaves are sheltered from radiation and dry air by accumulated dead leaves. For several months after fire, the vegetation is greener but leaf area indices increase slowly. Evaporation from the soil surface, stimulated by the low albedo of the black soil, is probably important at that point.

A healthy potato crop is likely to transpire at higher rates than páramo vegetation. However, during land preparation, and the early and senescent stages of the crop, and after harvest, evapotranspiration may be less than in páramos or grasslands.

As indicated above, evapotranspiration is highly sensitive to the radiation climate. Therefore, cloudiness is a crucial factor. The presence of clouds is likely to differ greatly according to altitude, time of day, and season. Orographic clouds are formed in the course of the day, and the moisture they contain is largely evaporated water of local origin. Thus, land use trends in this and neighboring watersheds may potentially affect cloudiness and water balances through an increased or decreased contribution of moisture to these air masses, but speculation on these changes would be premature.

In summary, actual rates of evapotranspiration are likely to be lower than potential rates calculated with the Penman formula, and there is little reason to believe that agricultural lands, on average, have higher evapotranspiration than natural lands. Monitoring of soil water depletion under different land uses throughout the year are needed to provide an answer to this question.

Retention and flow of soil water

All soils studied were deep, organic soils with low bulk density. Our results show that these soils hold large amounts of water but are not highly conducive to water flow. The literature on high-altitude tropical volcanic soils is limited, but the unique properties of volcanic soils have been demonstrated a number of times (e.g., Maeda *et al.*, 1977; Warkentin, 1992). The large amounts of allophanes (amorphous aluminum silicates) in young Andepts are held responsible for many of those properties. The large water-holding capacity is because of the numerous micropores (Warkentin, 1992), and is expressed in the low bulk density and the high water retention at high tensions. Our results are consistent with these general trends. Similarly, Hofstede and Sevink (1995) reported high field water content in Colombian páramo, in both the wet (70-80%) and the dry (40-60%) seasons.

In contrast with our results, hydraulic conductivity of volcanic soils is generally reported to be high with 2-hour rates of 50-200 mm h^{-1} (Forsythe, 1975). Our results for páramo are an order of magnitude lower. The values estimated by Hofstede and Sevink (1995) in Colombian páramo vary around 50 mm h^{-1}, in closer agreement, but still significantly higher than, our observations, even if we calculate conductivity for the first 30 minutes of the experiment as Hofstede and Sevink did. A possible reason for the low conductivity in soils with high porosity, apart from the small size of the pores, is the high tortuosity of the flow paths (Oleschko and Chapa, 1989). Other than our infiltration measurements, the low hydraulic conductivity of the soils in the watershed is illustrated by the existence of long irrigation channels, which are cut into the soil without sealing. Although some losses occur, water flows in these channels for many kilometers.

The forest soil that we sampled formed an exception in our series of observations. It had a lower water-holding capacity and much higher hydraulic conductivity. Probably forest soils have more macropores because of macrofauna activity or of voids created by root mortality.

When páramos are converted to potato fields, tillage changes the topsoil structure in such a way that sorptivity and hydraulic conductivity increase, and water retention decreases. These changes, however, are largely reverted soon after grassland develops on fallowed fields. The soil below the plowing layer remains unaffected.

Volcanic soils not only contain large amounts of moisture at low tensions and under field conditions in general but also have high water retention under high tensions. A considerable proportion of the water is therefore unavailable for plant growth. However, because the total amount of water held is high, plant-available water in allophane soils is not low (Maeda *et al*., 1977). Water retention properties change drastically when soils are dried. Allophane soils shrink irreversibly and lose their capacity to retain water. Colmet-Daage (1967) observed water retention of 2.55 and 1.92 g g^{-1} (dry weight) in fresh soils at pFs of 2.5 and 4.2, but these values decreased to 0.36 and 0.33 g g^{-1} after the soil had been air-dried. The irreversibility of changes in physical properties upon drying is an important characteristic of allophane soils and needs to be taken into account in their management.

Moisture release curves are not usually published for volcanic soils. Maeda *et al.* (1977) stated that for volcanic soils these curves are not useful in predicting soil water behavior in the field, especially because of hysteresis and volume changes.

