Living with glaciers, adapting to change
the experience of the Illimani project in Bolivia

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Abstract

Glaciers retreat's rate and its impact on rural livelihoods in the tropical Andes were studied and modeled. Tropical glaciers are more affected by climate change than their temperate counterparts due to larger sun exposure and the coincidence of the rainy season with the summer which reduces snow accumulation.

Global warming is occurring faster at high altitudes, causing glaciers' shrinking and affecting downstream communities' livelihoods where glaciers, important natural water regulators, are the only domestic and productive water source during dry seasons. Changing crop patterns and upward expanding of productive areas are also effects of the climate change.

The project studies the Illimani dependent area in a physical and socio-productive context to evaluate its vulnerability to climate change and climate variability, and the already taken autonomous adaptation strategies. Multidisciplinary results are integrated in watershed management models to develop technically and socially validated descriptions of the dynamics between the glacier and the basin, for actual and future scenarios, resulting in proposals for adaptation actions. The findings reveal that climate is not the only triggering factor for autonomous adaptation and the strong heterogeneity of adaptation requirements in mountainous areas even within small basins and the need for dynamic research-action oriented programs for which the vulnerability evaluation is essential.

Keywords: tropical glaciers, water rights, climate change, vulnerability, adaptation

1. Introduction

The Illimani glacier, Bolivia's second highest mountain, is a natural reservoir to provide water for the communities located on its watershed, especially during the dry season when it is the only water source for their agricultural activities.

Climate change with rising temperatures, more erratic rainfall and higher water demand is causing this and other Andean glaciers to shrink; it has been observed that global warming is occurring faster at high altitudes (Engle, 2010).

As a result, water conflicts in the area are rising, downstream communities' livelihoods are affected, the crop patterns are changing, and the productive areas are expanding upwards where before it was impossible to cultivate.

The Illimani project is handled by the Bolivian La Paz University and the Bolivian NGO Agua Sustentable, under the support of Canada's International Development Research Centre (IDRC). The project studies the Illimani dependent area in a physical and socio-productive context to evaluate its vulnerability to climate change and variability, and the already taken autonomous adaptation strategies. Multi-disciplinary results are integrated in watershed management models to develop technically and socially validated descriptions of the dynamics between the glacier and the basin, for current and future scenarios. Based upon these results, adaptation actions are proposed. The studies seek to be decision support tools to help to shape water use policies of the region, for an effective adaptation to a rapid shifting climate. To understand the dynamics of the studied area, the project evaluated the present vulnerability to climate change and variability, and the already taken autonomous adaptation strategies in the area.

2. General overview of the study area

The Sajhuaya (Illimani) River basin covers 59 km², it rises at the east of the Cordillera Oriental and is part of the central western flank of the Illimani Mountain (Figure 1). The peak of the watershed is located at 6350 masl. and its lowest point at 2500 masl. over the Palca river (Villarroel, Perez, Castel, & Torrez, 2010) at approximately 66 km from the city of La Paz, Bolivia's government city. The basin encloses the communities of Khapi, Jalancha, Challasirca, Cebollullo, Cohoni, Chañurani, La Granja and Tahuapalca (Figure 2 and Table 1). Llujo and Pinaya are also included because of their social interaction with the area. The main ecological strata in the area are Highland Andea Puna, Pre-Puna and Upper valley.

The main economic activities and water uses in the area are agriculture and livestock farming. The upper part of the basin has difficult access, harsh weather with several frosts days per year that limit their possibility for crops choice to potato and other native and underutilized crops. The lower part has more agricultural potential thanks to more benign temperatures. The reduced livestock units feed upon natural highland pastures and wetlands in the upstream communities.

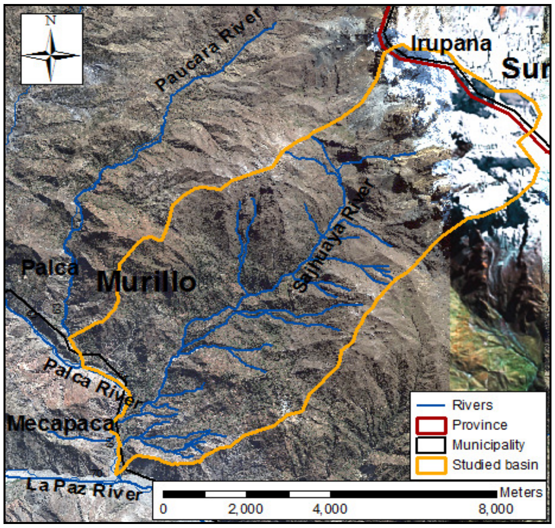

Figure 1: DEM and the hydrographic network of the studied area.

Table 1: Communities geographic locations

Community	X coord.	Y coord	Altitude
Khapi	622360.1	8155302.7	3494
Cebollullo	620861.0	8153427.6	2886
Challasirca	621353.2	8154287.2	3031
Cohoni	623819.6	8151978.8	3567
Pinaya	621821.8	8160096.1	3877
Tauhapalca	619931.9	8150940.7	2390
Jalancha	625002.7	8157894.4	4052
La Granja	619034.3	8153112.5	2545
Cachapaya	622127.1	8151706.4	2942
Cha±urani	621682.6	8153919.9	3039
Khapi	622360.1	8155302.7	3494
Cebollullo	620861.0	8153427.6	2886

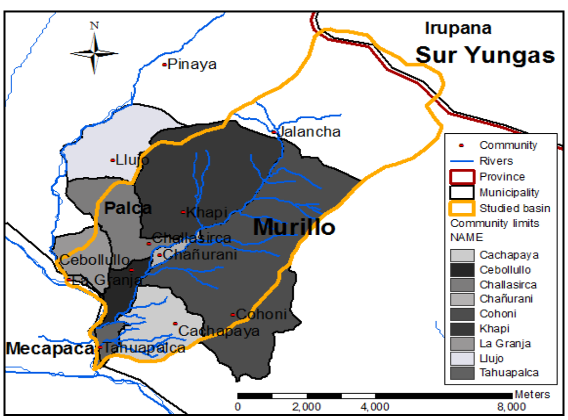

Figure 2: Local communities in the studied area.

