CLIMATE CHANGE AND THE POTENTIAL FOR CONFLICT AND EXTREME MIGRATION IN THE ANDES: A COMPUTATIONAL APPROACH FOR INTERDISCIPLINARY MODELING AND ANTICIPATORY POLICY-MAKING

by

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A Dissertation
Submitted to the
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of
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In Partial fulfillment of
The Requirements for the Degree
of
Doctor of Philosophy
Computational Social Science

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Dedication

To my wife, Diana, and my son, Rafael, for being a daily reason to give the best of me. This work had no meaning in my life without them.

To the Magallanes Latinez siblings (*mis viejos*): Alfonso, Consuelo, Yolanda, Leonor and Jorge; whatever I have of good in me, it is due to their effort.

To Mom and Dad, for their support and love.

To my closest relatives and friends, especially my in-laws, for enjoying my successes.

To God, for giving me so much in life.

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Abstract

CLIMATE CHANGE AND THE POTENTIAL FOR CONFLICT AND EXTREME MIGRATION IN THE ANDES: A COMPUTATIONAL APPROACH FOR INTERDISCIPLINARY MODELING AND ANTICIPATORY POLICY-MAKING

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I present an agent-based model to support the thesis that extreme migration and social conflict can emerge by simply extending the current social and natural conditions, and by replicating simple mechanisms at the individual level. To carry out this work, every available information on water supply and demand has been collected and organized using official data sources, producing a baseline dated in 2011; and the basic demographics of the population has been implemented using the last official census (2007). Based on these data, many computations have been made to find, calibrate and represent the trends in population growth and water balance. For the basic mechanisms at the individual level, field work guided both by theoretical considerations and ethnographic findings has been done. A key assumption on the processing of information, not identified from the field work, has been introduced via a Bayesian belief updating mechanism.

To sustain the emergence of migration, the information collected from the empirical work has allowed me to identify the hypothetical mechanisms that a person will use when facing extreme water scarcity, and how this situation will force him or her to migrate. In the same way, the emergence of conflict is sustained by the identified reactive mechanism that will lead people to become frustrated or relatively deprived. For the rural case, peri urbanization and immigration are assumed to play a critical role for the potential of conflict; for the urban case, it is population growth and negative water balance the key elements assumed to condition migration and conflict.

A model has been calibrated to represent the urban and rural areas of Huancayo, the most important province of the Central Andes in Peru, which strongly depends on the Shullcas river for water supply, a source that will soon be negatively affected by the total retreat of the local glacier Huaytapallana. The findings of this work help policy makers identify clearly that urgent measures are needed to create a system that saves at least the 13% of water from the rainy season to alleviate water needs during the dry season, so to avoid the emergence of these social problems in the next 50 years.

Chapter 1: Motivation

1.1 Research Questions

This work has collected information related to the current trends on water balance, population growth, and glacier melting in the most important city of the central Andes of Peru, Huancayo. As these trends may continue, I want to know what are the potential social issues that may arise, namely:

- Is it possible that extreme migration patterns will appear?
- Is it possible that social conflict will emergence in the area?

This work supports the hypothesis that those questions have affirmative answers, if no anticipative action is carried out. To test this hypothesis, I have organized multiple sources of knowledge and information into a logical account of this possibility. From there, I have built an agent-based model to transform this knowledge into an interdisciplinary computational tool. This will allow me to foresee different scenarios that may arise from my logical assumptions and information available.

The area chosen, Huancayo[1], is currently under study by different scholars and institutions whose objectives are similar yet lacking interdisciplinary integration. Different public research institutes are working to produce either glaciological, hydrological or climatological updates on the area; isolated researchers are doing small-scale models to either alert of different local water risks or propose adaptation programs in the communities more likely to be affected by the nature trends; while political authorities agenda is dominated by a modernization discourse that sees in the growth of cities the unavoidable sign of progress.

[1] I am using the name of the Province of Huancayo, but I am precisely dealing with the area that comprises the political Districts of Huancayo, El Tambo and Chilca that depend on the water from the Shullcas River.

This situation has led to a partition of the problem of water scarcity in the area and its implications among national, regional and local public officers and politicians, where each tries to solve a piece. So as of today, no model exists to allow knowledge integration and support political coordination.

