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Effects of Land Cover Variability on Evapotranspiration in the Llanganuco Valley

Aimee Higgins

Aimee Higgins is a senior Geography and Earth Science double major. This research project was funded by the Adrian Tinsley Program and she worked under the mentorship of Dr. Robert Hellström. She has presented this research at the ATP Undergraduate Research Symposium, the New England-St. Lawrence Valley (NESTVAL) Geographical Society meeting and the New England Undergraduate Environmental Research Symposium.

A process-based understanding of the effect land cover has on evapotranspiration (ET) in alpine valleys is lacking. It is conventionally assumed that ET is a negligible part of the water cycle in the Peruvian Andes, a critical source of water for the local inhabitants, due to lack of precipitation during the 6-month dry season and high humidity during the 6-month wet season. However, recent research findings from an embedded sensor network indicate that ET is in fact an important part of the Andean water cycle in Peru. Water resources within Peru are affected by the glaciers within the Cordillera Blanca, where the Llanganuco Valley is located, which will severely impact people away from the valley. This project incorporated GIS, remote sensing, meteorological data and ET modeling to further show that ET is affected by the valley's terrain and land cover and it varies according to seasonal and daily time scales.

1. Introduction

The correlation between land cover and evapotranspiration (ET), the sum of evaporation and transpiration from soil and vegetation, in the Andes Mountains is currently unknown. Previous research noted by Konzelmann *et al.* (1997) indicates that ET is a significant contributor to the hydrological cycle in mid-latitude regions. They found that the type of vegetation and surface terrain strongly control the rate of ET. Elevation also controls ET. Previous research by Vuille *et al.* (2003) demonstrated that ET is negligible in tropical regions. However, research by Hellström and Mark (2006) indicate that ET is an important part of the hydrological cycle in the Andes Mountains. Hellström and Mark (2006) used a processes-based hydrological model to estimate daily cycles of ET and other hydrological variables during a dry and wet season within the Llanganuco Valley, a tropical alpine valley located in northern Peru.

The Llanganuco Valley is located in the Cordillera Blanca, indicated in Fig. 1.Within the valley, there are ten meteorological data sensors recording the variables temperature, relative humidity, dew point temperature, vapor pressure, wind speed, solar radiation, wind direction and precipitation (Fig. 2). The valley has two distinct seasons, the wet season and the dry season. The central wet season months are December through February, while the dry season months are June through August (Fig. 3). It is important to consider the seasonal variation solar path. During the wet season, the sun is to the

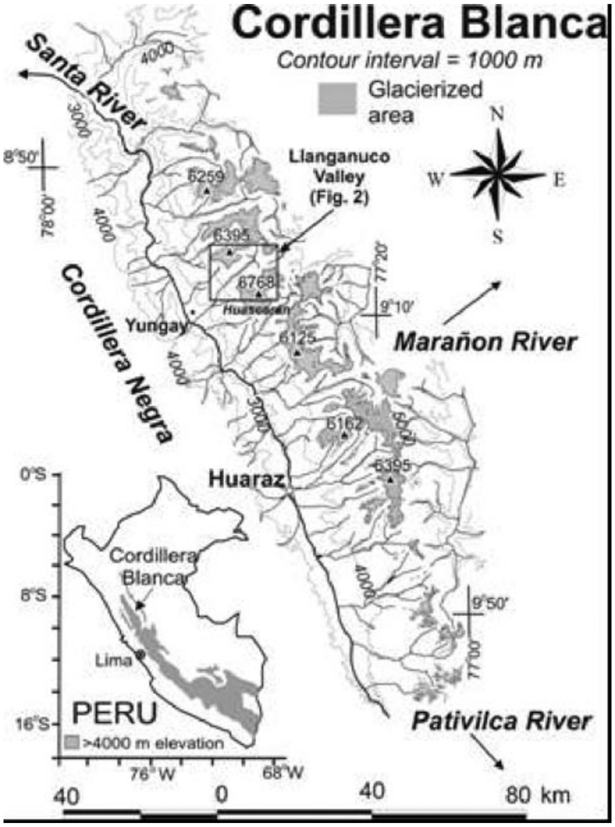


Figure 1. Regional and local map of the research area.

False Color Composite of the Llangunuco Valley

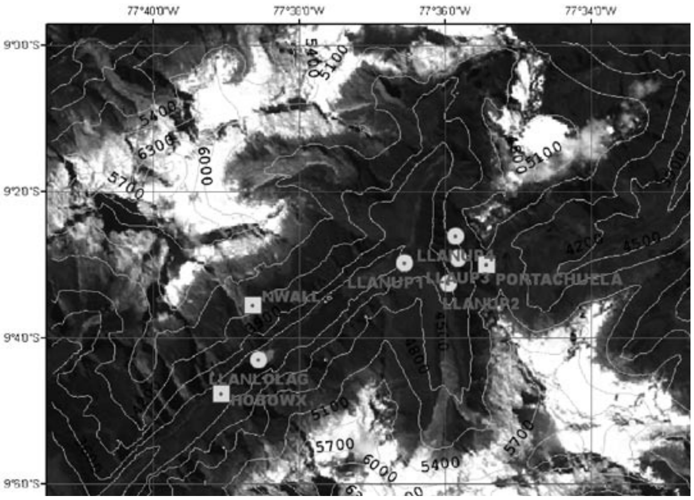


Figure 2. Locations of weather loggers within the Llanganuco Valley. Red shades denote vegetation. White is ice cover.

