Watersheds of Quito:

A Consultancy to Bolster FONAG's Contribution

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Executive Summary

Quito obtains the bulk of its water from the glaciers, talus slopes and high grassy paramos that surround three large volcanoes (Cayambe, Antisana and Cotopaxi) on the eastern range of the Andes. All of them included within a National Protected Areas system.

For ten years, FONAG (El Fondo Para La Protección del Agua) has been operating in Quito, Ecuador, with funds from different organizations, such as the Quito water board (EMAAP-Q), the Quito Electric Company, the Tesalia Springs Co, the Cervecería Nacional, The Nature Conservancy, and the Swiss Cooperation Agency, with the purpose of improving water yields from these distant watersheds.

Some of the key activities that FONAG has managed so far are the establishment of 2,000 hectares of forest plantations, largely with the native *Polylepis* species, and the establishment of weather and soil moisture measuring stations, which have been set up to determine the impact that common land use practices have on water yields.

Since a sizeable amount of funding for FONAG comes from USAID-Ecuador and its enormous interest in FONAG's activities, USAID called on the International Programs of the US Forest Service to provide a technical team to provide technical assistance to FONAG as well as to review their field related work. The review was performed between February 14th and 25th in 2010.

Six days of this review were spent in the field, viewing plantation and instrument installation activities already undertaken by FONAG and getting familiar with the watersheds that FONAG needs to provide advice on. During this period, the consultants asked innumerable questions and were involved in just as many conversations with FONAG personnel. They also gave in-field demonstrations and advice on 20 different hydrological modeling and research projects that FONAG might run and led several hands-on activities to build, install and use some additional, simple, watershed monitoring tools. An additional one day workshop in Quito was provided to further explain the use of these instruments in studies and experiments and review the appropriate analyses.

Results of this review indicate that FONAG-managed tree planting has been very successful at getting the *Polylepis* plantations established. They have also done a good job of getting some fairly sophisticated weather stations and soil moisture monitoring stations installed and working correctly. Never-the-less, the watersheds they are dealing with are enormous and complex and, so far, FONAG has only a most basic understanding of the water budget in any of them. Furthermore, there is almost nothing known about how changes in land-use activities might affect any of their respective water budgets. FONAG personnel need to learn more about hydrological sampling procedures for mountainous and alpine meadow types of areas, and much more about experimental design and

evaluation, before they will be able to understand existing watershed conditions and confidently predict the water-yield impact of each of the principle land use alternatives for these high Andean watersheds.

One strongly recommended activity to enhance FONAG's capacity to do this includes a future visit by some FONAG staff to California this next summer to see how watershed monitoring and assessment is done in the mountains of this state. The consultants would be pleased to host this visit.

Some additional salient recommendations with respect to hydrology include the installation of recording stream gauges at key locations downstream of plantations to allow development of water budgets and models and the development of soil characteristic curves for soil water at each of the monitoring locations. Two general recommendations that can be made, with no need for study, are that all springs should be fenced to keep grazing animals out and that wild horse herds should be reduced.

Some recommendations were also made that did not pertain directly to hydrological aspects. One of these was the need to finish the growth tables for the Polylepis species that are being planted. This probably means sending FONAG personnel to Peru, where there are much older Polylepis plantations, to get measurements of said trees so that the capacity of these trees to sequester carbon with age can be assessed much more accurately. FONAG also needs to understand what impact the widespread *Stipa ichu* and *Calamagrostis spp.* bunch-grasses and the high organic matter content of the very deep Andept soils may already be providing both in terms of watershed yields and carbon sequestration.

Towards being able to satisfactorily address most of the different hydrological questions that were raised by this consultancy, it will be enormously beneficial for some FONAG personnel to become more experienced with appropriate hydrological instruments and sampling procedures, and experimental design, analysis and interpretation. Ways of gaining this experience, from simplest to most involved, include the following: reflecting on discussions that were held in the field; reviewing the 30 plus flip charts that were presented during the workshop; studying this present report and contemplating each observation and recommendation; reviewing the stacks of literature that were given to FONAG by the consultants as well as reading information on watersheds in the Andes available on the web; going to California this summer to see how hydrological experiments are set up in that state; participating in some international forest hydrology courses; having some additional consultancies by USFS hydrologists in Ecuador; or having some FONAG staff take additional graduate studies. Various combinations of these activities would, of course, also be possible and probably preferable.

Quito is the first Andean city in the modern era being assisted by USAID to improve its watershed situation. Never-the-less, Quito is only one of thirteen cities in the Andean Region that is being assisted by USAID for this purpose. These circumstances underline the importance of reinforcing FONAG's ability to formulate and share optimal watershed recommendations.

Finally, it must be stated that the FONAG team which led this review, and which accommodated the review team for nine ten-hour days, designed a perfect trip and could not possibly have been more considerate or interested. Some very productive and satisfying conversations took place and some excellent professional ties were made. Briefing and debriefing also went well with USAID personnel. The authors were very pleased to have been allowed to participate in a project that is of such transcendent

importance for Quito, Ecuador (and the planet) and look forward to a continued association with FONAG.

Background

Ecuador's capital, Quito has been growing very rapidly over the last 50 years as a result of a very high live birth rate (about 45/1000) over most of this period, a low mortality rate (about 11/1000) and massive migrations to the metropolitan area of Quito from the rural areas of the country which are incapable of accommodating population increases (ref. US State Department handbook on Ecuador).

Exact figures are not available, but it is estimated that currently Quito is at least 10 times the size that it was 50 years ago both in terms of the geographic footprint of the Metropolitan area and in terms of population. (note: the senior author of this paper has been coming to Quito off and on over the past 40 years). One of the chief resources that has allowed, and even promoted, this growth has been a reasonably good natural water supply, the resourcefulness of the Quito water board, (the Empresa Metropolitana de Alcantarillado y Agua Potable de Quito (or EMAAP-Q)), and some timely foreign aid and loans, mainly from BID (IDB), that has allowed Quito to plan for and build the infrastructure needed to supply this water.

None-the-less, getting all of the water needed to supply a burgeoning Quito has caused the water authorities to continually tap into additional sources. A brief history of the water supply situation for Quito is summed up, below:

From the earlier stages of the Incan Empire, through the colonial days of the Spanish conquest and right though until about 1900, most of the water for the city of Quito came, via gravity feed, from Pichincha, a volcanic mountain that looms over the city to the NW of Old Quito. This source is still estimated to supply about 0.25 m^3 of water per second to Quito. The next watersheds to be developed were from the slopes of the Atacazo, Sinchoaqua, Illinizas, Ruminahui and Cotopaxi volcanoes. The rivers and canals from these watersheds fed into the Pita and San Pedro rivers and eventually into the Puengasí pumping station where, with a little uphill pumping, this water could to supply the main Quito area between Old Quito and the current international airport, and an industrial area immediately to the south of Old Quito. These sources collectively supply about 1.75 m^3 of water/second. Most of this water came from within the Interandean zone, which is positioned in a rain shadow from the wet air masses coming out of both the Pacific and the Atlantic, but there is at least one open canal that reaches well around to the northeast side of the Cotopaxi Volcano and brings with it much of the water from that mountain which would have otherwise drained into the Amazon. Much of the water in that particular system is derived from melt-waters off the Cotopaxi glaciers. Capturing Cotopaxi's waters was a big boost for Quito, but by 1960 it was apparent that the fast-growing Quito would be requiring even more water. The next most accessible area for water is in the current day Coca-Cayambe Reserve. Naturally, this watershed also drains exclusively into the Amazon Basin. Capturing its waters, via a series of a dozen interconnected lakes and pipelines, has been the largest project undertaken by Quito to date and supplies Quito with drinking water at a rate of at 4m^3/second. In this system water must be pumped up about 800 meters on two occasions; first to get over the eastern range of the Andes, from a lake near

Papallacta over to the Guayllabamba basin and then, once again from Tumbaco up to Quito. The total distance water travels in this pipeline is about 125 km.

In the Coca Cayambe reserve, there is a second watershed that is also being used. This one, referred to as the Oyacachi Station, captures water coming from the NE side of the reserve and then pumps it over the northern edge of the reserve to Tabacundo where part of it is also used as irrigation water for the fertile, yet otherwise dry, Guayllabamba basin.

The last station to be built so far was the Antisana La Mica station. Basically one large lake, Lago La Mica, collects most of the free water coming off of the SE side of the Antisana Volcano, which would otherwise go into the Amazon, and pumps it to Quito via another pipeline. Differences from the Coca-Cayambe Reserve are that this effort yields about $2m^3$/second and that the distances are even greater….about 150 km. A large proportion of the water coming into La Mica is from snow melt off of the glaciers of Antisana.