Water scarcity and droughts have an slow onset, so as time passes by, the majority urban and rural settlers do not pay much attention to this issue. These people in the watershed are not experiencing a critical condition, or at least not worse than the country-wide average conditions. In this situation, this work is presented in the right moment to serve as an input for anticipative political decisions, as neither are effective measures currently implemented. However, as it is clear, the presence of different actors with different goals and beliefs, makes it challenging for mainstream modeling techniques to provide the right guidance. So this work hopes to contribute methodologically to avoid a negative future for Huancayo.

1.2 Justification

I consider that this work is worth the effort for five reasons, namely, geopolitical relevance, geographical, methodological novelty, epistemological debate, and axiological considerations:

1. Huancayo has geopolitical relevance due to its location and economic situation. It is located in the middle of the only highway between the central jungle and the Lima, capital of Peru, being the only city with services and facilities any modern citizen requires. Besides, its local entrepreneurs have established an economy based on market trading and tourism, which has been enough to become a preferred destination for immigrants coming from the poorer neighboring communities since the last century. To the east, the central jungle offers the least densely populated region of the country and provides fruit and coffee for national and international markets, while getting the 90% of water caught by the Andes. Unfortunately, the jungle is a source of illegal, though attractive, logging and coca cultivation and cocaine processing; to the west,

Lima is the most populated city in the country (the 7^{th} most populated in America and the 26^{th} in the world), and even though it is a major source of highly-qualified employment and services related to them, it is a place of increasing inequality. Nobody is talking of conflict or massive emigration from Huancayo, but, if either of them happened, it would be important to have an idea of when that can be expected, who would go to Lima or the jungle, and what should be done to avoid negative scenarios.

2. Geographically, the case selected is a representative case for an environmental issue threatening the South America. From Figure 1.1, the Andean countries are highlighted as one of the mountain areas suffering the retreat of glaciers worldwide. However, the

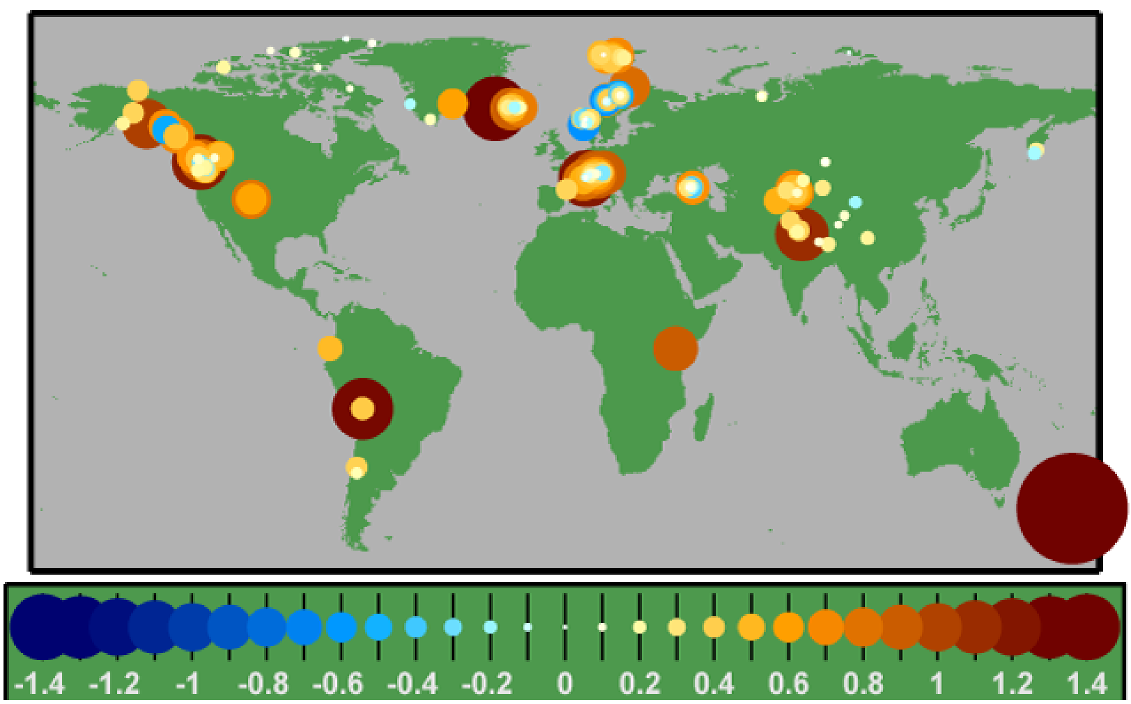


Figure 1.1: World glacier thinning in meters/year (since 1970).
Source: `wikimedia.org/wiki/Glacier_Mass_Balance_Map`