Monthly Average Precipitation: Llanganuco Valley

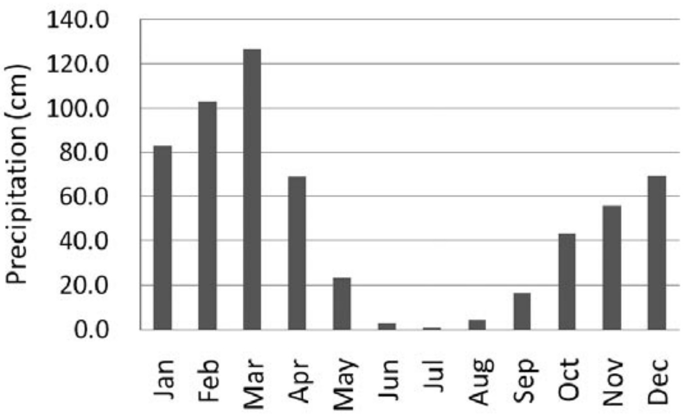


Figure 3. Annual precipitation variation in the Llanganuco Valley, based on 10+ years of data.

south of the valley, so that the sun is in the south at midday. During the dry season, the sun is to the north of the valley, so that the sun is in the north at midday. The seasons follow the path of the Inter-Tropical Convergence Zone (ITCZ). "Seasonal variations of humidity are governed by the oscillation of the Inter Tropical Convergence Zone which approaches the Cordillera Blanca… between October and April when about 70 to 80% of the annual precipitation [falls]. From May to September… the ITCZ is far north and a trade wind system causes dry conditions" (Kaser et. al., 2001). The dry conditon is enhanced further by the rain shadow effect downwind of the mountain range.

ET is an important part of the water cycle and is a part of the mass balance of valleys. "Transpiration is the loss of water from plant leaves. Water exits the leaf through stomata, which are tiny pore spaces in the leaf. The rate of transpiration depends on air temperature and solar radiation (Ritter, 2006). Transpiration is also affected by wind, soil-moisture availability and the type of vegetation (Burba et. al., 2007). Within the global water cycle, ET exchanges 73,000 km^3 of water annually (http://www.ucar.edu/news/people/Dai/hydrocycle.jpg). The actual measurement of ET is "difficult and labor intensive" (Hellström et. al, 2008; Georges and Kaser 2002). It is especially difficult to estimate ET in regions like the Llanganuco Valley, that have steep topography and are in remote locations (Hellström et. al, 2008). Finding a suitable model to estimate ET is necessary to alleviate these issues. A widely used suitable model is the Food and Agriculture Organization of the United Nations Penman-Monteith (FAO-56 P-M) equation. Hellström et. al. (2008) successfully applied this method in an alpine region.

Water resources are crucial to this region. "The availability of fresh water is a matter of increasing concern in many regions of the low altitudes" (Kaser *et. al.*, 2001). The waters from the Cordillera Blanca drain into the Rio Santa River, which is used for agriculture and industry (Kaser *et. al.*, 2001). The freshwater comes from glacial melt that is released during the dry season, between the months of May and September (Vuille *et. al.*, 2007). This is crucial to this area since this is the time of year that receives minimal amounts of rainfall (Fig. 3), approximately 480 mm of precipitation during these months (Mark & Seltzer, 2003). July is the driest month of the dry season, with 10 mm of precipitation on average (Mark and Seltzer, 2003). During the wet season, "the glaciers effectively buffer the runoff by storing much of the precipitation falling as snow" (Vuille *et. al.*, 2007). Since the glaciers are such a large contributor to water resources in this region, it is important to note that the Intergovernmental Panel on Climate Change (IPCC) indicates that the inter-tropical glaciers of the Andes are very likely to disappear, affecting water availability and hydropower generation (Magrin et. al., 2007). Though, "in the Northern Andes (between 6° S and 11° N), glaciers are less relevant as a source of water" (Buytaert et. al., 2007). The greatest impacts for the glacial melt are for people in southern Peru as well as Bolivia (Buytaert et. al., 2007).

Glacial decline in the Andes Mountains is due to several factors. One is the rise of temperature. However, it is now believed that variables including precipitation, atmospheric humidity and cloud cover are contributing more to glacial melt than previously believed variables like temperature (Vuille et. al., 2008). These variables appear to contribute to the decline of glaciers in Ecuador and Bolivia (Vuille et. al., 2008).