During the time of this visit, the impression was given that there was enough water to meet most current needs. However, there were reports that only a few weeks earlier there had been a real shortage of water for hydroelectric purposes, especially at the Paute reservoir (near Cuenca) and also there have been a lot of prognostics that Quito may run out of sufficient drinking water in the next five to ten years. The ever increasing population is cited as one of the factors that will be contributing to this shortage, but an even larger factor (or at least one factor that has been getting a lot more media attention) is that the glacial caps on the big volcanoes of Ecuador have been retreating at an alarming rate. They are said to have lost one third of their mass in the past 20 years, and that the lower edge of these glaciers has been rising at a rate of 25 m in elevation each year. Much of this loss of glacial mass is attributed to a rise in temperatures and the average year-round temperatures in the Andean zone have, indeed, increased by 1.5^{o}C over the past 75 years. Some reports have also indicated that the water levels in the lakes have been dropping. Specifically, the water level in La Mica has been dropping at 5.0 m per year over the past several years.

Faced with the prospect that water supply may again become a serious problem limiting the well being of citizens in the Quito metropolitan area, EMAAPQ in concert with USAID, and several other pro-active organizations (TNC, and private and public water users), decided to band together and form and support a trust fund called FONAG (El Fondo Para La Proteccion del Agua). The main purpose of FONAG is to help carry out conservation projects and to improve the management of watersheds located in the aforementioned reserves.

Since FONAG was initiated in the year 2000, it has managed the reforestation of over 2000 hectares of high country paramo, a grass-land populated with the Stipa ichu and *Calamagrostis spp.* bunch grasses, in several critical watersheds. The tree species *Polylepis incana* (an Ecuadorean native) and *Polylepis racemosa* (actually from Peru) have been used for most of this planting. FONAG has also set up a fairly extensive network of meteorological and soil-water monitoring stations with the purpose of learning how different land use practices affect water yield in landscapes within these watersheds. The

government of Ecuador is counting on FONAG to help make wise decisions so that all of its principle watersheds yield a maximum amount of high-quality water.

Terms of Reference for this Consultancy

After about 10 years of FONAG operations, USAID asked the International Programs of the US Forest Service to provide a technical team to provide technical assistance to FONAG as well as to review their field related work. Specifically the terms of reference for this review were to perform the following functions:

1) Perform an evaluation of the forest plantations that have been established under FONAG's leadership in terms of their geographic location, their ability to conserve and protect water, the species that were used etc;
2) Offer comments with respect to the equipment that has been installed for monitoring soil water and offer comments with respect to the measurement protocols that are being employed and the way in which data are being analyzed;
3) Define appropriate research themes that involve climate change, and help prioritize the next areas that should be targeted for plantations.
4) See if the current system of monitoring, which is based roughly on the Principals, Criteria and Indicators (of the Forestry Stewardship Council) needs some reinforcement, and also help develop Criteria for evaluating biodiversity in these new plantations.

The Consultancy Team

The team selected to perform this consultancy included the following individuals, all from the US Forest Service.

Camille McCarthy, Team organizer. Camille has 12 years of experience working in environmental issues and rural development in Latin America, and is currently working with the International Programs Office of the US Forest Service in Washington DC.

Barry Hill, Regional Forest Hydrologist for R5 (California and the Pacific Islands). Barry has 27 years of experience working in forested watersheds to evaluate how well they are producing water. He worked for 15 years in the watersheds of the volcanic islands of Hawaii (then with USGS) and, since 2006, has worked with the Forest Service in California. He is a self-described "meadows" man.

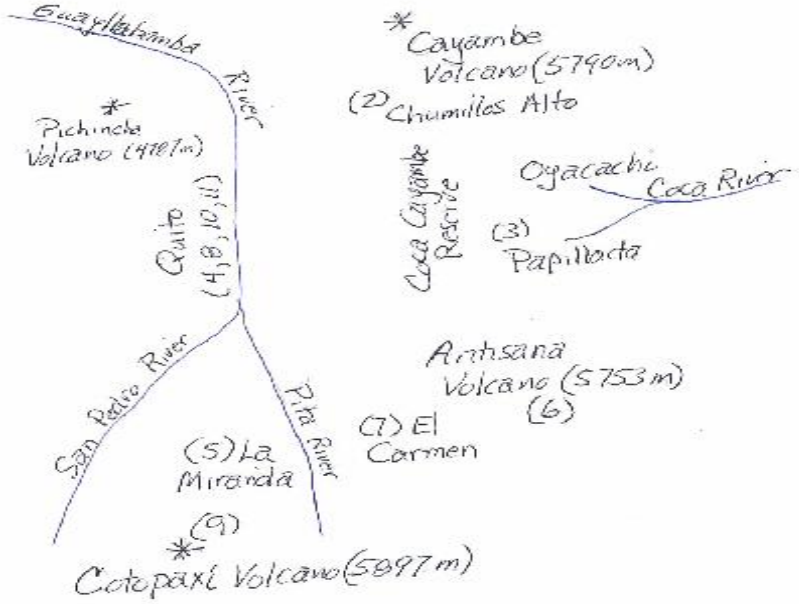
Phil Cannon, Regional Forest Pathologist for R5 (California and the Pacific Islands). Phil has 30 years of experience finding ways of growing trees well and spent 10 of these years in the Andean regions of Ecuador, Colombia and Peru. Strengths are in the areas of forest pathology, forest soils, forest genetics, silviculture and experimental design and analysis.

Chronological Outline of the Consultancy

The consultancy consisted of 12 very full days. Days 1 and 12 were travel days to and from Ecuador.

Days 2, 3, 5, 6, 7 and 9 were spent at field sites selected by FONAG (See Figure 1). Days 4, 8, 10 and 11 were spent in Quito. Day 4 was spent mainly learning about FONAG, its purpose and mode of operation. Day 8 was a presentation-preparation day. Day 10 was a six- hour presentation/workshop at FONAG and Day 11 was a wrap-up day at FONAG and final presentation day at USAID.

Figure 1. A schematic representation of all of the locations visited during the FONAG review (numbers indicate the trip day spent at the respective locate).



OBSERVATIONS

In this section, comments are offered on how FONAG is doing its job and suggestions are made for some additional activities that could help FONAG do its job even better. About 12 kilograms of selected books and reprints were brought down by the authors as a donation to the FONAG library. Occasionally there will be references to some of this literature.

How well does FONAG work with rural, indigenous communities to accomplish reforestation?

This part of the project seems to be coming very naturally to FONAG. Probably this is, in large measure, as a result of FONAG personnel, like Julio Rosero, who have a lot of experience (30 plus years) with tree planting in the Andes. Credit should also be given to a long list of forestry extension personnel that have been working in rural Ecuador for several decades with an intense passion for getting rural communities interested in tree planting activities. This group has certainly left very deep tracks in Ecuador. Of course, the community leadership also has to be recognized for its critical and amazing role that it plays in setting up reforestation as well. Leaders (forestry promoters) in three of the four plantation areas which we visited were impressively enthusiastic about the tree planting that each of their respective communities are doing (note: we did not see anyone at the forth plantation area that we visited as it was very remote). And, of course, credit must also be given to FONAG and to the institutions supporting FONAG for contributing funding so that this tree planting was, financially, a good deal for the community laborers planting these trees.

Special Note: The review team would be pleased if FONAG would re-thank Jose Manual Cobacango (President of Chumillos), Maria (Nursery Manager at Papallacta) and especially René (forestry promoter at El Carmen) for the time that they spent with us during this visit. Their comments were especially insightful and helped reinforce the consultant's impression that FONAG was dealing with communities in an especially good way.

How are the plantations doing?

At the first plantation, (Chumillos Alto), we visited, an exceptionally difficult (steep and convex) part of the plantation was deliberately chosen (because if any part of this plantation was to have low survival, this would be it) and a quick survival count was run. Each of four observers was asked to tally the number of surviving seedlings in a one-tenth ha. plot. Results were as follows: Oswaldo 16 seedlings, Phil 9, Alex 3, and Julio 6 for a total of 34 seedlings. Since there would have been 11 seedlings per plot if there was a 100 percent planting success (or a total of 44 seedlings from all 4 plots), this means that the survival rate, on this difficult site, was 77%. This seems good enough for this kind of reforestation. We did not do any more formal survival surveys on this trip, however, survival seemed to be at least this good on all of another dozen areas that we spot checked except in one small location (0.3 ha) where planting had apparently taken place in an area that was subject to waterlogging.

We asked some questions to the forest promoters at both Chumillos Alto and El Carmen to get an idea of the productivity that was being achieved in terms of tree planting. They indicated that villagers could make US$8.00 per day planting trees and that the expectation was that each villager would be planting

150 trees per day. They did acknowledge that there were some days where this level was not obtained. Still, when one couples this generally quite high number of trees planted and takes into consideration the very high survival rates (about 75-80%), this is extraordinary. Community tree planting success rates in many other parts of the Andes is almost never so high. For example, in the Department of Cusco, Peru, a study of tree planting success by Carlson et al showed that, on average, only two trees were likely to survive to age fifteen for each man-day invested in tree planting. It is speculated that community members work equally hard in both Ecuador and in Peru and most of the difference in survival rate is attributed to the much lower levels of available soil moisture in the Peruvian soils as compared with Ecuador's Andept soils (and, perhaps, Ecuador's more benign climatic conditions as well).

