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The Hydrology of Tropical Andean Ecosystems: Importance, Knowledge Status, and Perspectives

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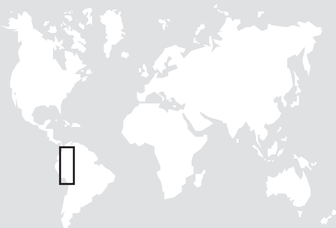

This article highlights the economic and ecological value of the water resource systems of Ecuador's páramo *and montane forest region and gives a description, based on a survey of recent literature, of the mechanisms controlling the rainfall–runoff process and how changes in land use alter the transformation. The review reveals that available understanding is partial, the result of individual and isolated research efforts, and is hindered by a lack of long-term complete and consistent data sets. Available knowledge does not yet permit up- and downscaling of findings. The article concludes by (1) citing some of the major gaps that impede hydrological understanding of the tropical Andean ecosystems and (2) proposing recommendations to speed up understanding and development of policies and measures to guarantee ecologically safe and sustainable development of the fragile water-based ecosystems of Ecuador's tropical Andean region.*

Keywords: Páramo*; montane forests; mountain hydrology; water cycle; Andes; Ecuador.*

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Water: a key economic and fragile ecological element in tropical Andean ecosystems

The water resource system fed by glaciers, *páramo,* and forests represents economic and ecological potential in the tropical Andes. In Ecuador, for example, the Andean highlands (locally called Sierra), comprising about 34% of the country's total area, are a unique natural resource system not only for freshwater but also for the sustainable development of society. The services and functions they provide encompass hydropower, irrigated agriculture, water for domestic and industrial uses, and ecoservices. If the water resources in these high mountain ecosystems are not properly developed and managed, they will rapidly decline, resulting not only in a loss in biodiversity but also in a distortion of the water-regulating capacity of the wet ecosystems of the Andes. A limited number of economic and ecological applications of Andean water resources, with a focus on Ecuador, are described here. Although the examples cited are from Ecuador, the services are likely to be common throughout the tropical Andes.

Ecuador's potential for generation of hydroelectric resources is of the order of 73,000 megawatts (MW), of which 30,000 MW is considered technically feasible while 21,000 MW seems to meet the economic criteria for profitability in the long term. Today only 1705 MW is generated, representing more than half of the current demand for electricity. These figures illustrate that the hydropower potential of Ecuador is enormous and far from developed. Factors hindering hydropower development are its huge initial investment costs and opposition from ecologists, who generally oppose construction of reservoirs and hydropower plants (Sternberg 2006). However, when planning, design, and implementation are preceded by research, ecological and environmental impacts can be anticipated and controlled (Sternberg 2008). According to Huizhou (2003), the negative impacts associated with hydroelectric plants can be minimized by implantation of small hydro plants, notwithstanding that the production costs of those plants are somewhat higher, between US$ 1500 and US$ 3000/installed kilowatt (kW) versus US$ 1000/installed kW for large plants. The advantages of small hydro plants are decentralized production, modular use, flexibility in operation, lower environmental impacts, and important socioeconomic benefits (Lipp 2007).

Another important economic function of water in Andean ecosystems is to irrigate agriculture in downstream areas. Runoff water is captured and fed to many agricultural fields to supplement rainfall. Roughly 97% of Ecuador's water resources in the mountain regions and the Guayas watershed in the Pacific coastal lowland, representing 10% of the country's total available water, are used to irrigate 540,000 ha (Herrmann 2002). Further development and intensification of the irrigated agricultural sector, accompanied by more efficient use of irrigation water, will help to boost economic activity in the Andean highlands. Also, most of Ecuador's population and its industrial sector depend in one way or another on water from the Sierra. Quito, for example, depends on the *páramo* for more than half of its water, and it is only as the

FIGURE 1 El Cajas National Park, Ecuador: a view of the *páramo*. (Photo by Wouter Buytaert)

FIGURE 2 Loja, Ecuador: a typical example of an Andean montane forest. (Photo by Wouter Buytaert)

Andean region becomes increasingly altered that attention is converging on this high-altitude water supply system (Buytaert et al 2006).