2. Methodology

2.1 Remote Sensing and GIS

This project incorporated remote sensing and geographic information systems. The data used for this project included a 90 meter resolution digital elevation model (DEM), a 30 meter resolution LandSat ETM+ image (http://landsat.org/), as well as hourly meteorological data from weather sensors in the valley. The DEM was used to find the slope and aspect of the valley. Slope shows the steepness within the valley while azimuth is the direction an object is facing. Both of these were calculated by terrain analysis using ArcGIS 9.2. The DEM was also used to calculate solar radiation annually within the valley as well as for each of the sensor locations. Solar radiation was calculated using a specialized function in ArcGIS that assumes uniform clear sky conditions (dry season) and standard overcast sky (wet season). Sun path graphs for the HOBO® automatic weather station (AWS) site were created for 26 June, 2005 and 19 December, 2005. These are the mid-points of two periods that meteorological data was recorded, one for the dry season and one for the wet season, which are close to summer and winter solstices.

The LandSat ETM+ image was used for vegetation analysis within the valley. The ArcGIS extension, Image Analysis created by Leica Geosystems, was used for the vegetation analysis. The Transformed Normalized Difference Vegetation Index (TNDVI) was used. This uses the product of [(Band 4 - Band 3)/(Band 4 + Band 3) +.5] $^{(1/2)}$ to create a map indicating where vegetation is located. It also indicates the health and type of the vegetation. Band 4 is the near infrared and Band 3 is the visible red wavelength of the electromagnetic spectrum emitted by the surface features. The TNDVI created a raster map which was used for unsupervised classification. The unsupervised classification created a new raster with classes making it possible to transform the raster into a vector which was needed for ET modeling. A final vegetation map was produced for the valley. The classes on the vegetation map are water and ice, exposed rock, lichen (ground cover less than 0.1 m tall), grass cover, shrub cover and tree cover (Fig 4).

2.2 Meteorological Data

Meteorological data was collected from eight different AWS and LASCAR sensors within the valley (Fig. 2).Weather data was logged for a forty-four day period during both the dry season in July-August 2006 and the wet season in January-February 2007. The LASCAR sensors recorded hourly air temperature (°C) and relative humidity (%); dew point temperature (°C) and vapor pressure (kPa) were calculated. The HOBO, centrally located within the valley at 3850 m and Portachuela site, located at the top of the valley (4750 m), recorded hourly values of wind speed (m/s), solar radiation (W/m^2), wind direction (°), soil temperature (°C) and soil moisture (m^3/m^3). In addition, an automatic rain gage, set up by an Austrian research team, recorded 15-minute precipitation (mm), which were totaled to hourly intervals. Many of these variables are needed for the ET model chosen.

2.3 ET modeling

The Ref-ET computer model, created by the University of Idaho (Allen, 2000), was used to model reference ET, ET_0. This program estimates reference ET using fifteen of the more common theoretical equations that are currently applied in the United States and Europe. The calculations require hourly or daily weather data measurements made available by the user (University of Idaho, 2002). This project incorporates the widely accepted FAO-56 algorithm of the Ref-ET model. Hourly values of air temperature, relative humidity, solar radiation, wind speed, and precipitation served as input to the Ref-ET model. Ref-ET's FAO-56 method was applied for dry and wet season data at the HOBO and Portachuela sites. All sites measured temperature and relative humidity. Solar radiation, wind speed and precipitation, were interpolated for the remaining six sites, all located at elevations between the Portachuela and HOBO sites. Actual ET samples for different vegetation types around the HOBO site were taken at noon