Finally some credit for this success with Polylepis has to be given to some excellent extension work. Approximately 12 years ago, the FAO Andean reforestation program (Programa Bosques, Arboles y Poblaciones Rurales) hired David Ocana to come work in Ecuador for three years. David had been working previously on reforestations projects in Peru (for about 20 years) and brought with him the knowledge and skills required for propagating *Polylepis racemosa* using vegetative propagation techniques. This technique was first transferred via workshops in several FAO-attended Ecuadorian communities and was picked up at that time by Julio Rosero (currently with FONAG) who has, in turn, trained several dozen more villagers in the ways of setting up Polylepis nurseries. One Polylepis nursery that we visited on this trip (Maria's place near Papallacta) had nearly a 100% success rate and was producing 34,000 rooted cuttings per year. Substantial kudos are due to FONAG for being able to quickly pick up and widely promote some very appropriate regeneration technology.

Although the Polylepis plantations were doing quite well in terms of survival (at least out to two or three years of age), the growth rate of these plantations was not especially fast - generally 20 cm of height growth each year and perhaps 2 mm in diameter growth over the same period. Currently the only thing done for these seedlings is to put in an 80 cm by 80 cm scalp into the ground at the planting spot (Note: a scalp consists of removing all the existing vegetation, including the root systems of said vegetation; it is usually effected by hoeing).

It is understood that FONAG, wanting to be environmentally savvy, is reluctant to use chemicals to try to accelerate the growth of these trees further. Still it is expected that Polylepis would grow substantially faster if other, more intensive, site prep measures were taken. These would include such things as the following:

1) clearing a larger planting spot area of competing vegetation - either by hoe or perhaps by using some systemic herbicides such as glyphosate(@Round-up);
2) loosening up the soil more in the vicinity of the planting spot, perhaps turning over ½ a meter^3 of soil at each planting site; and
3) fertilizing with chemicals including Nitrogen, Phosphorus, Potassium and Boron and, possibly, calcium.

If all of these site prep measure were taken, and optimized, it is expected that the young Polylepis trees might grow perhaps 5 to 10 times as fast (volume-wise) during their first three to four years. No effort will be made to push these prescriptions by these consultants, however, if FONAG does decide that it would like to see faster Polylepis growth, please let it be known.

Have the plantations been established in a way that will optimize water yields per unit of expense?

The plantations were established in a way that is exceptionally easy to administer (with 3m x 3m spacing between planting spots) and this simplicity certainly has some important merits. It is also especially easy to impress visitors with all the hard work that has been done. Never-the-less, it may, at least in some cases, turn out that a 3 x 3m spacing does not give the absolute best fit for the land. For example, for 500 or more years, many terraces in the Inca empire have been held in place by rows of Polylepis that were planted and cultivated on the last 2 to 5 meters of those terraces before they dropped down to the next terraces. The massive root systems of these trees are much appreciated for their capacity to bind the soil. Polylepis can also be used quite effectively as living fences and thereby separate pastures or crops from pastures. The advantages of using Polylepis in these kinds of configurations would be that it might provide many of the advantages of having Polylepis on the landscape to reduce erosion and perhaps help regulate groundwater flow. However, once these trees get big enough, say 2 meters tall or 8 cm in diameter at ground level, the landowners can still use the land in between these rows of Polylepis for other things like grazing cattle or cultivating food.

Although it is obvious that many villagers are real happy with the 8 dollars a day that they get for planting Polylepis, it is actually a little difficult to imagine that they are going to feel anywhere nearly as benevolent towards these 3m x 3m plantations a few years from now when they realize that they now have, say, 30% less land to use for farming or grazing their herds.

Are the plantations ever likely to be extensive enough to ever have a significant impact on water yields? Or on carbon sequestration? Or on slump?

So far the plantations that have been established via support from FONAG are still very young so their impact should not be expected to be too great, yet. As these plantations grow, their impact on water yields will become more pronounced. Where these plantations have and are being established over much of the land in the principal watersheds of a community (for example at El Carmen where 300 ha have already been planted and where the community expects to plant 2000 more of its remaining 4000 ha within the next few years) it can be expected that these plantations will have a very dominating effect on the amount of water that will be generated by these lands (similarly Chumillos Alto will be highly affected by their Polylepis plantations). However, the amount of land that is being planted by FONAG supported communities probably will not alter the amount of water reaching Quito or the Guayllabamba valley for at least two reasons: 1) Maximally only about 10,000 ha will be planted and this is only about 2.5% of the approximately 400,000 hectares encompassed by the watersheds that drain directly into some part of the Metropolitan Quito area; and 2) because the farming communities in the higher reaches of these watersheds are likely to use any surplus water generated by altered land use patterns for themselves.

In terms of carbon that will eventually be sequestered by FONAG-supported-Polylepis-plantations, that amount will depend on both the extent of these plantations and their growth rates. The rate of carbon sequestration by these forests will be discussed in some detail a few pages ahead. In some cases, FONAG may have to advise on a somewhat polemic issue, because the fastest growing Polylepis plantations may themselves be using a fair amount of water (how to estimate how much water these plantations are using will be discussed in the very next section).

It seems highly likely that Polylepis plantations could have a major role for reducing slump. This tree species produces a very robust root system. Certainly all of a land area does not have to be planted to avoid or reduce the incidence of slump. Usually slump prone areas can be identified in advance by some tell-tale incipient slump signs (slight inundations in the topography). Where this is possible it may be useful to just mark a line about 10 meters uphill from the point where the slump is anticipated and simply plant 5 to 10 rows of Polylepis above this line at a 3m x 3m spacing. Andept soils have thixotropic properties, which means that they behave like jello when they become saturated, and become exceptionally vulnerable to slump so tree planting to reduce slump should be given serious consideration in many of the watersheds that FONAG is watching.

How good a job is FONAG doing to monitor the effect of different land use options on water yield? Are there things that could be done to improve this monitoring?

This set of questions was tackled, with considerable zeal, by Barry Hill and therefore his contribution on this topic will be included in this report, *ver batum*. He begins with a little bit of discussion about the main landforms and soils that are found in those parts of the watersheds where the major amounts of water are being generated as this is important background information needed to take into account when optimizing the sampling approach needed to describe water movement in a watershed.

The watersheds of the northern Ecuadorian Andes include glaciers and talus slopes above altitudes of roughly 4,000 m and montane forests below elevations of approximately 3,400 m. A broad swath of native alpine grassland occurs between the forests and glaciers. These grasslands, known as paramos, are characterized by organic soils, native bunchgrass vegetation, and large capacities to both store and transmit water. Most of the current and potential land management activities in the watersheds near Quito are concentrated in the paramos. As a result, most of the recent hydrologic research conducted in Andean Ecuador has been focused on the paramos, which are considered to act as “sponges” that regulate the discharge of hillslope runoff to streams (Buytaert and others, 2005).

Fig. 2: a high-altitude paramo in Oyacachi zone

The unusual histic Andosol soils of the paramos naturally have a large water-holding capacity and relatively high permeability (Buytaert and others, 2005; Buytaert and others, 2006; Harden, 2006). As a result, the generally low-intensity year-round precipitation produces only limited amounts of overland flow (Poulenard and others, 2001), usually due to saturation of soils to the surface (saturation overland flow). The infiltration capacity of undisturbed paramo soils is generally not exceeded by rainfall rates.

Current land-use activities in the paramos include livestock grazing, cultivation, burning, and afforestation with native and non-native species. There are also some herds of wild horses. These activities can affect soil hydraulic properties through compaction and drying. Unlike soils in other parts of the world, disturbance tends to increase soil water holding capacities and permeabilities (Buytaert and others, 2005). In most hydrologic situations, these changes would tend to improve watershed regulation of streamflow. In the Ecuadorian Andes, however, the increased soil permeabilities, in combination with steep slopes, result in more rapid subsurface hillslope drainage, higher peak flows, and lower baseflows (Buytaert and others, 2006). The net effect is that less water is available for diversion into municipal water-supply systems.

All of the recent hydrologic research on the paramos has been conducted in southern Ecuador. Although southern Ecuador is generally similar to the more northern Quito area, the climate and soils conditions are somewhat drier, and results may not be completely representative of watersheds in northern Ecuador. Furthermore, although some studies of the hydrologic effects of non-native plantations (*Pinus*) have been conducted (Harden, 2006), no studies of native *Polylepis* plantations have been published.

Fig. 3: *Pinus radiata* plantation near Chumillos

Any attempt to assess land-use effects on the hydrology of the paramos will require a good understanding of the processes by which water moves through them. The recommendations for hydrologic monitoring, below, are intended to provide a basis for such an understanding.

Review of current monitoring systems

The following outline provides review comments on existing hydrologic monitoring conducted by FONAG, and recommendations for improvements, including web links to standards and guidelines for specific monitoring or analytical techniques.