CONCLUSIONS

Features of the climate and soils of high Andean ecosystems are unique and undoubtedly important for the hydrological functioning of the watersheds. Compared to many other tropical regions, rainfall is not particularly high, but the low evapotranspiration of the mountain climate ensures a considerable water surplus. Soil physical properties help explain the fate of rainfall. First, sorptivity and hydraulic conductivity are low. If rainfall intensities were high, this would cause high rates of surface runoff and a great risk of erosion. In the field one can see little evidence of this, although we observed some gully erosion in potato fields that had been ploughed parallel to the slope. Surface runoff does also occur locally in natural páramo, but the soil surfaces are covered with prostrate plants, mosses, and lichens and the soil seems tightly held by the dense root mass. Generally, rainfall intensities are low enough for the water to infiltrate the soil, despite the low sorptivity.

Water that has infiltrated is effectively retained by the soil, because of its depth and water holding capacity. A páramo soil of 1.5 m depth and a volumetric water content of 80% stores an amount of water that is similar to the annual precipitation volume. Variation in the amount of water stored is small because the vegetation transpires relatively little and occurrences of rain and fog ensure some input even in the dry season. Water movement through the soil is slow because of the low hydraulic conductivity. This means potentially long lag periods between rainfall and streamflow. Unfortunately, the scarcity and poor quality of streamflow data for the El Angel river do not allow an analysis of streamflow regulation (Almeida, 1997). Interpretation of these data is further complicated by the large and varying amounts of irrigation water that are taken out of the tributaries at 10 or more points between 3,460 m and the hydrometric station at 2,850 m (Almeida, 1997). The buffering effect of high Andean ecosystems may not be as pronounced as has been suggested. Figure 13 shows precipitation and discharge data for the Rio Otún watershed in Colombia. The upper part of this watershed is covered by páramo, and water reserves exist in the form of lakes and bogs as in the El Angel watershed, but at lower altitudes forests are more important (Van der Weert *et al*., 1986). The meteorological conditions of the two watersheds are largely similar. Rainfall in the Otún watershed is a little higher, but Veneklaas and Van Ek (1990) considered fog precipitation in the Otún region to be negligible. The lag period of about 1-month between seasonal maxima and minima in precipitation and discharge is rather short. Although discharge in the driest month is as much as 44% of that in the wettest month, differences in precipitation are also small, with rainfall in the driest month at 27% of that in the wettest month. The steep slopes and the abundance of streams that make drainage path lengths short may explain the limited buffering of discharge of Andean landscapes. The many irrigation channels in the landscape of the El Angel watershed, which run perpendicular to the natural streams, shorten the drainage paths and the mean residence time of water in the páramo.

To assess the overall effect of land use, the proportions of the lands in different uses must also be considered (Table 3 – yet to be inserted). Agricultural land use (potato-pasture rotation) is rare at altitudes greater than 3500 m. Expansion of potato cropping at these altitudes is probably limited. Steep slopes hinder mechanization, whereas flat areas are often waterlogged. Frost damage is also a problem at high altitudes.The requirement of long fallow periods further limits the areal extension of potato fields at any point in time. One year (two crops) of potato followed by three years of fallow implies that a maximum of 25% of the landscape is potato fields.

The hydrological impact of cropping at high altitudes in the El Angel watershed is small. This conclusion is supported by the well-distributed precipitation and the nature of the changes in soil physical properties that are temporary and limited to the topsoil. Further, the area actually covered by potato crops is a small percentage of the total area and opportunities for expansion seem limited. The grasslands that accompany potato cultivation have a hydrological behavior similar to the páramo.

Given the distinct hydrological behavior of forest ecosystems, massive deforestation in the past has probably had more profound effects on watershed processes than the ongoing conversion of páramo to cropland and pastures. Reforestation of the least productive and most vulnerable lands is worth considering. Native species should be preferred above exotic species, especially in the more humid locations, because plantations of exotic species imply environmental risks (Hofstede, 1997). The hydrological role of water reserves in lakes and bog ecosystems merits investigation. The dynamics of water flows in these systems is certainly different from that of upland sloping lands. Artificial drainage of bogs modifies this dynamic behavior, and leads to degradation or even disappearance of these ecosystems.

Knowledge of volcanic soils suggests that caution is warranted in soil management to avoid irreversible changes in soil properties caused by drying. We did not study erosion, but it may be important if potato production were to be intensified. Disappearance of part of the soil profile would reduce the total amount of water stored and negatively affect its regulatory function.

Even if the hydrological impact of páramo conversion to agricultural lands is limited, other important reasons exist for conserving this ecosystem. Examples are the high biodiversity with many endemic species (Luteyn, 1992), the exceptionally large amounts of carbon stored in the soils (Figure 12), and tourism. Further discussion of these aspects is outside the scope of this paper.