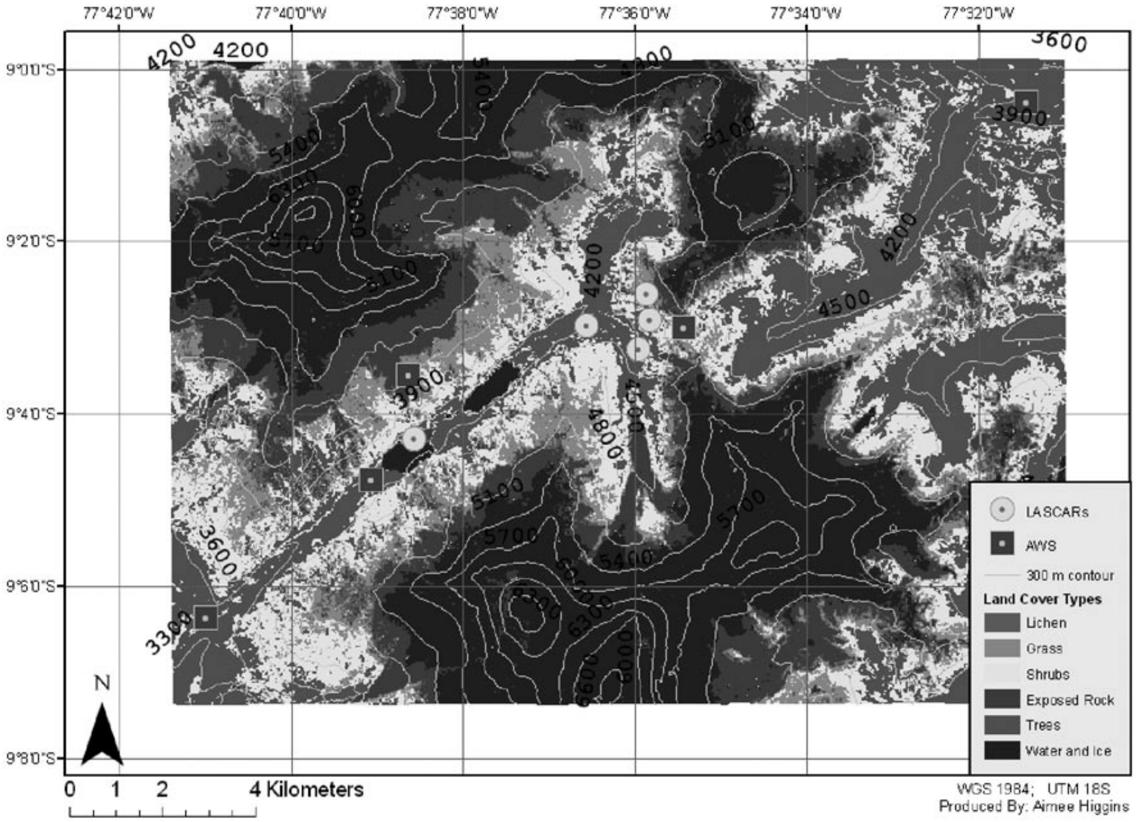

Land Cover Map of the Llanganuco Valley

Figure 4. These figures show the various types of land cover within the valley; note the two meltwater lakes between the two glaciated peaks. a) Vegetation is confined to subalpine areas below 5100 m. b) The most abundant land cover type is vegetation which makes up 52% of the valley. Within this group, there are four different types of vegetation – lichen, grass, shrubs and trees. These groups were used to model ET.

time in the dry season using a porometer that measures leaf transpiration directly (Hellström and Mark, 2006). Because of lack of rainfall, soil evaporation is negligible during the dry season, so ET is primarily transpiration. The samples were divided into the four different vegetation types based on height. Lichen was < 0.1 m, grass cover was <0.1 m to 0.5 m, shrubs were between 0.6 m to 2.0 m and trees were over 2.0 m. ET values were averaged within their group and compared against the Ref-ET model result for the HOBO location.

3. Results

3.1 Remote Sensing and GIS

GIS and remote sensing combined to create results for a large part of the project. The 90-m resolution DEM provided slope values, azimuth, and solar radiation modeling, and the LandSat image provided a 30-m resolution image for creating the final land cover map. GIS was used exclusively for extracting the majority of these features. All the sensors are located within low sloped areas in south facing directions. Also, all the sensors are in locations with intense solar radiation. However, the solar radiation output that ArcGIS creates is just a model estimation based on assumptions of clear or overcast skies depending on the season. Comparisons between observed and ArcGIS-modeled solar radiation suggests large differences during the wet season and good agreement for the dry season (Fig. 5). Hence, the model is unable to accurately determine the effects of cloud cover within the valley during the wet season, and thus overestimates incoming solar radiation. The LandSat image was primarily used to derive different land cover types. The TNDVI analysis (Fig. 4a) suggests that vegetation covers 52% of the area of the valley (Fig. 4b), hence the majority of the valley. Vegetation cover ranges from 4% for lichen to 21% for *Polylepis* trees (Fig. 4b,c).

3.2 Meteorological Data

All variables show their own seasonal patterns and daily (diurnal) patterns. Of the eight sites, the highest, Portachuela, and lowest, HOBO, locations were analyzed. Temperature cycles from coldest at night to warmest around midday at both sites and during both seasons. It is colder at night during

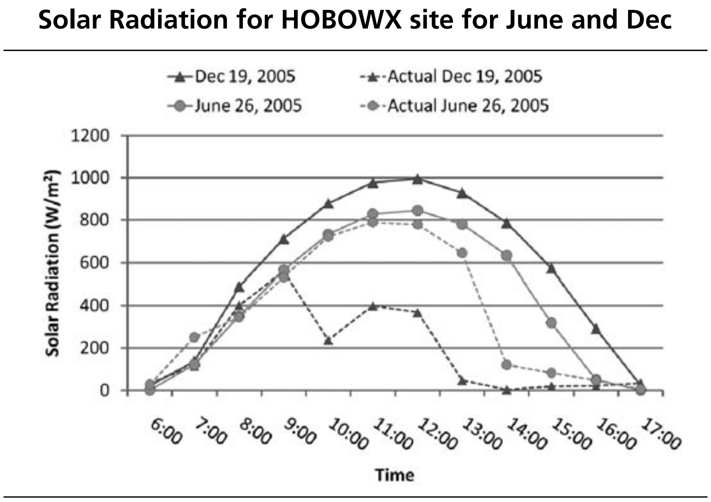


Figure 5. This is the modeled solar radiation versus the actual solar radiation from the HOBO site. The model does best during the dry season, especially in the morning hours. In the afternoon, it appears that there is topography that the model is not picking up due to the 90 meter resolution of the DEM. The model does not do well during the wet season. This is due to the unpredictability of clouds. The model is unable to predict clouds and precipitation on a certain day.