1. Atmospheric monitoring of plantations and watersheds
   a. Current systems
      i. All locations use appropriate technology. All stations have rainfall gages with recorders. At least one station in each plantation or watershed monitors rainfall, relative humidity, air temperature, wind speed and direction, and atmospheric pressure. Most of these stations include solar radiation monitoring.
      ii. Installation locations are appropriate, with adequate heights above ground and vertical clearance.
      iii. Equipment is well-maintained. Data are downloaded frequently so that long periods of missing data are unlikely. Raingage catchments are free of leaves and other debris.
      iv. Parameters monitored are useful for computing evaportranspiration, which is necessary for the water budget and model analyses discussed below.
   b. Recommendations
      i. Add solar radiation monitoring equipment to sites that do not already have solar radiation monitoring.
      ii. Install Class A evaporation pans at some stations to provide a comparison for calculated values of evapotranspiration.

      http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V8W-46RVB5H-

6&_user=4250274&_coverDate=10%2F31%2F2002&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1227705174&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=2f1fce4ffb7764ac55283e80022385aa

iii. Tipping bucket rain gages require annual calibration. As an alternative, rainfall can be collected, stored, and measured after passing through the tipping bucket.

http://www.waterlog.com/Products/Sensors.html

http://www.hydroserv.com.au/products/meteo.shtml

http://www.sutron.com/

iv. Add real-time capability via satellites, radio, cell phones, or meteor burst technology to improve data quality and reduce chances for missing record.

v. Additional monitoring stations in the Antizana area after ownership is transferred.

Fig. 4: A meteorological station at Oyacachi

2. Subsurface monitoring of plantations
   a. Current systems
      i. TDR technology is a good choice for range of data and reliability.

      http://www.cprl.ars.usda.gov/wmru/pdfs/DekkerEvettTDR.pdf

      ii. Monitoring depths (30, 60, and 90 cm) are generally good.
      iii. Chumillos soil-moisture monitoring is a good use of paired plots.
   b. Recommendations
      i. Develop soil characteristic curves (soil moisture vs. pressure) for representative soils in plantations and critical watersheds.

      http://www.css.cornell.edu/faculty/hmv1/watrsoil/charcurv.htm

ii. Install lowest TDR sensors at expected lower limit of rooting zone (about 2 m).

iii. Locate installations at paired locations to minimize effects of other factors (slope, elevation).

iv. Install piezometers and monitoring wells with submersible transducers:

ftp://ftp-fc.sc.egov.usda.gov/NSSC/wells/monitoring_wells.pdf

Fig. 5: Installing a piezometer at La Miranda

3. Surface water monitoring
   a. Current systems
      i. Surface float method with cross sections is reasonable and cost-effective.
      ii. Method is in current use by USGS for floods that cannot be measured with current meters or acoustic equipment.

Fig. 6: A surface-velocity float measurement at Cotopaxi

   b. Recommendations
      i. Find gage locations with bedrock controls or build weirs.
      ii. Use volumetric measurements for very low flows.
      iii. Use current-meter measurements for most situations.

http://ga.water.usgs.gov/edu/streamflow2.html

      iv. Construct stage-discharge relations for gaged sites.

http://ga.water.usgs.gov/edu/streamflow1.html

v. Install continuous stage monitors (submerisible or dry transducers).
vi. Use critical-depth measurements for high flows that cannot be safely measured with current meters.
vii. Runoff plots or small crest-stage gages can be used to evaluate the areal extent of surface runoff. If used in conjunction with subsurface monitoring techniques such as monitoring wells and piezometers, the processes generating surface runoff (infiltration-excess vs. saturation overland flow) can be determined.

Recommendations for analyses of land-use effects on water yield

The ultimate goal of hydrologic monitoring is to evaluate the effects of land uses on water yields. Three approaches for such evaluations are described below. The approaches vary in terms of spatial scale and the monitoring efforts required, and also in terms of their potential usefulness for evaluating and predicting land-use effects on water yield. The descriptions below include brief analyses of the benefits and limitations of each approach. As a general consideration, effective land management to improve water yield requires a conceptual understanding of the processes and pathways by which rainfall and snowmelt generate streamflow.

1. Water budgets

http://www.brown.edu/Courses/GE0158/web2_revised/dennis/pages/budget.html

Water budgets are quantitative comparisons of hydrologic inputs, outputs, and changes in storage specific to an area and a period of time. Water budgets are most easily developed for natural hydrographic units such as watersheds, but can be developed for smaller hillslope or plot areas if boundary conditions can be defined through monitoring. Water budgets allow hydrologic changes resulting from land-use changes to be detected and quantified through comparison of managed and unmanaged areas. The primary advantage of the water-budget approach is that it can be applied to small areas where changes in land use have been or will be implemented, for example, pine and polylepis plantations. The monitoring effort required to do a complete water budget is high, particularly at the hillslope scale where boundary conditions must be defined by monitoring of subsurface and surface water movement.

a. Inputs
   i. Rainfall—excellent existing coverage
   ii. Groundwater—use hydraulic head data from wells and piezometers to determine water-table elevation, directions of flow, and estimated inflow using Darcian approach (2 to 8 installations per plot)
b. Changes in storage
   i. Soil moisture—Use TDR measurements to estimate storage at 0 to 0.3 bars (available for groundwater drainage and streamflow), 0.3 to 15 bars (available to plants), and >15 bars (unavailable) (3 locations per plot)

ii. Groundwater—same as for inputs

c. Outputs

i. Evapotranspiration—determine stomatal conductivity and use Penman-Monteith equation to estimate for pine, polylepis, and stipa

http://www.fao.org/docrep/X0490E/x0490e06.htm

ii. Groundwater—same as for inputs

iii. Surface runoff—runoff plots with volumetric measurements (minimum of one location per plot)

2. Paired watersheds

http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=7207219

The paired watershed approach is the classic approach to evaluating effects of land uses in forest hydrology. The approach requires finding two nearby watersheds that are similar in all factors likely to affect water yield (slope, aspect, elevation, vegetation, geology, rainfall) except the land use of interest. This requirement limits the usefulness of the paired watershed approach in many areas owing to difficulties in identifying suitable paired watersheds. The monitoring effort is restricted to rainfall (1 to 3 stations per watershed) and streamflow (one station at the mouth of each watershed). Watersheds are treated as "black boxes," and no information on flow paths or processes is obtained.

3. Watershed modeling (Topmodel, PRMS, etc.)

http://www.epa.gov/nrmrl/pubs/600r05149/600r05149topmodel.pdf

http://water.usgs.gov/cgi-bin/man_wrdapp?prms

Watershed models use time-series rainfall/snowmelt and streamflow data to infer flow pathways and processes within watersheds, and are therefore useful for predicting how changes in land use will affect watershed hydrology and water yield. Monitoring and data collection requirements are comparable to the water-budget approach, and a minimum of one streamflow gage at the mouth of the watershed is required. A minimum of one year of rainfall/snowmelt and streamflow data are needed for model development. Calibration and validation periods of one year each are generally required after model development. Empirical relations between land uses and hydrologic effects are needed to use models to analyze land-use scenarios. Although watershed models require substantial and lengthy efforts, they provide a means of evaluating the effects of land-use scenarios before decisions are made, which makes them an effective watershed management tool.

i. Rain gages (1 to 3 per watershed)

ii. Stream gages (1 per watershed)

iii. Soil moisture and groundwater monitoring (5 to 30 locations per watershed)
iv. Soil hydraulic properties—infiltration, specific yield, soil characteristic curves, hydraulic conductivity (minimum of 3 samples for each major soil type)
v. Air temperature, solar radiation, relative humidity, wind speed and direction, and atmospheric pressure data are needed to quantify snowmelt and evapotranspiration.

https://info.ngwa.org/GWOL/pdf/872944333.PDF

http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=C71B965061E897637D20734AB9DBAA31?purl=/838946-VLIWDs/native/

What does FONAG know about Andept soils, their properties, and ways that they can and ways they probably should not be manipulated?

As was alluded to in the previous section, essentially all of the soils in the watershed areas where FONAG is working with are Andepts and in most of the areas where we went the very dark A horizon of these andepts extended down at least three meters so this is the predominating feature of these soils. FONAG staff did not indicate much familiarity with the special nature of these soils so some of their characteristics ended up being a point of long discussion during some of the field visits. These soils are very unusual, marvelous and amazing. And a lot has been written about them. No attempt will be made to review all of the literature about these soils here. For the Spanish reader who would like to learn a lot more about where these soils came from and some of their physical and chemical properties several chapters in the following reference could be instructive.

Cannon, P. C. 1983. Fertilizacion Forestal en El Cauca y El Valle. Investigacion Forestal, Carton de Colombia.