The main course is the Sajhuaya River, which along with neighbor courses are tributaries of the La Paz River (Figure 1).

Agriculture uses mostly surface water from river and springs whilst human consumption sources are mainly springs (Villarroel, Perez, Castel, & Torrez, 2010).

In several springs water is available along the year only facing reduced discharges during the dry season (June and July); however, the springs discharge during this period can be larger than the one provided by rivers receiving water directly from the glacier (Villarroel, Perez, Castel, & Torrez, 2010).

3. Methods

3.1 Estimating Glaciers retreat

The change on the Illimani's shape and volume was performed using aerial photos of the studied area, 60% overposed, for the years: 1963, 1975 y 1983 with scales 1:30000, 1:60000 and 1:50000, respectively. Additionally, a present-day photogrammetric flight was carried out in July 2009. The aero-photos were digitalized using a photogrammetric scanner (1200 dpi resolution); internal and externally oriented and calibrated. Absolute coordinate of 12 support points were identified in the photos and field, and linked to the GPS' national permanent network to aero-triangulate the aerial photos and to compose stereoscopic models of the glacier for every year. Using a photogrammetric digital restitution station and the stereoscopic model, the contours of the Illimani Glacier were digitalized for each analyzed year. The snow extension of the whole glacier and snow thickness along 5 longitudinal profiles over the most representative glacier fronts were then measured (Ramirez, Machaca, García, & Alurralde, 2011).

3.2 Vulnerability

In this case, vulnerability is understood as the susceptibility of the studied systems to support the adverse effects of climate change and climate variability. An integrated approach is taken, which studies the different types of observed vulnerability in the Illimani area (García & Taboada, 2010).

3.2.1 Biophysical vulnerability

The biophysical vulnerability takes into account the physiographic and climatic characteristics of the studied area. The identified indicators of this type of vulnerability are:

- Physical description of the studied area
- Glacier retraction
- Climate risk
- Observed Temperature and Precipitation trends

3.2.2 Socioeconomic vulnerability

The most relevant indicators of the socio-economic vulnerability are poverty indicators, as such, the following indicators were taken into account:

- Demographic information, age distribution and poverty index
- Educational level, analphabetism index
- Non agricultural activities
- Health

- Infrastructure, transportation and potable water access
- Migration

3.2.3 Productive vulnerability

This type of vulnerability is strongly related to climate (biophysic vulnerability); extreme events like floods and droughts or recurrent events like frosts and hailstorms have huge impacts on production. The irrigation frequency, method and quantity have also an important influence on the productivity. The identified indicators for this type of vulnerability are:

- Cultivated surface
- Changes in the agricultural activities and agro-bio-diversity
- Irrigation availability, frequency and efficiency
- Changes in the irrigation requirements

Productive information has been evaluated through a participative monitoring of the productive activities and water use in the studied area in 3 representative communities (Khapi, Cebollullo and Tahuapalca), during 16 months (August 2009 until December 2010).

2 monitoring plots were established in each one of the 3 communities: 1 maize and 1 potato plots in Khapi, and 1 maize and 1 lettuce plots in Cebollullo and Tahuapalca.

The monitoring evaluated productive structure in each community as follows: the cultivated areas (crops types, distribution and seasonality), the irrigation systems (canals and its operation), the water use and rights for domestic and agricultural purposes (irrigation turns, amounts, efficiency and methods).

Because of their observed similarities, the information from Khapi was extrapolated to Challasirca and the upper part of Cohoni. The information from Cebollullo was extrapolated to Chañurani, Cachapaya and the lower part of Cohoni. The information from Tahuapalca was extrapolated to La Granja. Due to altitude limitations, limited production is observed in the communities with high altitude (Jalancha and part of Cohoni).

3.2.4 Institutional vulnerability

The vulnerability of a system also depends on the strength and organization of the formal and informal institutions working on it. Governmental institutions

- Social actors, organizations and institutions
- Other institutions

The institutions working in the area were identified, as well as their geographical and temporal range.

The adaptation strategies to climate change are strongly based on Risk Management, a concept that Andean communities have always applied with a wide diversity of strategies as part of the life and dynamics, at community and family levels. These strategies can include the management of ecosystems, organizations, social relationships, market issues, productive chains, etc. (Villarroel, Perez, Castel, & Torrez, 2010).

The autonomous strategies presented further were observed by the project team in parallel to the productive structure monitoring (García & Taboada, 2010).

4. Results and Discussion

4.1 Glaciers evolution

The photogrammetric restitutions give an estimation of the glacier extension for 1963, 1975, 1983 and 2009 (Figure 3, 2009's photo). The longitudinal profiles' axes, used to estimate the snow thickness lost between each period, are also indicated (profiles A, B, C, D, E and F).

Glacier surface loss is not uniform, since some parts maintained a similar extension between 1963-1983 (A, B, D and E) while others suffered appreciable losses for the same period (C and F). During the last period, 1983-2009, the glacier mass loss is larger and more uniformly reduced in all the studied glacier profiles.