Tropical Andean ecosystems, which provide much ecological value, rely on the fragile water-based ecosystem of the region. The vast array of slopes, peaks, and isolated valleys yields a multiplicity of microhabitats that led to the evolution of an incredible number of plant and animal species (Mast et al 1996). Authors such as Mittermeier et al (1997) claim that the range of small to medium-size mammals in the Sierra is greater than that found on the extensive Amazon plain. Complexity, vastness and accessibility, and the relative low level of research funding invested in exploration of the biodiversity of the Andean *páramo* and forest systems in comparison to other research areas means that these ecosystems are far from understood. Similarly, the services provided by these ecosystems are greatly undervalued by society. In addition to vegetation that can be used directly by animals and humans, natural ecosystems produce a large variety of natural products that can be extracted from many hundreds of species, supplying diverse inputs to industry, including gums and exudates, essential oils and flavorings, resins and oleoresins, dyes, tannins, vegetable fats and waxes, insecticides, and multitudes of other compounds (Myers 1983; Leung and Foster 1996). Another important potential service of this natural humid high mountain ecosystem is its organic carbon storage (Hofstede 1995; Hofstede et al 2002, 2003). The revenue from the carbon-offset market could help to fuel international, national, and local initiatives that aim to conserve the *páramo* and forest ecosystems and also market ecosystem services.

It is likely that if no mitigation measures are taken, economic profits from the development of this high mountain region will be exceeded by the environmental costs caused by the degradation of environmental goods and services, basin regulation, and loss of water supply and associated hydropower potential. To avoid this, and to account for the potential impacts of climate change (Vuille et al 2008), developments must go hand in hand with the implementation of measures and mechanisms that conserve and protect the natural ecosystem. Sustainable development measures, conservation, and rehabilitation require, among other things, knowledge about the hydrology of natural and altered ecosystems and about relationships between the water system and anthropogenic and natural impacts. Given the importance of good understanding of the hydrology, the present article describes the state of the art of Andean *páramos* and forests (Figures 1, 2, respectively), based on a review of international literature, primarily related to Ecuador. The review is further used as a basis for the formulation of recommendations to enhance investigation of the hydrology of Andean wet ecosystems.

Knowledge status of the Andean *páramo* and montane forest hydrology

Páramos

Hydrology of natural páramos*:* According to Buytaert et al (2006) and Tobón and Arroyave (2007), the water yield of small *páramo* basins (<3 km^2) can reach 67% of total rainfall. These values are supported by the physical and chemical properties of the soil, the evapotranspiration rate, and the seasonality of precipitation. Andosols, being the main soils, are rich in allophanes (Fontes et al 2004; Buytaert et al 2005a), and the clay assemblage, together with the high organic matter accumulation, contributes to their water-holding capacity. According to Buytaert et al (2006), organic matter content can surpass 40% in the humid *páramos*, while in younger and dryer *páramos*, values in the range of 4–10% are common (Buytaert et al 2005a). Soil water content at saturation is normally above 80% (Buytaert et al 2006). Soil infiltration capacity and saturated hydraulic conductivity are higher than rainfall intensity. Buytaert et al (2007) observed rainfall intensities of 39.6 and 15.7 mm/h for 15- and 60-minute events. On the other hand, the saturated hydraulic conductivity of the soils is in the range of 10–60 mm/h (Poulenard et al 2001; Buytaert et al 2005b). Hortonian flow is practically nonexistent, and the runoff, considerably less than subsurface lateral flow, is generated by saturation excess.

Natural grassland evapotranspiration is relatively low. Hofstede (1995) and Buytaert et al (2004) report values in the range of 0.8–1.5 mm/d, which is due to a combination of low temperature and frequent occurrence of cloud cover, mist, and fog (Poulenard et al 2003). Precipitation in the *páramo* is fairly uniformly distributed. Célleri et al (2007) report that seasonality of rainfall hardly exists, which is supported by analysis of monthly rainfall in the Machangara *páramos*, South Ecuador, whereby each month, with the exception of June, was once the wettest month of the year in the period 1964–1998.