Some of the absolutely outstanding features of these soils include the following. When young (less that a few thousand years since the volcanic ash was deposited) and when uncompacted (as by grazing or vehicular traffic) the bulk density of these soils can be exceptionally low (eg less than 0.9 gm/cm3. Also, because of their chemistry (commonly a high Aluminum saturation) and the low temperature conditions that prevail at altitudes above 3,500 masl (and all of FONAGS activities are above 3,500 masl), organic matter cannot decompose anywhere nearly as quickly as it can accumulate. As a consequence, Andept soils (that have been untampered with by man or uncompacted by grazing cattle) tend to have exceptionally high organic matter contents. Usually these OM contents in the top horizons will range from 20 to 25% of the total dry weight of the soil. Furthermore, these Andept soils, because of both the inorganic and inorganic chemical properties of the soil and the exceptionally low bulk densities, tend to be able to store very high amounts of water in them before the water can drain through the soil. Indeed an Andept soil at field capacity (0.3 bars of tension) will hold about twice as much water as a clay soil at field capacity and at least ten times as much water as sandy soil at field capacity. The moisture release

curves of Andept soils are also exceptional with a fixed volume of Andept soil providing approximately double the amount of plant-available water as a clay soil and approximately 100 times as much plant-available water as a sandy soil. These high moisture retention capacities may at first appear to be quite desirable, and they are, when one is trying to grow plants or trees on such soils, but when it comes to free-water getting down through these dark organic layers of the Andept down into the water table, these soils may be exceptionally stingy. Indeed it is suspected that with the low amounts of amounts of rainfall in the Interandean Zone, and the drizzly form in which most of it arrives, it is doubtful that more than a tiny fraction of the precipitation coming onto perhaps as much as 95% of the paramo actually makes it down through the soil profile to the water table.

Indeed it is only in the base of these valleys, where the streams emerge, that it is apparent that soil saturation has finally been achieved. In is only in this situation, which appeared to occupy less than 5% of the total area of these high Andean watersheds, that it could be estimated that most precipitation will be transmitted into the watershed. Studies really do need to be run to check this out. The methods outlined in the previous section can help provide a much more exact representation of what happens with precipitation in these Andept soils. Obviously knowing exactly what the water situation is at present with these soils will have a huge impact on deciding what land management changes, if any, would be important to put into action in the future.

There is one very important note to make here. The outstandingly benign features of undisturbed Andept soils have been referred to above. It is worth also noting, however, that many of these outstanding features deteriorate with alarming rapidity when these soils are compacted or tilled and exposed to the elements. Organic matter contents can drop quickly as mineralization rates rise swiftly due to direct exposure to sunlight and compaction can quickly lower the high moisture retaining capacity of these soils. In many places, (in fact most places), that we visited during this consultancy, there had already been a history of grazing and in most cases this grazing is continuing into the present and the foreseeable future. (Note: the bulk-density sampling device, which was demonstrated on several occasions, provides an excellent tool for evaluating the amount of compaction that has gone on).

The exact impact that all this grazing (and burning and tree planting and tillage) has/is having on water yields in these Andept soils is extremely important to understand. The hydrological protocols outlined in the previous section provide some of the tools that could be used to make studies to find exact answers to these questions. If a more immediate idea of the importance of tillage, grazing and burning is needed, the reader is referred to the following articles:

Buytaert, Wouter, Celleri, Rolando, De Bievre, Bert, Cisneros, Felipe, Wyseure, Guido, Deckers, Jozef, and Hofstede, Robert, 2006, Human impact on the hydrology of the Andean paramos: Earth-Science Reviews 79:53-72.

Buytaert, W., Iniguez, V., Celleri, R., De Bievre, B., Wyseure, G., and Deckers, J., 2006, Analysis of the water balance of small paramo catchments in south Ecuador, in: Krecek, J., and Haigh, M. (eds.), Environmental role of wetlands in headwaters, Springer, Netherlands, p. 271-281.

Buytaert, W., Wyseure, G., De Bievre, B., and Deckers, J., 2005, The effect of land-use changes on the hydrological behaviour of Histic Andosols in south Ecuador: Hydrological Processes 19: 3985-3997.

Harden, C.P., 2006, Human impacts on headwater fluvial systems in the northern and central Andes: Geomorphology 79(3-4):249-263.

Poulenard, Jerome, Podwojewski, Pascal, Janeau, Jean-Louis, and Collinet, Jean, 2001, Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian paramo: effect of tillage and burning: Catena 45: 185-207.

Copies of each of these articles were left for the FONAG library.

There is no doubt that at some point FONAG is going to be called on to report results from their own hydrological studies performed by them within their zone of influence. During this brief consultancy a very large number of possible hydrologic studies were discussed and several opportunities were taken to set up instrumentation for making hydrologic measurements. Never-the-less, this consultancy was just a quick stint and it would be unrealistic to suppose that FONAG personnel completely captured all of the ideas or protocols that were discussed or demonstrated.

As such, some additional experience would be desirable for FONAG personnel and particularly in the arena of evaluating water yields in mountain meadow situations. Coincidently, Barry has planned to spend about six weeks this summer doing evaluations of water budgets in the meadows of The Sierra Nevada mountains (this subject is of utmost interest to California Governor Arnold Schwarzenegger). He has indicated that he would be willing to host a small contingent of FONAG personnel to join him as he conducts this study. Funding for flights, per diem, and lodging would have to come from other sources (USAID or FONAG funds), but all training and most within-California transportation would be on the house.

What does FONAG know about Stipa ichu and Calamagrostis grasses, their growth habits and special characteristics, and ways that can be manipulated to increase water yields, and other ways that they probably should not be manipulated?

Stipa ichu, and *Calamogrostis intermedia*, are the bunch grasses or paramo tussock grasses that cover at least 90% of the high elevation Andean regions where FONAG is operating.

Julio Rosero, who has been working in forestry in Ecuador for a long time and has taken the lead for carrying out many of FONAGs tree planting projects has been working around *Stipa ichu/ Calamagrostis spp.* much of his life. He knows how much of it has to be cleared if trees are to be planted and expected to survive. All of the field personnel at FONAG are used to seeing *Stipa ichu* all of the time when they are in the field and they are also aware of some of the management activities that Ecuadorian cowboys go through to make sure that the grass blades being produced by this grass are in a palatable enough and abundant enough condition for their cattle. Burning is the main, time-tested approach for getting rid of the old silica-rich grass blades and getting the tussock bunches to shoot out a new crop of young leaves. Never-the-less, there are some very progressive communities, like El Carmen, that have now embraced

the concept of paddock fencing and forced pasture rotation. Where pasture rotation is used, the *Stipa ichu* is cropped back very hard until only a small tuft of 15 cm tall blades is left. If the cattle are removed at this time, these tufts will quickly leaf out and resume essentially their original size and with all green leaves. In spite of the fact that some of these new pasture management tips are becoming known, it is doubtful that Julio or anyone else at FONAG has an in depth understanding of how *Stipa ichu* affects water movement into and through the soil, how *Stipa ichu* affects the amount of organic matter that is built up in these soils and how either fire, or grazing or tillage or any other activity that alters the condition of these grasses affect either this water situation or this carbon situation. Since water yield and carbon sequestration are at the core of things FONAG needs to know, it behooves them to know a lot more about *Stipa ichu* and especially how changes in land use can alter the influence that *Stipa ichu* has on water yields and carbon sequestration.

It is beyond the scope of this current consultancy (and outside the experience of the consultants) to offer much accurate information on these subjects. Never-the-less, there are a few salient features that were noticed about *Stipa ichu* that may be worth studying in more depth. One of the things noticed was that the root system of *Stipa ichu* is impressively pervasive and thick. When we were making the auger pits to set up the piezometers (at Miranda) it was always necessary to remove the first 15 cm of soil just to get the auger started. Fifteen cm was about the depth to which the roots were penetrating at this site but they formed a dense mat in this top 15 cm. It was the impression of at of the consultants that the *Stipa ichu* grass roots might be intercepting essentially 100% of the moisture that might be arriving at this site during almost the entire year.

This is one of the reasons that removal of slightly more *Stipa ichu* grass at the time of plantation establishment would be expected to allow the Polylepis cuttings to grow substantially more quickly (for example, if a 2.25 sq meter scalp were used (1.5m x 1.5m) instead of the current 0.64 sq meter scalp (0.8m x 0.8m) the Polylepis cutting might have nearly 4 times as much water available to it to use for growth.

Of course when one reads about the detrimental effects that tillage can have on the structure and water holding capacity of the exposed Andept soils, one might be reluctant to expose these soils. In this situation one might prefer to use a herbicide which would kill the root systems of the *Calamagrostis* and *Stipa ichu* but will not alter the soil or lead to the removal of any of the organic material provided by these grasses. (Note: in another lifetime, one of the consultants found that killing Calamagrostis at a planting spot using the systemic herbicide glyphosate (@Roundup) led to a fabulous growth response of planted coniferous seedlings as compared to coniferous growth on untreated planting spots. Note: if glyphosate is applied after the Polylepis have been planted it will be important to use a directed spray or wick applicators to be sure that the Polylepis seedlings get no herbicide on their leaves. Work with this chemical should not be done when wind speeds exceed 10 km/hr.)