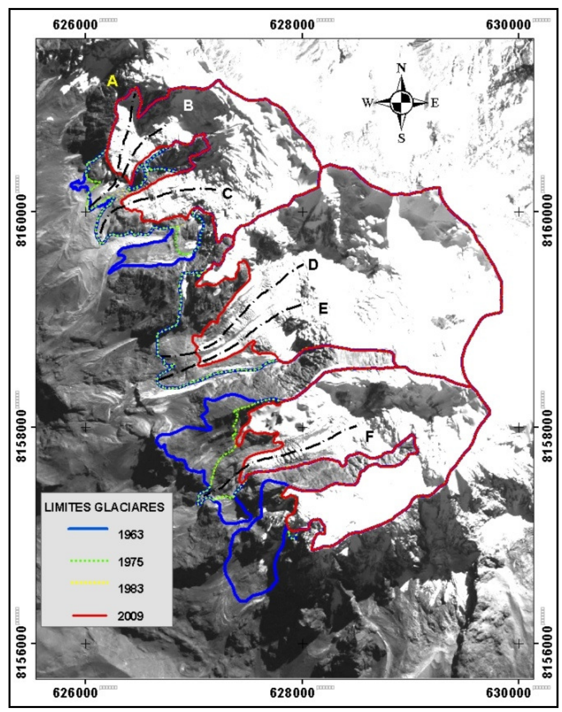

Figure 3: Illimani Glacier extension for 1963 (blue line), 1975 (green), 1983 (yellow) y 2009 (red). Longitudinal profiles axes (black dashed line)

The glacier surface loss is not uniform along the whole glacier, some parts maintained a similar extension between 1963-1983 (A, B, D and E) while other glaciers suffered appreciable losses for the same period (C and F). During the last period, 1983-2009, the glacier mass loss is larger and more uniformly reduced in all the studied glacier profiles.

Table 2 and Figure 4 show the estimated surfaces of the Illimani Glacier between 1963 and 2009. According to morphological similarities, the glacier has been divided in 3 sectors corresponding to the studied longitudinal profiles defined in Figure 3. Sector I corresponds to glacier close to profiles A, B and C; Sector II to profiles D and E, and Sector II to profile F on the continuous main glacier. During 1963-2009 (46 years), the glacier lost approximately 21.3% of the surface observed in 1963

Table 2: Surface evolution of the Illimani Glacier, period 1963-2009 .

Year	Glacier fronts surface (km^2)				% Lost Surface
	I	II	III	Total	
1963	2.31	4.13	3.12	9.57	0.00
1975	2.17	4.13	2.37	8.67	9.37
1983	2.06	4.13	2.37	8.56	1.22
2009	1.77	3.62	2.14	7.53	10.70
T. lost	**0.55**	**0.51**	**0.98**	**2.04**	**21.30**

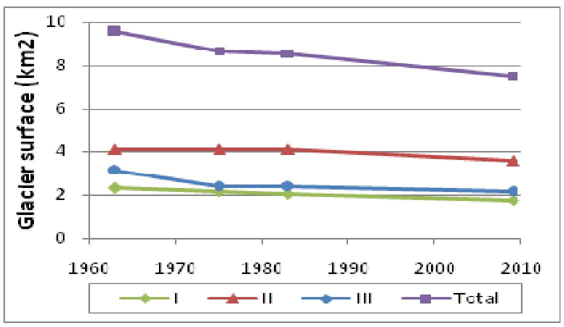

Figure 4: Surface evolution of the Illimani Glacier, period 1963-2009.

The lost snow thickness is evaluated along the profiles shown in Figure 3 (profiles A, B, C, D, E and F). These profiles are selected in the direction of the actual glacier fronts (2009). The estimated loss per studied period and profile, relative to 1963, is shown in Table 3 and Figure 5. The average rate of loss during each period and profile is presented in Table 4. In average, this glacier has lost 22m between 1963 and 2009 which gives a rate of 47 cm/year. The thickness loss is occurring faster in profiles A, B, C Since 1980 but is slower in profiles D, E, F.

Glacier mass losses (surface and thickness) depend on the extension, orientation, altitude and slope of the studied glacier front.

Table 3: Snow thickness lost in the Illimani Glacier, period 1963-2009

	Snow thickness lost per profile (m)					
PERIOD	**A**	**B**	**C**	**D**	**E**	**F**
1963-1975	0.37	0.18	3.19	14.00	8.06	13.71
1975-1983	1.14	1.58	3.67	1.09	9.77	3.93
1983-2009	2.04	11.26	17.61	9.70	11.15	17.96
TOTAL	**3.55**	**13.01**	**24.47**	**24.79**	**28.98**	**35.61**

Table 4: Average rate of snow thickness loss in the Illimani Glacier, period 1963-2009.

Period	Snow thickness lost per profile (cm/year)					
	A	**B**	**C**	**D**	**E**	**F**
1963-1975	3.1	1.5	26.6	116.6	67.1	114.3
1975-1983	14.2	19.7	45.9	13.6	122.1	49.2
1983-2009	7.9	43.3	67.7	37.3	42.9	69.1
1963-2009	**7.7**	**28.3**	**53.2**	**53.9**	**62.9**	**77.4**

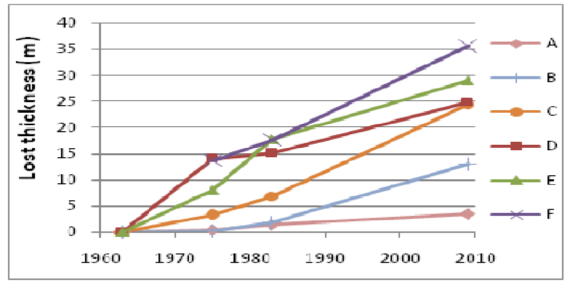

Figure 5: Thickness loss per Illimani Glacier's front, period 1963-2009, respect the thickness on 1963.

4.2 Vulnerability

4.2.1 Biophysical vulnerability

The water use monitoring showed that the studied area has enough water availability for the present requirements during most of the year. However, at the same time, communities show a constant erratic production pattern that might disturb the production system soon. In general, light to severe erosive processes are common mostly caused by the periodic storms (rain, wind, hail) between December and February (especially in the upper areas) (García & Taboada, 2010).