Effects of land use change on páramo *hydrology:* Poulenard et al (2001) studied the effects of burning and tillage on Andosols using a rainfall simulator. They found that runoff coefficients increased from 10–15% for *pajonal* to 30–50% for the altered plots. For subsequent rainfall events, runoff coefficients from *pajonal* plots remained below 25%, but values for the altered plots increased to 65–75%. While erosion in the altered plots reached values of 200–1400 g m^{-2}, soil loss in the *pajonal* plots was small. In addition, the direct exposure of dark Andosols to sunshine when converted to cropland results in drying, shrinkage, and water repellency, causing a sharp decline in soil water retention capacity, which in certain cases rises to 40% (Buytaert et al 2002; Poulenard et al 2004). This effect was also reported by Díaz and Paz (2002), who found a reduction in water content at saturation and wilting point from 100 and 77% to 85 and 63%, respectively. Using a paired catchment approach, Buytaert et al (2004) and Buytaert et al (2005b, 2005c) compared the hydrological response of a natural *páramo* with a cultivated catchment. A significant change in the hydrological regime was found, with a strong reduction in base flows (up to 50%) and an increase in peak flows (20%). Analyses of the flow duration curves indicated a loss of 40% in catchment regulation capacity.

Afforestation with pine produces strong effects as well. Farley et al (2004) found that soils under pine registered changes in water retention and organic carbon content. In their comparative study, upper and lower soil horizons in a 25-year-old plantation exhibited 35% and 57% less organic carbon than did soils in nearby *pajonal*, while soil moisture content at saturation was reduced by 14%, at 10 kPa negative soil water pressure by 39%, at 33 kPa by 55%, and at 1500 kPa by 62%. Buytaert et al (2007), comparing the outflow of a *páramo* and pine-afforested small-scale catchment, found a reduction of 50–66% in annual runoff.

The main effect of intensive grazing on the soils is an increase in bulk density associated with a change in pore size distribution. Quichimbo (2008) reported an increase from 0.40 g/cm^3 in *pajonal* to 0.62 g/cm^3 under grazing, and Díaz and Paz (2002) observed a change from 0.19–0.30 g/cm^3 to 0.81–0.86 g/cm^3 under long-term intensive grazing with a reduction in soil water retention.

Relations between water and other ecosystem services: Farley et al (2004) and Molina et al (2007) state that soil water retention in afforested *páramos* is reduced due to an overall loss of soil organic matter. Furthermore, Orrego and del Valle (2009) revealed that although pine plantations increase carbon stocks in aboveground biomass, they reduce the carbon stored in the soil. The main concern is that carbon is being transferred from a stable and safe reservoir, the soil, to biomass that is highly susceptible to loss by fire. Finally, after harvesting, the net effect on the ecosystem will be negative, since even the litter layer is usually burned before a new plantation is established. The long-term effect produced by the loss of soil carbon is a reduction of both the water retention capacity and regulation of the hydrological cycle (Brown et al 2000; Orrego et al 2003; Farley et al 2004; Orrego 2009).

Andean forests

Hydrology of Andean forests: Although only a few studies have reported on the hydrology and water cycle of Andean montane forests (Bruijnzeel 2004; Licata et al 2008; Vanclay 2009), it is recognized that they provide excellent regulation of the hydrological cycle. The water balance of upper and lower montane forests and cloud forests is quite different (Pizarro et al 2006). The permanent presence of fog and mist in cloud forests produces a reduction in incident solar radiation and an increase in relative humidity, which results in less loss by evaporation and transpiration (Bruijnzeel 2004). Moreover, frequent contact between forests and clouds produces increased interception and greater water input to the system. This results in high water yields from cloud forests. Tobón and Arroyave (2007) report a 55% water yield for a Colombian cloud forest. In his research on rainfall interception in Sierras de las Minas (2550 m), Guatemala, Holder (2006) found that cloud interception represents 7.4% of the total precipitation. However, interception during the dry season can rise to 19% of the total precipitation. On the other hand, cloud interception in upper and lower montane forests is negligible. For lower montane forests in South Ecuador, Fleischbein et al (2006) report a 40% interception loss out of 2500 mm of total precipitation, an estimated water yield of 41%, and a negligible cloud water capture.