One caution about reducing the amount of *Stipa ichu* or *Calamagrostis* on the landscape; it could lead to replacement by a weed species which could have many properties that may be far less desirable than either of these grasses. One of the invasive plant groups that we found during this trip were the cushion paramo plants, *Plantago rigida* and *Azorella pediculata*. These plants are resupinate (they grow pressed

against the ground) and have no forage value. Also, where they become established, their root systems tend to form a very deep mat - up to 50 cm deep of nothing but tough, 0.3 cm diameter, roots. One very ironic feature is that where the ground has been locked down with *Azorella pediculata* there is often a lot of free water at or very near the surface. It is suspected that during heavy rainfall events (and especially if the ground is already close to saturation) a lot of water landing on Azorella will simply roll right off. Ironically, it may turn out that these small patches of Azorella end up acting as almost impermeable surfaces. If this is true, then these patches of Azorella could become significant sources of water in some of these Andean Paramos. Also there would be very little if any erosion from this so the water coming off the Azorella patches could be quite clear.

One final note about *Stipa ichu* grass; it is a grass that is extraordinarily well adapted to the extremely harsh climate of the paramos. Estimates of the amount of below-ground biomass are not available, but Ramsey and Oxley found that above ground net productivity for this grass was, on average 4.7 tons per hectare per year.

P.M. Ramsey and E.R.B. Oxley. Primary productivity in Andean Grasslands of Central Ecuador. http://ww.bioone.org/doi/abs/10.1659/0276-4741(2001)

Furthermore, as previously mentioned, on Andept soils ,where Stipa ichu and Calamagrostis grow well , soils often develop a 25% organic matter content. If the first 3 meters of the profiles of these soils have this high an organic matter content then these soils are already storing about 7,500 tons of carbon per hectare in them. It would almost seem that a more important mission that FONAG might be able to contribute with respect to carbon is to make sure that this carbon pool is not released. It would also behoove FONAG to carefully evaluate whether Polylepis plantations could possibly be expected to fix more carbon than what is already being stored annually by *Stipa ichu* and *Calamagrostis*.

What does FONAG know about cattle management when cattle are grazing in a watershed where water must be collected?

Ecuadorians have a long history of grazing cattle and many people in this country know a great deal about what can be done to raise a healthy herd. Still there are signs that new innovations (rotating pastures, new grass seed mixes) are continually being explored. When it comes to the influence of cattle grazing on water yields, however, the knowledge base about the influence of cattle does not appear to be very deep. For example, Oswaldo indicated that FONAG has been in the process of trying to purchase 10 very large cattle ranches that are in the Antisana-La Mica area. There is a general concept that by removing cattle and perhaps by planting Polylepis trees that the amount of water that will make it down through the watershed to La Mica should increase the amount of water that reaches the La Mica lake. Never-the-less, so far, there is no assurance that this is really so and there absolutely no idea by how much watershed yields should be expected to increase (or decrease!) if either or both of these practices were to take place.

Even Barry was at once puzzled and fascinated by this conundrum and spent a lot of time thinking about what studies should be undertaken to find the answers to these important questions. In a previous

section, and during much of the time we were in Ecuador, he described the sampling procedures that could be used to find answers to this question.

What is the level of understanding of how water moves into the aquifers under the principle different land use patterns found in the Alto Andino zone of Ecuador?

At best, this understanding could be considered incomplete. It seems very likely that for each of the large glaciated volcanoes that we saw there is a lot of water coming off of the glaciers. There is also, probably, a lot of water that is going into the ground on the talus slopes that (found below the glaciers but above the zone where the Andept soils begin). Some of the water from the volcanoes is held above ground in streams, but then there is another portion (unknown in its magnitude and its exact location) that just ducks underground and works its way down-slope through unseen aquifers. Occasionally these aquifers work their way back to the surface and often re-appear as springs. Since springs are wet and since, as mentioned earlier, Andept soils have thixotrophic properties, there are often some major landslides associated where these aquifers re-emerge to the surface, especially on steeper ground.

Barry was fairly adamant that FONAG and their partners could do themselves a substantial favor by protecting all springs from compaction from cattle. The scene that we saw on perhaps 20 occasions during this visit was that the springs were unfenced. The cattle were coming into these springs to get water and, in fact, were doing a lot of compaction. Barry's point was that compacted springs will eventually get plugged up. To avoid this happening, Barry strongly recommended fencing off all springs (at least ten meters above the point where any sinkage (caused by insipient slump) is observable in the topography). To provide water for the cattle he prescribed the use of a gravity-fed pipe from the spring to a water trough at least 20 meters beyond the fence-line. (Note: salt-licks, should be placed at least another 500 meters away from that).

What does FONAG understand about how to set up statistically defensible experiments to compare different land use practices for their impact on water yields?

Some FONAG personnel had some pretty good ideas about forest sampling (see next section on carbon sequestration), but there seemed to be a general lack of information and experience about how to conduct statistically defensible (credible) forestry experiments. For this reason, a fair amount of time was spent describing how to set up experiments especially when it was desirable to find out what the influence of different land-use practice might have on water yield. Indeed, during the six hour workshop that we held on Day 10, about half of this time was spent going over flip chart drawings that had been prepared to help show good experimental designs that will help FONAG find answers to many of their critical questions. It is hoped that those flip chart drawings will be maintained and referred to by FONAG personnel from time to time.

Additionally, in the field, a great amount of time was spent laying out possible experiments that could be set up to find answers to these questions. In some cases, and especially where hydrological measurements were required, Barry guided the group through the installation of such equipment as piezometers and wells (useful for determining underground depth and movement of water tables) and showed the group how to estimate stream flow volumes using natural control sections.

To the degree that was possible, we tried to set up experiments in areas where there were already different land use practices underway and also where some instrumentation had already been set up. In fact, nearly 20 different experiments were discussed.

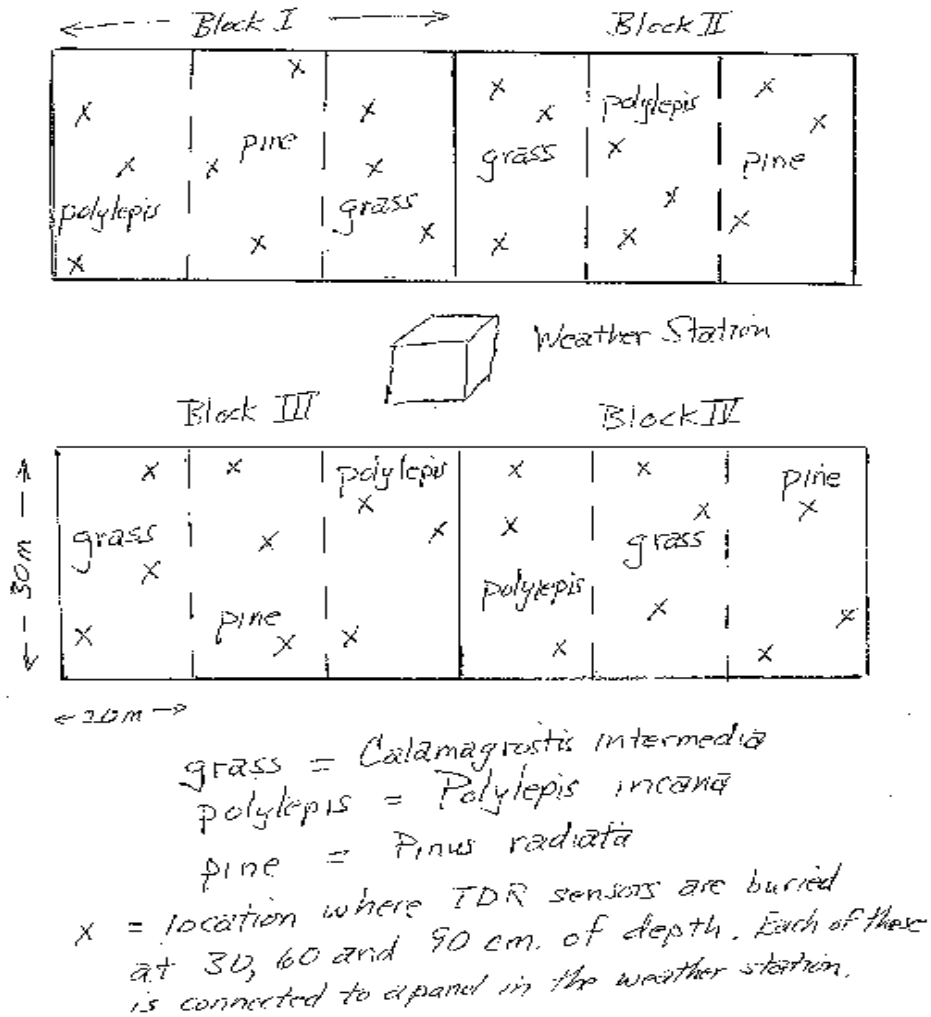
To graphically depict and verbally describe each of these experiments in this report would require about 100 pages and more time than any of the consultants has. Besides, FONAG personnel already have the mega flip chart which diagrams most of these experiments. Never-the-less, as an example, and because knowing how to determine and compare the impact of different land use practices on water yield will be so important for FONAG, let us consider the design of one experiment. In this experiment let's assume we would like to pin down, in a statistically defensible experiment, the impact of three different possible land use scenarios on water yield: a field of ungrazed Stipa ichu grassland; a *Polylepis incana* plantation and a *Pinus radiata* plantation.