The most common climate risks are snowfalls, frosts and hail storms (especially in the upper part of the basin), unusual distribution of rainfalls (generally delay), droughts (high risk) or flooding (low risk). Frosts occur sporadically between April and September, and might damage the production. Hailstorms occur between December and February and snowfalls in winter (July-August, maximum 3 times), increasing the soil water storage (PDM-Palca, Palca's Municipal Plan of Development, 2007-2011), (Quiroga et al, 2008) and (Center for Emergency Operations, COE). No historical records of extreme events in the studied area are available but 80% of the inhabitants reminded some important climatic events in the past 25 years. The 1983 El Niño event is the most clearly reminded (recorded as the driest year in the Bolivian West). This event proved to be strongly affecting families' behaviors because they started to periodically irrigate since then. Table 5 presents the actions assumed by families to face extreme events. Families use their savings since government aid reaches less than 20% of the population in the low communities (Cebollullo and Tahuapalca) and did not reach Khapi community. In Khapi, some farmers had to migrate outside their community (17%) to work and compensate their economic needs.

Table 5: Reaction of the interviewed families (%) to face past extreme events (García & Taboada, 2010).

Community	Savings	Migration to work	Government aid
Khapi	70,6	17,6	0.0
Cebollullo	61.9	4.8	19.0
Tahuapalca	33.3	7.4	18.5

Within the Andes, traditional methodologies exist to predict climatic risks in advance (local climatic indicators) specially dry or wet years, which help farmers to plan their actions. Therefore, this behavior was evaluated in the area. Table 6 shows that the use of these indicators is well spread in Khapi (upper part of the basin), (55%), while in the lower part of the basin less than one quarter of the population knows them relaying on irrigation.

Table 6: Bioclimatic indicators knowledge (García & Taboada, 2010).

Community	Bioclimatic indicators knowledge (%)		Total
	Yes	No	
Khapi	55.0	45.0	100
Tahuapalca	25.7	74.3	100
Cebollullo	12.5	87.5	100
Total	27.6	72.4	100

Families in Khapi affirm that local indicators always make correct prediction; while in Tahuapalca and Cebollullo, most persons say indicators make correct predictions only sometimes. The reasons behind this different perception might lye in the reduced knowledge of the indicators that was identified in the lower altitude communities.

Given that no long climatic records were available in the area, climatic data from 5 nearby highly correlated stations (El Alto, Patacamaya, Viacha, Bolsa Negra and Achachicala) were statistically correlated with the available data (three years) coming from the stations installed in the basin. As such the historic data was reconstructed and analyzed in its trends.

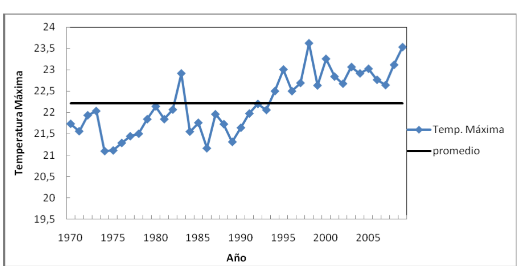

Figure 6: Maximum temperatures reconstructed for the studied area, period 1970-2009 (García & Taboada, 2010).

The reconstructed series (Figure 6, Figure 7 and Figure 8) show a clear upward tendency for temperature (high significance in the Mann-Kendall test) while a less clear reducing trend is appreciated for rainfall (no significance).

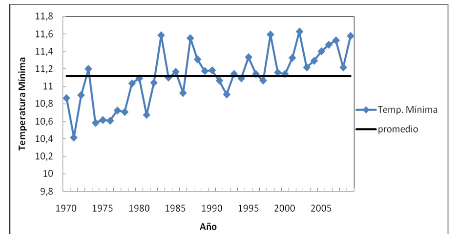

Figure 7: Minimum temperatures reconstructed for the studied area, period 1970-2009 (García & Taboada, 2010).

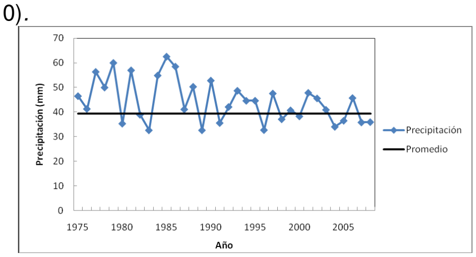

Figure 8: Total monthly precipitation reconstructed for the studied area, period 1970-2009 (García & Taboada, 2010).

Thus, farmers' perception on temperatures increase is confirmed, but the perception concerning a reduction in the precipitations is not verified. Related studies (Seth et al, 2010) indicate that between latitudes 10 to 20ºS, it is observed that the total precipitation amount is almost maintained but it is the temporal distribution that is changing. Less precipitation is expected during the spring (Sept-Nov), delaying the beginning of the rainy season; more precipitation is expected from December until April; and then, a faster reduction is expected at the end of the rainy season. This explanation fits better the drought perception of farmers. Then, under a warmer scenario, a shorter rainy season and the glacier retraction might provoke situations where temporal water saving and storage structures should be promoted.

4.2.2 Productive vulnerability

4.2.2.1 Changes in cultivated surfaces, agricultural activities and agro-bio-diversity

During the last 20 years, crops systems have changed (Table 7). Thanks to the increasing temperatures, the studied communities are expanding their productive areas upwards where, at present the possibility exists to cultivate fruits and maize. However, the improvement of road connections in 1985, also affected strongly thanks to a large market integration of the communities. The most important limitation for production is the very small size of land (**Erro! Fonte de referência não encontrada.**). Properties vary from 250m^2 (in Tahuapalca, with a maximum of 1ha) to 4ha (in Khapi).

All those factors (small size of land, more market integration and higher temperatures) are changing the lower communities farming systems, to more intensive (two or more harvests per year) and more profitable crops like lettuce and they shifted from agro-forestry to a completely agricultural system.

Table 7: Cultivated crops produced in the studied area (farmers %) (García & Taboada, 2010).

Crop	Khapi		Tahuapalca		Cebollullo	
	I	II	I	II	I	II
Potato	100	100	0	0	0	68
Maize	80	95	15	72	15	70
G. bean	60	50	0	0	-	-
Lettuce	30	-	95	0	87	0
Tomato	0	0	25	6	15	0
Gladiolus	0	0	15	0	10	0
Parsley	0	0	0	68	-	-
Fruits	15	0	2	70	0	70

I Present (2010)
II 1990

Table 8: Cultivated surface (%) per size ranges (García & Taboada, 2010).