Effects of land use change on Andean forest hydrology: Wilcke et al (2009) analyzed the effects of selective tree cutting on hydrological response and nutrient fluxes in a lower montane forest (1900–2200 m). Thirty percent of the study catchment was thinned. One year after trimming, a significant change in nutrient fluxes within the forest, with an increase in the cleared areas, was noticed. As a preliminary result of the conversion of Andean forest to pasture in South Ecuador, Crespo et al (2009) report that although the annual water yield of the converted plots was higher, the water regulation capacity decreased. In fact, while at the end of the dry season the forest catchments still had a noticeable base flow, the creeks draining the converted parcels were completely dry. Ataroff and Rada (2000), Hamza and Anderson (2005), Harden (2006), Pizarro et al (2006), and Molina et al (2007) studied the effects of conversion from forest to pastures and concluded that intensive grazing reduces interception and transpiration but increases runoff. Also, Gentry and Lopez-Parodi (1980, as cited by Tobón 2008) conclude that deforestation results in an increment in river discharge. Indeed, during the first 2–3 years after deforestation, it is possible to observe an increase in water yield. Lower water consumption, higher-than-average soil water content, and interception of the new land use/cover are the main processes responsible for this. In the medium and long term, primarily due to an increase in organic matter decomposition, soil compaction, and erosion, soil water retention significantly decreases, causing a reduction in water yield and loss in catchment regulation capacity characterized by higher peak and lower base flows (Bruijnzeel 2004; Tobón 2008).

Relations between water and other ecosystem services: The water cycle is closely linked to the forest's biophysical properties, especially to its vegetation, soils, and climate. Climate anomalies can affect both the water cycle and biodiversity. Pounds et al (1999) studied the composition and population size of lizards and frogs in Central America and found a dramatic reduction in species size in years with reduced cloud incidence. The associated increase in solar radiation and evapotranspiration and reduction in water input resulted in a reduction of the water yield.

Forest removal reduces the capacity of the ecosystem to capture atmospheric carbon and fix it to the biomass, the litter layer, and the soil (Letts 2003). In addition, deforestation produces large losses of biomass carbon stocks. In fact, Fehse et al (2002) demonstrate that the amount of aboveground biomass in secondary Andean forests is comparable to those in tropical rain forests. Their measurements exhibit 241 Mg ha^{-1} (for a 45-year-old *Alnus acuminata* forest) and 366 Mg ha^{-1} (for a mature *Polylepis incana* forest). In primary montane cloud forests in Costa Rica, Nadkarni et al (2004) found 523.2 Mg ha^{-1} of total aboveground biomass.

Finally, a relationship between precipitation and within-forest biodiversity is possible. Although there is a large spatial variability in throughfall, which depends on forest structure (Fleischbein et al 2005), its magnitude is very stable over time. Therefore, it is likely that this persistent variability contributes to the creation of ecological niches within the forest (Zimmermann et al 2007; Wilcke et al 2009).

The way forward

The literature reviewed offers insight primarily into the hydrology of Ecuador's Andean ecosystems and how the water cycle in those systems is affected by land use change. Knowledge about the likely impact of climate change on the response of those systems is less extensive. Uncertainties in the projections of global circulation models are still very large resulting in wide streamflow prediction ranges (Buytaert et al 2009).