the dry season at both sites and cooler during the day at the HOBO site. At Portachuela the midday temperatures are about the same for both seasons. The Portachuela site, because of its higher elevation, is the coldest of all sites on average. There is a negative correlation between elevation and temperature during both seasons, the slope of which is commonly known as the lapse rate (Fig. 6b). It is colder at sites with higher elevations compared to the lower elevations. Extrapolating to the freezing point of water, 0 C, Fig. 6b suggests that the freezing elevation is 5100 m during the dry and 5350 m during the wet seasons. The higher freezing line during the wet season would promote enhanced glacial melt above that of the dry season.

Relative humidity is highest during the nighttime hours and lowest during the midday hours. Both sites experience their highest relative humidity during the wet season. The Portachuela site has less variance in relative humidity between the two seasons, plausibly due to its higher elevation and exposure to the free atmosphere. The timing of lowest relative humidity during the day differs between the sites. At the HOBO site, the lowest relative humidity was at 13:00 LST, while at the Portachuela site is lowest one hour later at 14:00 LST.

Vapor pressure reaches higher values during the wet season, which tends to reduce evaporation. During both seasons, the HOBO site experiences the higher vapor pressure values compared the Portachuela site. Throughout the valley, the higher elevations experience the lower vapor pressures with a weak correlation to air temperature for both seasons.

Precipitation is heavy during the wet season and nearly absent during the dry season. During the dry season, the Portachuela site experiences the most rainfall as compared to the lower HOBO site. The HOBO site receives little rainfall during the dry season, receiving the least during the midday hours. During the wet season, the HOBO site receives the majority of its precipitation during the early nightfall hours, between 17:00 and 20:00. Another peak of rainfall is seen between 20:00 and 23:00. The Portacheula site receives a large amount of its rainfall during the periods 9:00-12:00 and 21:00-23:00, largely due to topographic enhancement. In general, precipitation occurs in the late afternoon and evening within the central part of the Llanganuco Valley and morning and evening in upper portions.

Wind speed does not vary between the seasons as much as it does throughout the day. The HOBO site has the most variance in wind speed during the day. Wind remains calm during the night and peaks at midday. Wind speeds do not have a similar pattern at Portachuela. Portachuela is the windier of the two locations, largely because of its exposure to the free atmosphere as the highest elevation of all sites along the valley axis.

3.3 ET Modeling

Estimating ET was the primary objective of this project. When comparing all eight sites to each other against elevation, it is noted that ET values are lowest at higher elevations and highest at lower elevations (Fig. 6a). The trend is stronger during the dry season than it is during the wet season. ET also has a diurnal cycle at all eight sites during both seasons. Both seasons experience the most ET during the daylight hours. The time where ET reaches its peak is different for the seasons. During the dry period, ET peaks from 11:00 to 13:00. During the wet period, ET reaches its peak at 10:00 at some sites and at 14:00 at others. The HOBO site was the only site to have real ET measurements taken. These were only taken at noon during the dry period. During the dry season, lichen produces the most ET per unit area while the trees have the least (Fig. 7a). All these values were higher than the Ref-ET model measurement. However, when you compare the volume of ET between the Ref-ET measurement of 0.55 mm/hr and the actual ET results, there is no significant difference (Figs. 7 c&d). Trees are responsible for the most volume of ET and lichen is responsible for the least volume of ET.

4. Discussion

The meteorological variables within the valley show a distinct diurnal cycle between the two seasons and this affects the variability of ET. A strong annual precipitation cycle creates a distinct differentiation between the two seasons – the dry and wet season (Fig 3). Solar radiation is affected by cloud cover