Cultivated area (m^2)	Khapi	Cebollullo	Tahuapalca
<2500	10	60.0	62.5
2501-5000	35	22.9	21.9
5001-10000	25	11.4	15.6
>10000	30	5.7	-

The intensive mostly monocropping pattern improves the economical condition of farmers, but is already reducing soils fertility and increasing the impact of crop plagues and diseases with resulting higher use of fertilizers and pesticides.

Climatic constraints are not significant in Tahuapalca and Cebollullo because most farmers are connected to the irrigation system and frosts are not frequent. On the other hand, Khapi's production systems are very exposed to climatic events due to their higher altitude (hails are more frequent and strong there) and only part of the farmers are connected to irrigation systems.

The changes in agricultural practices are increasing production losses' risk. During 2008-2009, more than 80% of the population reported important agricultural losses. The principal perceived causes are presented in Table 9. Plagues and diseases are the most frequent causes of production losses in all communities; climatic events affect much more to Khapi while market prices impact harder Cebollullo's economy, showing their high market dependence. In general, results suggest that the change in agricultural patterns is improving farmers' life quality but land size is a big constraint and the sustainability of the system is still to be analyzed in the long term.

Table 9: Main perceived causes of production losses (2008-2009, García & Taboada, 2010).

Community	Plagues, diseases	Climatic event	Low market prices
Khapi	80	100	15
Cebollullo	100	28.13	43.8
Tahuapalca	82.9	31.43	27.6

4.2.2.2 Irrigation availability, frequency, efficiency and requirements

There are 15 irrigation systems in the basin (Figure 9 and **Erro! Fonte de referência não encontrada.**. The systems present overlapping in water use, the excess of irrigated water or the remaining water in a canal is used by downstream areas/canals, even if they belong to other communities or systems. Table 10 shows the irrigated area per community. (Villarroel, Perez, Castel, & Torrez, 2010).

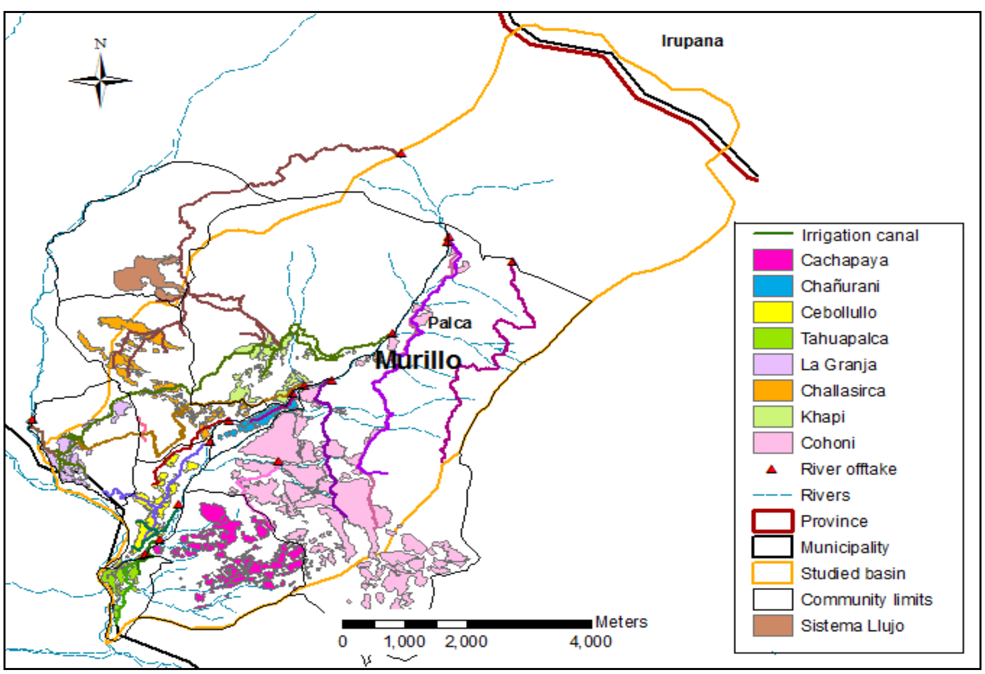

Figure 9: Irrigation systems in the studied basin and their irrigated areas (Villarroel, Perez, Castel, & Torrez, 2010).

Table 10: Irrigated area per community (Villarroel, Perez, Castel, & Torrez, 2010).

Community	Area (ha)
Khapi	43,12
Cebollullo	37,43
Tahuapalca	19,03
La Granja	33,91
Challasirca	68,47
Cachapaya	99,76
Chañurani	16,99
Cohoni	375,26
Total	**693,44**

* This irrigated area only takes into account the area irrigated by Canal Llujo, but not the whole irrigated area.

Two types of collective water rights (irrigation systems can include more than one community) and one type of individual right can be identified in this basin (Table 11, Villarroel, Perez, Castel, & Torrez, 2010).

At Collective level, the irrigation period for each irrigation system can be strongly reduced. During summer months the low stream systems practically do not irrigate, depending on the rain, which mostly falls in the upper basin communities like Khapi, Challasirca and Llujo. The most critic cases are La Granja and Tahuapalca, because both depend on irrigation along the complete year, but frequently do not have the availability for it.

Table 11: Type, subject and expression of water rights in the Sajhuaya basin.

Type	Subject	Expression
Collective Right	Irrigation System	Discharge available in the river uptake. Remaining discharge after upstream systems took their part.
	Community	Period with available water in the community canal. During the rainy period it is available every day, during dry period only few days per week.
Individual Right	Family or person	Period with available water in the individual user's canal. Turns only during dry period. Free access on rainy season.

At individual right level, the flexibility of the rules for shifts assignation depends on the water availability; for example, in La Granja (low altitude with highest water deficit), the shifts rules are very strict, they have fixed turns schedules that are applied every year with all users having established schedules without considering the size or type of crops. In communities with less water stress, the shifts are given according to the user's arrival order, the farmers fill a list every day and each user can use all the required water during his turn.