Actually, during this consultancy we described three different sets of instruments that could be used to run this experiment: a) where TDRs (Time Domain Reflectometry measuring devices) are used to determine the moisture content at three different soil depths; b) where piezometers and wells are used to determine piezometric heads and lateral flow in the watershed; and c) where deep trenches, on the lower side of treatment plots, collect all ground water and runoff water from said plots. However, since FONAG personnel, and especially Sergio, already have a good amount of experience with TDRs we will run through this experiment using TDR's as the evaluating device. To run this experiment well a very important first step is to choose a site that can adequately accommodate the experiment. Figure 7 shows one possible site situation where this type of experiment could be expected to run well and also shows the location and size of the three different types of treatment plots in each of the four different blocks (replications) of this experiment. Also shown in Figure7 is the approximate location of the three different points in each plot where TDR sensors are to be buried. At each point one sensor would be buried at 30 cm, one sensor at 60 cm (or just below the effective rooting depth) and one sensor at 90 cm.

TDR readings need to be made at the onset of the experiment, to establish a baseline, and at a minimum of about twice per year thereafter. A reading about a month into the rainy season and most of the way through the dry season would be of interest.

After data have been collected, analyses of variance can be run to see if there are any statistically significant differences between the moisture content caused by these four different land use options at any of the three soil depths being sampled during any of the seasonal measurements and these differences can be quantified.

Figure7. Layout of an experiment to evaluate land use impact on soil water content.



How well has the plantation-carbon sequestration question been developed?

FONAG is off to an excellent start on being able to predict how fast Polylepis plantations will be sequestering carbon dioxide. They have had some good coaching from the forest mensuration professor at Loja University who did his PhD thesis on a related theme and their initial approach has been excellent: a) they have correctly identified that Polylepis is rarely a single stemmed plant and have developed their volume regressions with the independent variable being the sum of all of the basal areas of the principle stems; b) they have used an acceptable process for scoping in on a highly significant (high R^2 value) equations and yet are using a sufficiently simple regression equation (only

two independent variables); c) their general approach to selecting a variety of plantations is good; and d) the way that the work is set up to transition from volume estimates to bone dry biomass and then to C-sequestered and then CO_2 sequestered is all correct.

Never-the-less, to date the regression equation that they FONAG has developed is of extremely limited use mainly because they were not able to find any old plantations to sample and because they only sampled one plantation on one site type at each age.

To get the attention of any entity interested in purchasing some carbon offsets, FONAG will have to be able to show that Polylepis plantations are capable of sequestering several tons of CO_2 per hectare each year. So far, up through age 7, it is only possible to show that they are capturing a few kilograms of CO_2 each year.

To get Polylepis stands at more advanced ages, two recommendations were made. One is to use the very old natural stands of *Polylepis incana* that still exist as remnant forests. The stand that we stopped at in en route to Papallacta would be just fine for this purpose. Julio should definitely be along when the stands are chosen because he knows their history far better than most people. Some of the stands are ancient and some of the stands are actually sprout stands (distinguishable, according to Julio, because their foliage is a much lighter green) that have come back following a fire that went through about ten years ago. It may be very difficult to get the exact age of the old trees in this natural stand, but it is expected that this stand will have long ago reached a static plateau in terms of its volume (this stasis is reached when the amount of new growth is approximately balanced by the amount of natural mortality that is going on). Any regression equation that might be developed that showed higher amounts of biomass (CO_2 sequestering) than these old stands should be immediately suspect as being misleading.

The other possibility for improving the data for these equations and for getting a lot more data points for Polylepis stands with ages of 10, 20, 30, 40 and 50 years of age might be to go to Peru. There plantations with *Polylepis racemosa* have been a part of tree planting activities with the FAO Holanda/Infor project since the 1970s. David Ocana, the same person that brought the racemosa rooted cutting program to Ecuador, is again living in Peru and could help find the right stands to sample.

How well has FONAG documented the impact of selecting different land-use options on biodiversity?

During the time that we were with FONAG, we did not hear of any studies that FONAG has sponsored to test the hypothesis that tree planting with Polylepis, will lead to significant increases in biodiversity. Never-the-less, there are studies that have been done in both Peru and Bolivia that do show that Polylepis stands are markedly richer in terms of bird diversity. Two papers that describe this impact were left with the FONAG library.

Although, information about the impact of Polylepis on biodiversity in Peru and Bolivia is encouraging, there is no doubt that someday FONAG will be asked to quantify the impact that Ecuadorian Polylepis plantations are having on biodiversity.

A most excellent book published by the Forest Service was donated by Cheryl Corrothers and left with the FONAG library. This book describes the protocols that should be used to evaluate every kind of biodiversity known to occur in forests.

Birds are commonly used as an indicator of biodiversity. To get a feel for how biodiversity can be assessed we did a practice ten-minute, seven-point biodiversity "Land Bird" assessment on the North slope of the Cotopaxi volcano. This exercise was not difficult, but by doing it we quickly identified three things that might be important to take into account the next time a similar bird count is attempted:

1) We should be sure to do the bird count in the early morning, probably beginning soon after sunrise to be able to find the largest number of birds;
2) We might have to modify the sampling procedure somewhat since the current "Land Bird Biodiversity" procedure requires at least ten hectares of contiguous land with the same land treatment. Maybe this design works great in Kansas, but much of Ecuador has extreme topography and it is rare to find 10 contiguous hectares that are all similar;
3) We should bring a good ornithologist along; one that can recognize bird calls.

In spite of the lack of experience with evaluating biodiversity on lands with different treatments, the impression was that this particular task would be relatively simple for FONAG to conduct (especially compared with some of the hydrological studies that they will be tasked. Furthermore, Ecuador is gifted with a large number of really talented and passionate ornithologists who could be easily induced to help with these studies.

Note: Fernando Ortiz, who worked for USAID Ecuador for a number of years, was one of the most dedicated ornithologists in Ecuador. Unfortunately, he met his demise in a boating accident on Lake La Mica. A moment of silence was held out of respect for Fernando during the biodiversity part of this consultancy.

Will FONAG experience be useful to other cities in Ecuador and other Western South American countries?

Quito is not the only city in South America that is being faced with solving water shortage problems and, in fact, USAID is also in the process of setting up similar support for water supply improvements in a dozen other cities and towns along much of the length of the Andes:

1) Cartagena
2) Medellin
3) Bogota
4) Palmira
5) Cali
6) Quito (FONAG)
7) Paute
8) Tungurahua
9) Riobamba

10) Cuenca
11) Zamora
12) Amaluza
13) Lima

To date FONAG is the organization where this improvement process is most advanced, and it has a longer than average trust fund (80 years) to draw on so there is, understandably, a great deal of interest to see if the FONAG experience can be transferred to some of the other areas. Undoubtedly there will be some unique questions to be addressed for each area. However, with respect to most of the plantation questions, Andept soil questions, water yield questions, *Stipa ichu* questions, carbon sequestration questions and biodiversity questions, many of these other areas have a sizeable amount of paramo in some of their watersheds should profit substantially from the experiences that FONAG is running through (and they should also profit from the reading of this report). This would definitely include cities (situations) 4, 5, 7, 8, 9, 10 and 11 from the above list, and, to a lesser extent, because they have much less paramo, cities (situations) 2,3,12 and 13.

How well is FONAG set up (financially and personnel-wise) to be able to cope with this immense array of suggestions?

The consultants will not comment much about the financial situation of FONAG other than to mention that good finances were obviously something that lead administrators at FONAG were very serious about maintaining. Clearly, if some of the studies and other activities that have been proposed in this report are to take place, some additional funds will be required.

In terms of personnel, three of FONAG's personnel have had some formal education in watershed science (at either the masters or undergraduate level). Still, if FONAG has to fly solo, there is not enough of a collective grasp to know how to most effectively undertake the watershed studies that will be needed in order to answer the important watershed management questions that Quito has for FONAG.

Additional formal education in this field would, of course, be possible and might be a good investment for Ecuador. Another experience that this group of consultants strongly recommends is for two or three of FONAGs top watershed personnel to come to California this coming summer for a period of two to three weeks and join in with Barry Hill as he sets up all kinds of watershed measuring devices and monitors watershed studies in various location in the high Sierra Nevada mountains of this state. In many of these areas, the environmental conditions have many similarities with the high Andean zone of Ecuador. By seeing how Barry does the field work and makes the water budget calculations for California's watersheds, FONAG personnel would quickly gain experience and confidence in preparation for doing the same in Quito's watersheds.

What are some of the alternatives if FONAG fails to deliver?