Although it is clear that land use changes negatively affect the supply of water from Andean ecosystems, research results hardly make it possible to derive generic knowledge that can be applied in a rigorous way to ungauged catchments. Moreover, available knowledge does not yet permit upscaling of the findings derived at microscale to meso- and macroscale. The review clearly demonstrates that current knowledge is largely based on analysis of available observations and that, due to the lack of data covering the different ecosystems in the Andean mountain range and the limited use of mathematical models to complement data scarcity, many gaps in our knowledge still exist.

Gaps in knowledge, notwithstanding the technological advances in data monitoring and the increasing power of computers to facilitate data collection, processing, and application of complex hydrological models, can be summarized in the following nonexhaustive statements:

1. Lack of process knowledge hinders selection of the most appropriate hydrological modeling system for analyzing the water cycle in Andean ecosystems.
2. Lack of data not only obstructs advances in the understanding of the hydrology but also hinders model calibration and validation, dealing with temporal and spatial variability, and assessing model prediction uncertainties.
3. Ongoing debate focuses on whether more physics should be included in hydrological models so as to derive a better description of the processes and gain greater predictive capacity.
4. Current understanding does not yet permit extrapolating knowledge of processes at small scales to larger-scale catchments.

Realizing the multitude of unanswered research questions and the complexity of the hydrology of tropical

Andean ecosystems, we need to remain modest about what we really know and search for ways to improve hydrological knowledge of natural basins and basins impacted by global changes (land use change, management change, climate change). In this respect it is important to identify and quantify the synergy and feedback mechanisms between simultaneously occurring changes. Can synergy and feedback between externalities be measured and modeled? Can we, for example, with our current knowledge predict the changes in soil parameters and natural biota under conditions of climate change?

The challenges ahead are tremendous. In Ecuador and other Andean countries, population pressure on resources and the downstream demand for water resources and services will continue to grow and will likely be increasingly affected by climate change (Ruiz et al 2008). From the past we have learned that unscrupulous exploitation of the high-altitude *páramo* and montane forests results in the degradation and loss of unique ecosystems—the major water providers for the Andean highlands. The degree of degradation reached in an ecosystem limits the possibility to recover its water cycle regulation capacity. While degradation in midmountain areas can be partially recovered by restoring natural vegetation, the destruction of *páramo* soils is considered irreversible. This underscores the need to protect and conserve the *páramo* ecosystem. Today we realize that we lack the hydrological knowledge to formulate scientifically based appropriate mitigation strategies. Knowledge about rainfall–runoff transformation, hydrological processes, and water cycle controls is essential for the determination of water-provision services from Andean environments. This raises the following question: How can we accelerate the development of scientific knowledge and the transfer of knowledge and skills between academicians and practitioners?

To make real progress, produce generic knowledge, and enable the formulation of mitigation policies and measures, there is need for a structured and integrated approach requiring the following:

1. Pulling together financial resources from national and international public, nonpublic, and private organizations.
2. Developing integrated projects and networks that are a primary instrument for making progress in understanding and managing the complex hydrology of the high-altitude *páramo* and forest ecosystems. The aim should be to create critical mass and incentives, compelling researchers to work together and cooperate with national and international programs.
3. Formulating relevant global and detailed research questions and hypotheses centered on the integration of long-term planning strategies and medium-term allocation strategies, considering socioeconomic and ecological evolution and hydrological variability and taking account of global change.
4. Initiating a search for suitable and comparable study basins and enabling assessment of the hydrological effects of various impacts, identification of the processes controlling rainfall–runoff at different scales, the quantification of model parameters and how these vary in space and time, identification—as a function of the objective and data availability—of the most simple and suitable model structure, development and testing of procedures for model calibration, validation, and determination of the confidence limits in simulation results.
5. Using observation methods and monitoring and data processing techniques yielding data that are comparable between projects.
6. Organizing continuing education for knowledge and skill transfer to practitioners in the correct use of hydrological information and modeling tools and the development and testing of mitigation measures and policies.

If these objectives are met, sufficient progress that keeps pace with growing economic and social pressures can be made in predicting and managing the impacts that changes in land use, management, and climate will have on the water resources of the high-altitude Andean basins.

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