The agricultural characteristics of the three communities (agricultural calendar, crop cycles, irrigation practices, etc.) and climatic data were used to estimate the irrigation requirements for each community following FAO guidelines (Allen, Pereira, Raes, & Smith, 2006), during the historical period 1975-2009 (

Figure *10*, Figure 11 and Figure 12), (García, 2010).

Water irrigation needs increases in all communities due both, to increasing temperatures and larger irrigated plots. As such Tahuapalca's requirement increased 500%, while Khapi only doubled its requirement. The difference is produced by different crops patterns; Tahuapalca produce lettuce with higher water requirements and is sowed 3-4 times per year.

Applied water to lettuce is approx. 796mm while lettuce optimal requirement should be approx. 350mm. Similarly, the applied irrigation to maize is approx. 972mm being maize optimal requirement of approx. 550mm. In summary, irrigation efficiency in this area is very low, because farmers irrigate in function of their water rights and not the crops' requirements.

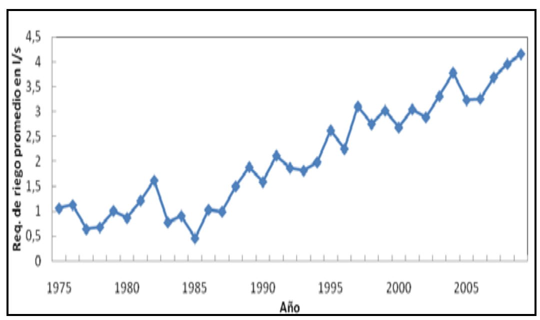

Figure 10: Average annual water irrigation requirement in Khapi community, period 1975-2009 (García, 2010).

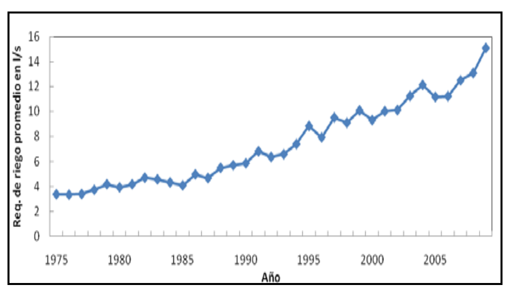

Figure 11: Average annual water irrigation requirement in Cebollullo community, period 1975-2009 (García, 2010).

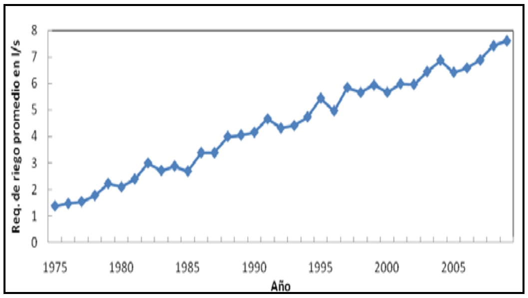

Figure 12: Average annual water irrigation requirement in Tahuapalca community, period 1975-2009 (García, 2010).

In general, farmers in the area only perceive water stress during the two driest and coldest months (June and July), when they must be very strict with the water distribution. Water restrictions and therefore water conflicts are increasing with the irrigation demand (more cultivated surfaces, change to more water consumptive crops, more continuous planting, increased evapotranspiration demand, etc). Nowadays, Tahuapalca and La Granja must irrigate during almost the whole year. If the Glacier continues retracting all these communities will have water for irrigation only during the rainy season.

4.2.3 Socioeconomic vulnerability

According to the last national census, Cohoni Canton (which includes the studied communities) has a population density of 23hab/km^2 (INE, 2001).

The average number of persons per family in the monitored communities is presented in Table 12, which is an important income indicator in rural areas where the families are characterized by their double production: direct production (work in familiar productive activities) and reproductive production (new members can enforce the direct production or they can work outside the family activities with an external salary). Considering that the average family's property in this area is 1 ha, it can be affirmed that the man power of an average family (3 to 5 persons), is enough to fulfill most of the land work requirement without hiring other workers.

Table 12: Average number of persons in each family. Tahuapalca, Khapi y Cebollullo communities (García & Taboada, 2010).

	Number of persons per family					
#	**2**	**3**	**4**	**5**	**6**	**7**
%	12.64	18.39	14.94	16.09	11.49	11.49

The age distribution in three monitored communities is presented in Table 13. Similar distribution is observed in the three communities, where Adults (25-60 years) are more than 50% and the Elders (>60) are the minority. The young people proportion in these communities is higher than the average in rural areas (where migration to big cities is usually higher).

Table 13: Age distribution per community (García & Taboada, 2010).

Age (years)	Population percentage (%)		
	Khapi	**Cebollullo**	**Tahuapalca**
Young (19-25)	20	28.6	25.7
Adults (25-60)	65	62.8	51.4
Elders (>60)	15	8.6	22.9

According to the census, 46.8% of Palca's population is living in extreme poverty. The average income per capita is 652 $uS/year(INE, 2001). This poverty indicators show their elevated vulnerability to any external stress or climatic extreme events because their very low incomes (for subsistence only) limit them to make any investment to reduce their vulnerability, especially to protect their agricultural production that is their principal income (eg. pressurized irrigation, fertilizers, reservoirs, protection structures, etc.).

Education is a key development index that improves the communities' capacity to solve their own problems, accepting and applying new technologies and strategies, which benefit their production (Lacki 1995, Iqbal 2007, Mgaba-Semgalawe 2000, Namara et al., 2007).

There are 7 school units in the studied area: Cachapaya and La Granja communities have units from 1st to 3th of primary level. Cebollullo, Challasirca and Chañurani communities have units from 1st to 6th of primary level. Only Tahuapalca and Cohoni communities have educational units with complete educational levels, from 1st to 4th of secondary level where the students of other communities must assist to finish their high school education.