There was a great deal to reflect on during this consultancy. FONAG has a very important mission because is has been charged with seeing if greater metropolitan Quito needs to do some things

differently with the land in the watersheds that are providing the water to this city. Basically, the consultants found that FONAG was plenty serious about their mission, and they also found some things that need doing that FONAG, no doubt can move ahead with directly.

One example of a shovel-ready project would be the fencing of all springs in the watersheds.

However, the consultants also found that there were quite a large number of propositions that were still unresolved.

For example, is the planting of Polylepis really something that will enhance water yield?

Or is the protection of the paramo from burning and cattle grazing really important?

We will not really know what the added amount of water that could be until results from the studies recommended in this report are undertaken and then, of course, until political resolve can be found, and the financial backing obtained, that will ensure that the best water-yield policies are adopted.

If FONAG and Quito do not figure these things out, the question could be asked, does it matter? Probably the answer to this question is a definite yes. By figuring out how to best optimize water yields from the watersheds that they are already tending, FONAG and Quito will be able to at least postpone the next serious water crisis as long as possible and therefore buy time that they will probably need to come up with other more serious, more complicated and much more expensive solutions to getting more water.

This, of course, begs the others questions, what other options does Quito have for obtaining water?

There are a few things that could be done locally in Quito: One would be to embark on a program of better water use efficiency which would involve some cultural adjustments. Another big one would be to try to recycle water. No exact measurements were made, but during our stay in Quito the waste-water chute that empties down from Quito into the Guayllabamba appeared to be delivering, non-stop, about 3 to 4 m^3 of waste water per second. There is no attempt to recycle water in Quito so far. Certainly this is a very expensive proposition, but it will have to be one possibility that Quito will have to consider progressively more frequently.

In terms of other major watersheds that could be tapped, we did see a ridge that runs down the eastern flank of Antisana. Oswaldo mentioned that there was another watershed on the other side of this ridge (in other words on the NE side of Antisana). It was implied that it could also be tapped and that it might also expected to render about $2m^3$/second of water. If this was to be tapped, the general idea was that the water would be piped over the ridge to La Mica and then pumped through the same pipeline (or in a parallel pipeline) to Quito.

Beyond that, however, we did not hear of any other “local” watersheds that could be tapped. Indeed, the only other project that has gotten major press is the Rios Orientales Project. This project is about to start in the coming years and costs about $700,000,000 (2008 dollars) and would route water from

several of Ecuador's tributaries of the Amazon from a much lower elevation than all previous watershed projects.

All of these alternative projects will be very costly and certainly, at least for the near future, it is in Quito's best interest to try to enhance Ecuadors' current capabilities for providing itself with water by following some of the relatively cheap land use recommendations that FONAG should be able to provide. The ability of FONAG to provide this wisdom will be in direct relation to their ability to totally understand the impacts that all of the most common land use practices ((a) leaving the land in ungrazed bunch grasses; b) leaving the land in burned and grazed bunch grasses; c) leaving the land in unburned but rotationally grazed bunch grasses; d) planting the land with Polylepis species; and e) planting the land with *Pinus radiata*) actually incur on the ability of paramo lands to render water.

Summary of Recommendations

Results of this review indicate that FONAG-managed tree planting has been very successful at getting the *Polylepis* plantations established. They have also done a good job of getting some fairly sophisticated weather stations and soil moisture monitoring stations installed and working correctly. Never-the-less, these watersheds are enormous and complex and, so far, FONAG has only a most basic understanding of the water budget in any of them. Furthermore, there is almost nothing known about how changes in land-use activities might affect any of their respective water budgets. FONAG personnel need to learn more about hydrological sampling procedures for mountainous and alpine meadow types of areas, and much more about experimental design and evaluation, before they will be able to understand existing watershed conditions and confidently predict the impact of each of the principle land use alternatives for these high Andean watersheds.

One strongly recommended activity to enhance FONAG's capacity to do this includes a future visit by some FONAG staff to California this next summer to see how watershed monitoring and assessment is done in the mountains of this state. The consultants would be pleased to host this visit.

Some additional salient recommendations with respect to hydrology include the installation of recording stream gauges at key locations downstream of plantations to allow development of water budgets and models and the development of soil characteristic curves for soil water at each of the monitoring locations. Two general recommendations that can be made with no need for study are that all springs should be fenced to keep out grazing animals and that wild horse herds should be reduced.

Some recommendations were also made that did not pertain directly to hydrological aspects. One of these was the need to finish the growth tables for the Polylepis species that are being planted. This probably means sending FONAG personnel to Peru, where there are much older plantations of this species, to get measurements of said trees so that the capacity of these trees to sequester carbon with age can be assessed much more accurately. Another important advance FONAG needs to make is to gain a full understanding and appreciation of the benefits (or at least impact) that the widespread *Stipa ichu* and *Calamagrostis* grasses and the high organic matter content of the very deep Andept soils may already be bringing to the watersheds of Quito and to the planet.

Towards being able to satisfactorily address most of the different questions that were raised by this consultancy, it will be enormously beneficial for some FONAG personnel to become more experienced with appropriate experimental design, analysis and interpretation. Ways to do this, from simplest to most involved, include the following: reflecting on discussions that were held in the field; reviewing the 30 plus flip charts that were presented during the workshop; reviewing the stacks of literature that were given to FONAG by the consultants; going to California this summer to see how hydrological experiments are set up in that state; participating in some international forest hydrology courses; having some additional consultancies by USFS hydrologists in Ecuador; or perhaps having some FONAG staff take additional graduate studies. Various combinations of these activities would, of course, also be possible and probably preferable.

Additional Photos

At the old Alexander von Humboldt house near the base of the Antisana Glacier. From left to right: Sergio Torres, Barry Hill, Julio Rosero, Camille McCarthy, and Phil Cannon. Among von Humboldt's claims to fame is the establishment of the world's 36 different life zones. Within Ecuador's borders 27 of these life zones have been described. Were he alive today, von Humboldt would certainly have been rattled by the recession of the Antisana glaciers which have been retreating at a very speedy rate over the past few decades.

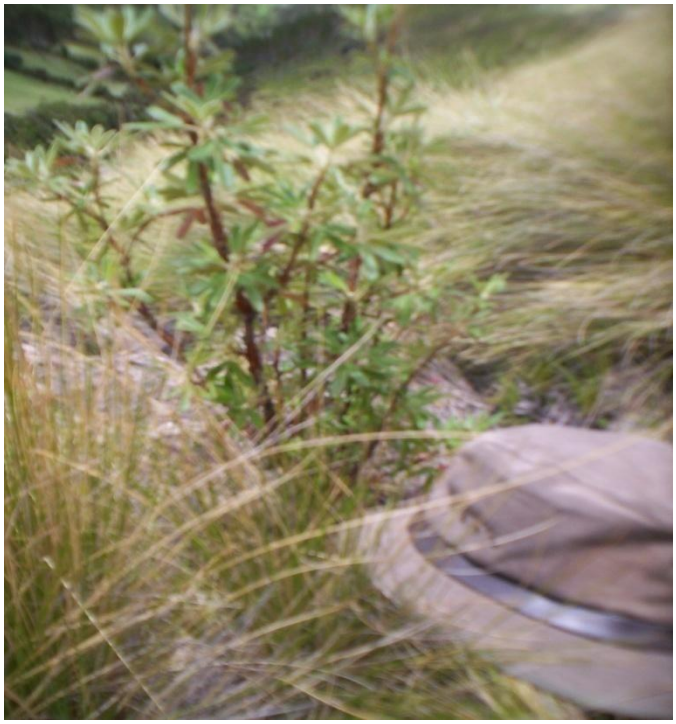
The Antisana Volcano complex on a rare clear day. Right now these glaciers contribute hugely to Quito's water supply. How much less water will Quito's current supply system deliver when these are gone?

Barry calculates stream flow near a suitable natural control section that he found near El Carmen.

Oswaldo Proano and Alex Pelle discuss how the number of TDR recorders could be increased.

One of a dozen lakes in the catchment system in the Coca-Cayambe Reserve. The water level is almost down to the intake valve.

The Cotopaxi volcano; an important source of water and where the biodiversity exercise was conducted. About 1/3 of the glacial mass has been lost during the past 20 years. When the senior author climbed this peak 20 years ago the glacier was just above the climbers hut (top of the grey patch of rock just below, and slightly to the left, of the peak). It looks to be about 300 meters in elevation higher today.



A typical, three-year-old, multi-stemmed *Polylepis racemosa* rooted cutting surrounded by *Stipa ichu* grass.

Camille, Barry and Alex working to get the auger down through the massive root system of the paramo cushion plant. Note the overland flow of water in this location.

René, the enthusiastic forestry promoter at the El Carmen community. Note the typical prevalence of the *Stipa ichu* bunch grass on the slopes and the dark black color of the soil indicating very high levels of organic matter. A six-month old *Polylepis incana* rooted cutting is barely visible behind his left hand; the entire area has been planted with this species.