The generally poor knowledge of high Andean hydrology is surprising, given the importance of water supply to often densely populated regions. We recommend further efforts in quantifying water balances and streamflow regulation. The best way to integrate this information is by using a spatial model, with inputs and validation based on long-term monitoring of climate and discharge rates. Although some of the currently available models have yielded promising results (e.g., ANSWERS, Beasley *et al*., 1980; TOPOG, O'Loughlin, 1990; LISEM, De Roo *et al*., 1996), the challenge for landscapes like that of the El Angel watershed is great. Apart from the lack of data, landscape heterogeneity is wide (complex and steep topography, small fields with different land uses), drainage pathways are often modified, and the physical properties of the soils (high porosity but low conductivity, strong hysteresis) differ greatly from those of the common soil types in temperate and tropical regions.

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Table 1.

Sampling sites for rain and fog precipitation in the el angel watershed, carchi, ecuador.

Sites	Coordinates	Code	Altitude (m)
Colegio "Alfonso Herrera", El Angel	77° 56'42'' W 0° 37'08'' N	ANG	3020
El Cerrote, casa	77° 55'02'' W 0° 40'24'' N	CC	3500
El Cerrote, medio	77° 54'17'' W 0° 40'33'' N	CM	3610
Loma Seca	77° 54'17'' W 0° 40'28'' N	LS	3650
Hacienda "Intihuasi"	78° 00'42'' W 0° 42'41'' N	INT	3550
San José	77° 54'14'' W 0° 38'51'' N	SJ	3355
El Salado	77° 58'01'' W 0° 42'13'' N	SAL	3460

Table 2.

Sampling sites for soil and vegetation parameters

Sites	Vegetation	Code	Altitude (m)
Páramo	typical páramo, Graminae + Espeletia	PAL	3575
	typical páramo, Graminae + Espeletia	PAH	3705
Potato field	potato, recently planted	PO1	3480
	potato, close to harvest	PO2	3500

Pasture	fallow, age 3 months	GR1	3450
	age 2 years	GR2	3510
	age >3 years	GR3	3450
Shrub páramo	shrub-invaded abandoned pasture	SHR	3540
Forest	cloud forest	FOR	3390

FIGURE LEGENDS

Figure 1. Rainfall at eight locations in the El Angel watershed, Ecuador, between 1 March and 30 November 1997. See Table 1 for location codes.

Figure 2. Relationship between rainfall and altitude for the months of May to September 1997. The broken line is calculated from graphs in Nouvelot *et al*. (1994), showing the relation of annual rainfall with altitude and the seasonal course of rainfall in the study region.

Figure 3. Number of days with more than 1 mm of rain at medium altitude (3,020 m, broken line) and high altitude (3,350-3,650 m, continuous line) in the El Angel watershed, Ecuador.

Figure 4. Fog catches at eight locations in the El Angel watershed, Ecuador, between 1 March and 30 November 1997. See Table 1 for location codes.

Figure 5. Estimated seasonal courses of potential evapotranspiration and rainfall at altitudes of 3,000, 3,500, and 4,000 m. Rainfall was calculated from graphs in Nouvelot *et al*. (1994), showing the relation of annual rainfall with altitude and the seasonal course of rainfall in the study region.

Figure 6. Sorptivity as measured in the field at nine locations in the El Angel watershed, Ecuador. See Table 2 for land use codes.

Figure 7. Hydraulic conductivity at different depths as measured in the field at nine locations. The values are based on the period between 45 and 120 min after commencing the infiltration experiment. Values of 0.1 mm h^{-1} and lower are not visible on the graph. See Table 2 for land use codes.

Figure 8. Saturated hydraulic conductivity as measured in the laboratory for soil samples taken at different depths, grouped by land use. The shrub-invaded grassland is included in the páramo group.

Figure 9. Volumetric soil moisture content at different depths after saturation in the laboratory. See Table 2 for land use codes.

Figure 10. Volumetric soil moisture content at different depths after equilibration at pF 1.9 in the laboratory. See Table 2 for land use codes.

Figure 11. Soil bulk density at different depths. See Table 2 for land use codes.

Figure 12. Soil organic matter content at different depths. Data for the PAH profile at 80-120 and 120-150 cm depth are not available. See Table 2 for land use codes.

Figure 13. Seasonal course of rainfall and discharge in the watershed of the Rio Otún (altitudes 1,550-5,000 m), Colombian Andes. Modified after Van der Weert *et al*. (1986).