Table 14 shows that more than 65% of parents assisted to primary level (well distributed primary schools in the area). However, the secondary level was reached by a much smaller proportion, 77% of the parents with secondary level are young people (19-35 years old), which is a promising indicator of change. More than 70% of the parents with secondary level live in Tahuapalca thanks to the closest location to secondary level school).

Table 14: Educational level of the parents in Tahuapalca, Khapi y Cebollullo communities (García & Taboada, 2010).

Educational level	Observed proportion (%)	
	Husband	**Wife**
None	2.47	7.69
Preschool		2.56
Primary	67.9	80.77
Secondary	27.16	7.69
Σ	97.53	98.71

Similarly to other rural areas, approx. 80% of women have primary education, but less than 10% reached secondary level (mostly young people, 19-35 years old).

In general, the analphabetism index in these communities is less than the observed in the whole Municipality (PMA, 2002). The educated people percentage is increasing; most of them are young, which can reduce their future vulnerability.

Approximately, 30% of the interviewed families have salaried extra activities (very common in rural areas of this region). The husband is the most common family member that sells his working power in extra activities (92%); sometimes, the older sons also help (4%).

The most common extra activities are presented in Table 15. More than 50% of the people with extra activities work as salaried construction worker.

The actual improvement of the profit opportunities with market integration and more intensive production is keeping this population away from a massive migration to work in big cities like in other areas of the country.

Table 15: Identified extra agricultural activities (García & Taboada, 2010).

Extra agricultural Activity	Observed proportion (%)
Agricultural worker in another owner's land	12%
Salaried construction worker	66%
Salaried vehicle driver	8%
Machinery operator	12%
Σ	98%

Migration rate in the studied area is lower than typical rural areas (less than 10%). The interviewed people's perception affirms that migration increased the last 10 years (91.95%), few says it is the same (5.75%) and the least says it has decreased (2.3%).

After the 90's, most of the interviewed people went outside the community for their first time (77.27%), while only 13.64% did it between1970 and 1990 and 9.09% did it before the 70's. This change could be the influenced by the roads improvement, but also by the age of the interviewed persons.

An important amount of residents in this area are already migrants that arrived from the Andean plateau after the Agrarian Reform (1952), which increases the proportion of interviewed people with family outside the communities (72.4%). Only 13.1% of familiars living outside the communities help economically to those who remain.

The low migration in the area is thanks to their recent market integration which has improved their profit opportunities, generating permanent incomes. However, the increasing water demand together with the glacier's retraction (reduce in water offer) could increase future migration rates in the area.

4.2.4 Institutional vulnerability

4.2.4.1 Governmental institutions

Municipal Government of Palca

This institution has a Section for the Development of Agricultural Production, but it does not have any department related to environment, natural resources, climate change or disasters' prevention/assistance.

Since 2004 until 2009 the Mayor has been changed seven times. This situation limits the municipal structure, planning and development.

National Service of Irrigation (SENARI)

This institution depends on the Irrigation Viceministry. It has to regulate, plan, manage, and promote the government investments to develop the irrigation for agricultural and forestall production.

This institution develop four projects within the Palca municipality: "Rehabilitation of the microirrigation Hampaturi", "Rehabilitation of the microirrigation system Hampaturi", "Rehabilitation of the irrigation canal Retamani" and "Irrigation project Khapi".

National Program of Climate Change (PNCC)

This institution developed the project "Adaptation to the impact of accelerated glaciers retraction in the Tropical Andes" (PRAA), financed by the Global Environment Fund. The project pretended to implement a basin integrated management plan for adapting agriculture and livestock farming to the deregulation and reduction of water sources that the glaciers retraction causes in the Bolivian Andean plateau and the high valleys. The results of this project did not reach this municipality due to a poor diffusion.

Mayor de San Andrés University (UMSA)

It is the only governmental institution investigating and working on climate change in the area.

Others

According to the Palca's Municipal Plan of Development, other governmental institutions in the area are: District Educational Direction, the National Police, and the Municipal Network of Health.

4.2.4.2 Social actors, organizations and associations

The communities in this area have Aymara's origin, thus, they are organized in "ayllus" and Agrarian syndicates at each community. Families play an important role in the community organization and economy.

Due to the absence of a formal administrative organization from the municipality, the social organizations, through their traditional local authorities must promote the planning and development of their area.

Local organization

Palca municipality is composed by three "cantones": Palca, Quillihuaya and Cohoni. Each "canton" has a neighbors' assembly. The studied area is located in Cohoni's canton (which organization is schematized in Figure 22). Cohoni community is a special case; it is a Cantonal Central that includes also the Agrarian Centrals of Khapi and Kayimbaya.

Except Cohoni, the other studied communities are part of Khapi's Agrarian Central and then, from Tahuapalca, Llujo and Pinaya Agrarian Subcentrals (**Erro! Fonte de referência não encontrada.**).

Table 16: Organizational scheme of Cohoni "canton" (Torrez, 2011).

	Agrarian Central	Subdivision
Cohoni's Cantonal Central	Cohoni's Cantonal Central	Arasaya
		Pucarani
		Tiwanaku
		Caripo
	Khapi's Agrarian Central	Composed by 5 Subcentrals and aprox. 25 communities
	Kayimbaya's Agrarian Central	No available data

All authority positions in each Agrarian Central are rotational, they change every 2 years. Each position is democratically elected among the Subcentral and the corresponding community in turn. The turn of each community is fixed since the Haciendas period. The following positions are established in Khapi's Agrarian Central: General Secretary, Relations Secretary, Justice and Conflicts Secretary, Financial Secretary, Ways and Viability Secretary, Communication Secretary, Sports Secretary, Agriculture and Livestock Secretary, Acts Secretary, and 2 Vocals. Each syndicate has meetings every, two or three months, in some cases, when it is necessary, they have monthly meetings.

The Agrarian Centrals are part of the Syndical Federation of Farmers of La Paz. Because the irrigating workers do not have a separated organization, they are not part of the Departmental Association of irrigating workers of La Paz which limits their representation at province and municipal levels to promote their irrigation projects.