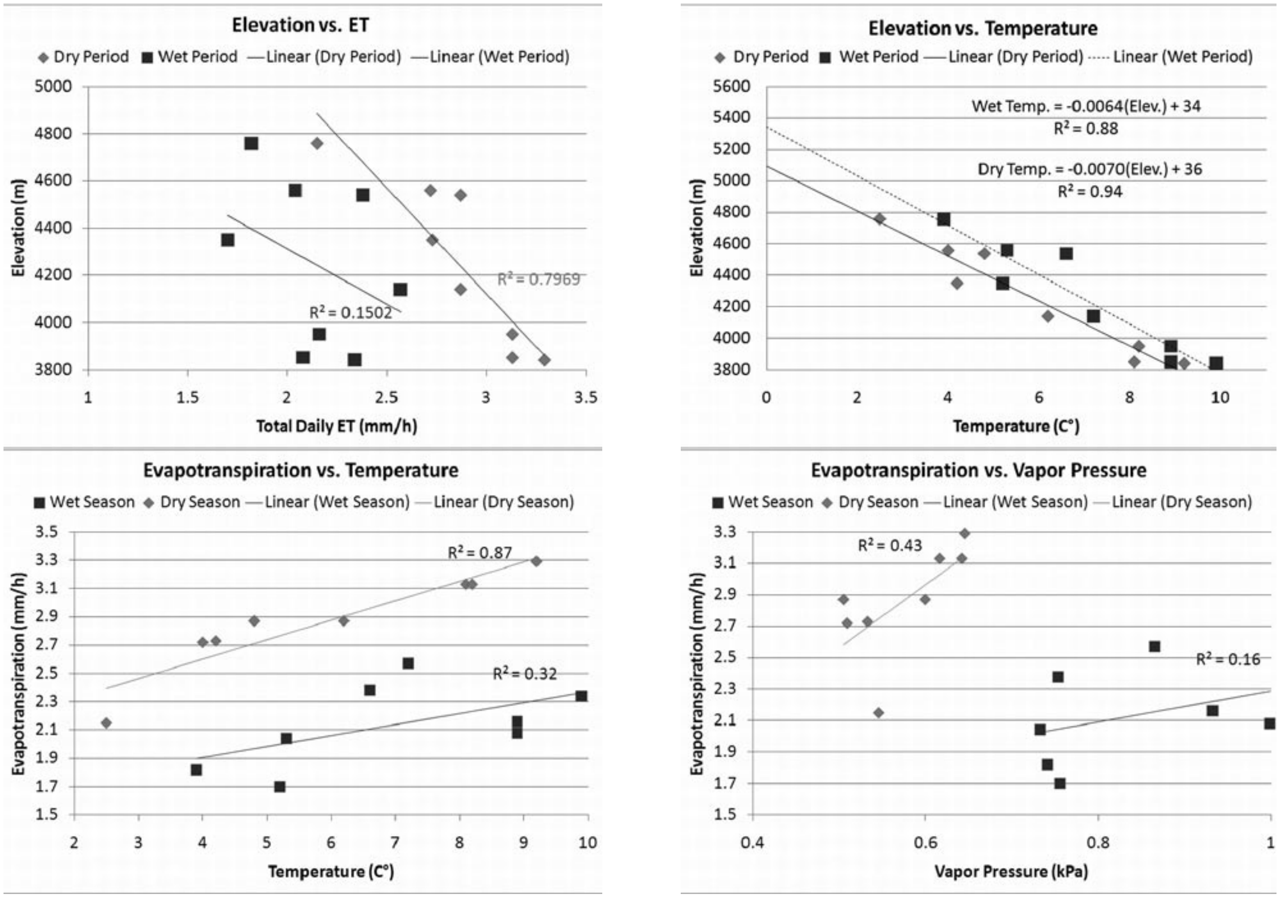
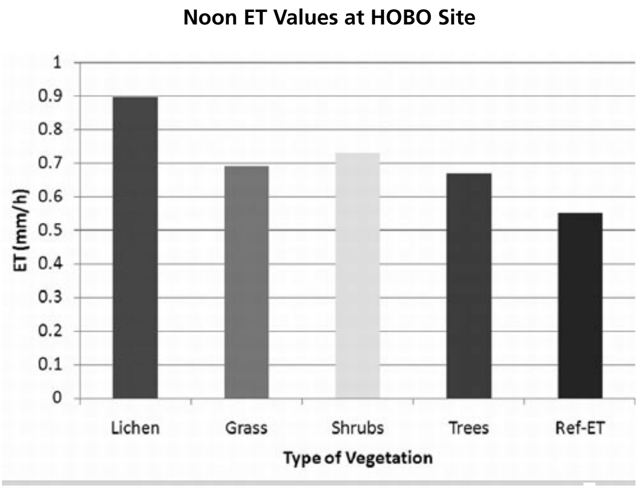


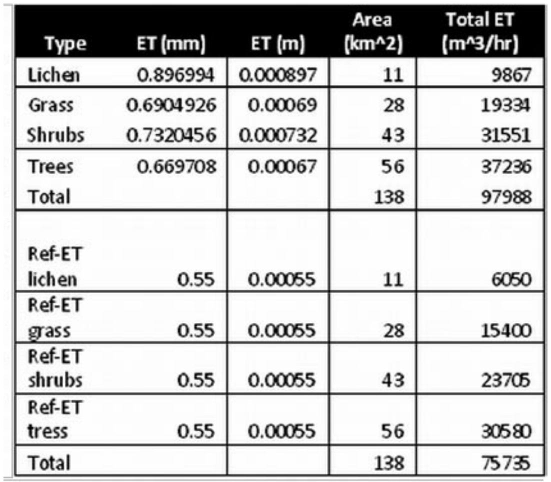
Figure 6. Both seasons experience a negative correlation between elevation and total daily ET. However, the dry season has a stronger correlation between the two, noted by the R^2 value of 0.7969. The wet season has a weak R^2 value of 0.1502. However, the highest ET rates occur at the lowest elevations. ET is higher at all elevations during the dry season. b) This figure demonstrates the positive correlation between ET and temperature. Evapotranspiration increases with temperature. The dry season has a stronger correlation, indicated by the R^2 value of 0.87. c) This figure demonstrates the positive correlation between ET and vapor pressure. Evapotranspiration increases with vapor pressure. The dry season has a stronger correlation indicated by the R^2 value of 0.43 compared to the wet season, with a weak R^2 value of 0.16. d) Temperature decreases with elevation. The slope of the line shows that temperature decreases more rapidly during the dry season.