Each community has its own Agrarian syndicate (very common in all rural communities based on important former Haciendas).

At Agrarian Syndicates, all authority positions are also rotational but changed every year. Everybody in the community has the obligation of assume an authority position by turns, this is very positive to ensure that every water user knows his rights, the water uses and customary rules. In this case, this knowledge is not only for few authorities (like in other places).

In most communities, the responsible for irrigation water is the General Secretary, sometimes together with the Agriculture Secretary. Only Cebollullo community has 3 Canal Presidents (one per each canal in this community).

The responsible authority for domestic water is more variable, some communities have an extra responsible called water committee, plumber, domestic water responsible; in Khapi the responsible is the Social Prevention Secretary.

The "cabildo" is an assembly that gathers all the farmers in the area to take important decisions in the municipality. The responsible to ensure the execution of these decisions are the authorities of the Agrarian Centrals, Subcentrals and Syndicates.

4.3 Autonomous adaptation strategies

The most traditional adaptations of Andean systems, to prevent climate variability and climate change, are the following (García & Taboada, 2010) (Villarroel, Perez, Castel, & Torrez, 2010):

- The typical vertical spatial occupation at communal level, which means to have communal land over more than one ecological stratum. Before colonial times, the range could undertake several strata, even discontinuous spaces, but due to the impact of the Colonial and Haciendas periods this structure has been broken resulting in communities with relatively small altitudinal range. However, even with its reduction, the vertical spatial occupation can still be considered a potential adaptation strategy for food security.
- Each family uses to have access to almost all the community's ecological strata (in the later years it is decreasing due to population increase, migration and others). In this way the family can have wide crops diversity, the basis of food security. This arrangement also ensures the survival of crops at least in one ecological stratum during extreme weather conditions.
- At each ecological stratum, the crop plots dispersion decreases the plagues and illness propagation
- The soil conservation, to prevent soil erosion, is improved by having small plots in very steep hills, while bigger plots in less steep hills. This terraces cultivation also improves the retention and absorption of water.

- These communities also developed a system called "aynoqas" which ensures a constant crop rotation than prevents the productivity reduction usually caused by monocropping. However this system is present in very few places nowadays.
- The increase in temperatures observed since the 80's is generating that more crops can be cultivated in the area, even at altitudes were previously it was impossible or not profitable (eg. Gladiolus flower). Nowadays it is possible to cultivate the year if the irrigation is enough during the dry season. This benefits the food security but stresses the irrigation systems operation because the water demand has increased a lot.
- The improvement of the access to the studied area after 1985 promoted the commercialization of the products in La Paz and El Alto, two close big cities, generating the change from agriculture of subsistence to a more intense one.
- The pressure of the market is also promoting the almost monocropping of more profitable crops which sometimes require external supplies (e.g. lettuce, the most profitable crop, cultivated in the lower part of the basin). This lost in agrodiversity and the increasing temperatures are turning the system more vulnerable to plagues, external supplies provision and the external market prices of few products.
- In several and very different irrigation systems, it was observed that water management is more complex as water deficit is more pronounced. This studied area is located in the intermediate level, where the systems start to make the rules more complex due to an increase in water deficit or water demand.
- The usually small properties are inherited and divided between all the sons of a family generating every time smaller properties and a impassable subsistence economy because this farmers do not have enough land to try bigger inversions or to get productive credits. This situation promotes the migration to the big cities, which for the moment is not so important.

5. Conclusions

The different degrees of application and acceptation of management rules show that these communities have a high degree of flexibility and potential adaptability to changes in the ecosystem and therefore to possible impacts of climate change.

It has been estimated that the Illimani Glaciers had lost approximately 21% of its area since 1963 until 2009, with a rate of 4.4 ha/year. The loss in permanent snow thickness during the same period varies from 3.5m until even 35.6m, depending on the location of the selected profile, which means average rates of loss between 7.7 and 77.4 cm/year.

Glacier mass losses (surface and thickness) depend on the morphologic characteristics of the basin, mainly on the altitude, slope, orientation and size of the glacier front.

Other studied tropical glaciers show an evident change in melting tendencies at the middle 70's or the beginning of the 70's. However, the Illimani Glacier shows a homogeneous tendency that can be attributed to its high altitude (6300m.a.s.l.) and its remaining recharge area (principally in the Amazonas's basin).

The Illimani Glacier is still on relative balance, but if the temperatures continue increasing and the rainfall patterns changing, the melting rate will become faster and devastating for the downstream people depending on its water resources.

There are several sources that can unbalance or perturb a typical agricultural production system, like the constant damage during its productive activities, the contradiction within its operation rules, the surrounding socioeconomic changes, and the stressing climatic events. All these factors are constantly changing the systems' structure in a dynamic way. To survive all the perturbations, the systems must enforce their adaptability to new changes.

Some autonomous adaptation strategies to climate change are successfully being applied by these communities. The increasing agro-forestry-diversity on the upper part of the basin, caused by the increasing temperatures reduces their vulnerability by ensuring food security and self supplying broader spectra of products. The introduction of more profitable products also reduces their vulnerability by increasing their savings, an important factor to face extreme events.

However, the lower basin's tendency to a more intense production based on monocropping is fitting the situation at short term (it reduces vulnerability by improving their economy), but it can result dangerous and not sustainable at long term because it is increasing the vulnerability to environmental problems like the lost of fertility, the increase of crop plagues and diseases, and the contamination by using irresponsibly pesticides.

These fragile mountainous systems, in general, are very vulnerable to external impacts, including climate change due to their weak economies and institutions. Additionally their institutional stability is not promising and seems to weaken more in the future, which could hamper their adaptation possibilities.

The plans to enforce the adaptability of agriculture in the studied area must include integral actions that seek the sustainability of the productive system, improving the water and environmental management, strengthening their institutional organizations and ensuring a fairer insertion of these communities to the market.

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