often accompanied by late afternoon daylight precipitation events during the wet season. One would expect that the solar radiation would be more intense during the valley's summer months of December-February, in agreement with the ArcGIS model (Fig. 5). However, as shown in the results above, the wet season increases the probability of cloud cover, especially in the afternoon. At the HOBO location, there is a notable drop in solar radiation between 10:00 and 11:00. This is an odd discovery at first, because one would expect solar radiation would be almost reaching its peak around this hour. However, after looking at the precipitation chart, there is a spike in precipitation between the two hours. Between 15:00 and 16:00 at the Portacheula location, there is an increase in rainfall which could explain the rapid deterioration in solar radiation between those hours. The results emphasize the importance of understanding the factors that affect cloud development in the Andes Mountains.

Air temperature has a distinct diurnal cycle. During the wet season, it is warmer by night, likely due to nocturnal cloud cover, which can be related to precipitation. However, each site tells a different story during the daylight hours. Temperature at Portacheula is nearly constant between the hours of 12:00 and 15:00, which corresponds to hours when Portacheula receives a significant amount of its precipitation during both seasons. Between 15:00 and 16:00 during the dry season, the Portacheula site has a decrease in precipitation.

Elevation has a negative correlation on most variables within the valley. Elevation impacts temperature, vapor pressure





Type	ET (mm)	ET (m)	Area (km^2)	Total ET (m^3/hr)
Lichen	0.896994	0.000897	11	9867
Grass	0.6904926	0.00069	28	19334
Shrubs	0.7320456	0.000732	43	31551
Trees	0.669708	0.00067	56	37236
Total			138	97988
Ref-ET lichen	0.55	0.00055	11	6050
Ref-ET grass	0.55	0.00055	28	15400
Ref-ET shrubs	0.55	0.00055	43	23705
Ref-ET tress	0.55	0.00055	56	30580
Total			138	75735

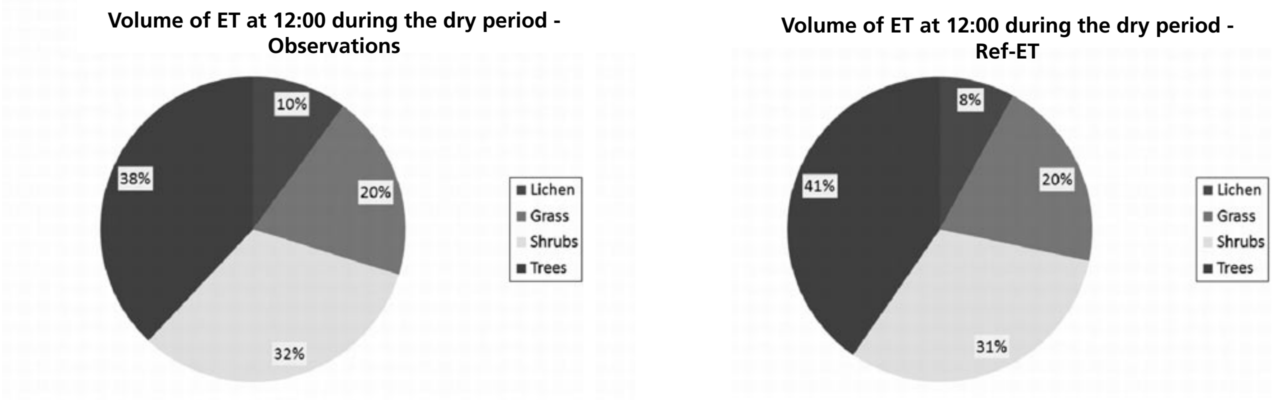


Figure 7. a) This compares actual ET results of vegetation types around the HOBO site to the modeled Ref-ET value from the HOBO site. The recorded values were from 12:00 during the dry season. This shows that the Ref-ET model underestimated ET at this site. However, it does indicate that the Ref-ET model can be used for this valley. These charts compare the observed total volume (97,988 m^3 per hour) of ET to the Ref-ET model volume of ET. b) and c) These show that trees produce the largest volume of ET while the lichen produce the least volume of ET. There is very little difference in the percentages between the observed volume of ET produced compared to the Ref-ET model. This also indicates that the Ref-ET model used does a fairly good job at modeling ET within this valley.

and ET (Fig. 6). In all cases, higher elevations cause lower temperatures, lower vapor pressures and lower ET rates. When comparing ET to temperature, locations with greater temperatures have higher ET values (Fig. 6c). The dry season, despite having lower temperatures on average, has higher rates of ET compared to the wet season. Locations with lower vapor pressure have higher ET rates (Fig. 6d). The dry season has the higher ET rates with the lower vapor pressure values. The wet season has the lower ET rates with the higher vapor pressure values. In both comparisons, ET and temperature as well as ET and vapor pressure, have positive correlations that are stronger during the dry season.

There is a unique relation between slope, elevation, land cover type and ET. It appears that sites in the 0°-13° sloped areas have higher amounts of vegetation types which produce more ET (trees) (Figs. 4, 7 & 8). Locations with higher slopes, like the North Wall site which has a slope ranging from 22°-28°, have higher amounts of vegetation which produce less ET (lichens) (Fig. 4,7 & 8). The areas with vegetation types that have higher rates of ET are typically in areas with the lower elevations (Figs. 4 & 7). The HOBO site, Lanlolag site, Up1 site and Up2 site have elevations between 3840 m – 4140 m (Fig. 2). These sites predominantly have tree cover as the main type of vegetation (Fig. 4). Lichen cover appears to have a factor of elevation and slope. Portachuela is in a relatively low sloped location, between 0°-13° and predominantly has lichen for its vegetation type (Figs. 2, 4 & 8). It is also the highest site within the valley, at 4760 m (Fig 2). Up4 and the North Wall site both have an elevation of 4540 m (Fig. 2). Up4 is in the 29°-34° slope area and is lichen is the predominant vegetation type (Figs. 4 & 8). The North Wall site has a slope of 22°-28°, and like Up4, lichen

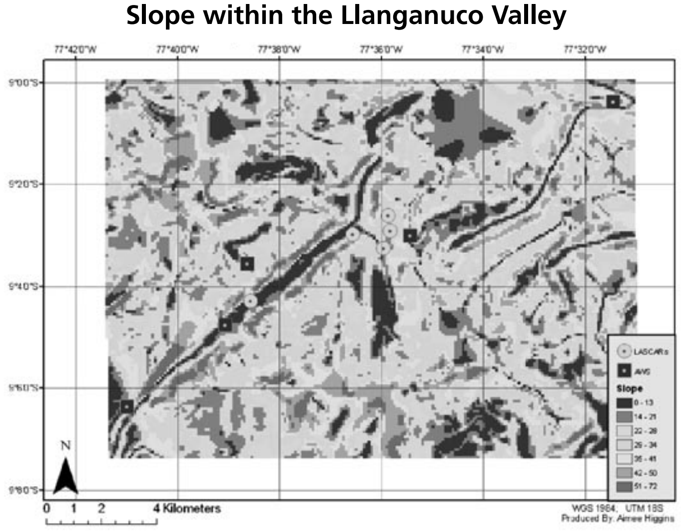


Figure 8. Slope variation of valley as derived from the 90-m DEM using ArcGIS.

is the predominant vegetation type (Figs. 4 & 8). Up2 has a low elevation of 4140 m, and a high slope of 29°-34° and has tree cover as the main vegetation type (Figs. 2, 4 & 8). This shows that elevation has more of an impact on land cover than slope. However, slope does seem to have somewhat of an impact. This research demonstrates what Konzelmann et. al. (1997) found in their research – that vegetation as well as terrain do factor into ET in an alpine region and that these variables should be "considered more carefully for model calculations of the ET in high mountain areas" (Konzelmann et. al., 1997).

ET was modeled using the Penman-Monteith FAO 56 method. During the dry season actual measurements were taken that could be used to compare to the modeled results. All vegetation types that had actual measurements had higher ET rates compared to the model (Fig. 7b). Despite the model underestimating ET in the alpine valley, it is still an indicator that using this method would work in future research. Konzelmann et. al (1997) also found that "The values of actual ET favorably correlate with those computed with Penman's formulation" (Konzelmann et al., 1997). Garcia et. al. (2004) also found that actual measurements of ET in a Bolivian highland were comparable to modeled results using the Penman method. Garcia et. al. (2004) found that the Penman-Monteith method is "able to account for the effects of the high elevation (high solar radiation but low radiation term) and of the moderate aridity reflected in the vapour pressure deficit, temperature and wind" (Garcia et. al. 2004).

5. Conclusion

This researched aimed at determining how land cover affects ET within the Llanganuco Valley in the Cordillera Blanca. The results show that ET is affected by the type of vegetation as well as the elevation and slope of the valley. Model measurements were primarily used to determine the rate of ET at eight different sites within the valley. In the dry season, actual measurements of ET were taken at one site (HOBO). They valley itself has distinct diurnal as well as seasonal cycles, shown by meteorological data taken in the valley. These meteorological variables (mean air temperature, average relative humidity, solar radiation, wind speed, and precipitation) factor into the modeled ET rate. It is no surprise there is such a diurnal and seasonal difference of ET due to the fluctuations in meteorological variables.

The research would probably have different results if several things were changed. A 30 meter resolution DEM would have probably been able to give more accurate representations of slope, aspect, and elevation within the valley. This should improve the results, especially in the solar radiation model that ArcGIS generated. Secondly, more ET measurements from the field would have been beneficial for furthering validating the RefET model as well as effects of land cover on ET in the valley. Having ET measurements at all eight sites during the daylight hours in both seasons would help validate Ref-ET's estimations.

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