case of the glaciers in the Andes is different from the glaciers in other zones of the planet. In general, glaciers melt in summer and recover snow during winter. The *middle latitudes glacier*[2] are also retreating but they follow that pattern [1]. Here one can find the Himalayas; the Alps; the Pyrenees; Rocky Mountains and Pacific Coast Ranges of North America; the Patagonian Andes in South America; and mountain ranges in New Zealand [2]. However, the Andes glacier, located between the Tropic of Cancer and the Tropic of Capricorn, have different patterns [1, 3] that require attention:

- The Andean glaciers are located in the warmest part of the world.
- The temperatures are warm year round, resulting in a lack of a colder winter season in which snow and ice can recover.
- The glaciers are in mountains, on average, shorter than the ones in the middle latitudes, making most of the Andean glaciers smaller than those found elsewhere.
- Related to the previous differences mentioned, they are the most likely glaciers to show rapid response to changing climate patterns. As of today, the forecasts state Kilimanjaro glaciers will disappear by 2020 [4]; and the same fate will follow the remaining glaciers in Oceania [5], also by 2020.
- However, the African and Oceania glaciers represent only the 0.36% of these *tropical glaciers*, and the Andes of South America represent 99.64% of tropical glaciers [6].

It is also worth mentioning that Huancayo and the Huaytapallana, as well as other five tropical glaciers (see Figure 1.2) were selected for glacier monitoring, an initiative from the Andean Community of Nations between 2009-2012. Most of the data for water balance in this work came from the material produced during these years.

3. This work also represents methodological novelty for policy making. As the mainstream policy making techniques follow a top-down approach, a bottom-up approach

[2] between the Tropic of Cancer and the Arctic Circle, or between the Tropic of Capricorn and the Antarctic Circle

Figure 1.2: Relevance of Huaytapallana for Andean countries.
Source: `http://www.comunidadandina.org/Cooperacion_mapa_PRAA.aspx`

is be proposed to complement the policy process, bringing a new road to allow the integration of inductive and deductive techniques.

4. Related to the previous, this work expects to raise epistemological debate as it represents an attempt to harmonize different kinds of data and knowledge, expecting also to present key insights for interdisciplinary research supported by innovative methods heavily dependent on computational tools. This represents a particularly challenging opportunity for computational social science to demonstrate its versatility to deal with coupled systems.

5. Finally, this work introduces a case for understanding the dynamics of urban sprawl in the developing Andean countries affecting rural populations and landscapes. I expect that its dissemination serves to do better policy making as local stakeholders are taken

into consideration, bringing into further discussion issues related to gender, inequality, deprivation, and discrimination, which even though are not considered explicitly in the model built, there may be many reflections that could be guided out of the modeling process and results.

1.3 Literature Review

There have always been changes in the climate that have taken us to where we currently are; however, at the beginning of the 21^{st} century, we are all wondering where these changes are taking us. These changes may mean the end of the modern development paradigm, the human race or simply a different configuration where our knowledge and technology will bring a new world very different from the trajectory started since the beginning of the Holocene. These concerns are the focus of the Intergovernmental Panel on Climate Change (IPCC), which after five reports since 1990 [7–11] keeps reaffirming that the earth temperature trends will harm every ecosystem and that new approaches to policy and political decisions must be adopted. In these reports, the IPCC brings us a world view that makes one think humans know what is really going on. The truth is that all these compendia are only rich at a very aggregate level, and have been produced presuming that each country has an adequate system to measure what is requested. That is, we can not expect to know much of the problems faced or yet to be faced by local areas around the world. In this situation, methodological issues arise as local sufferings need particular research [12–15] to prevent models working with national averages from biasing decisions excessively. The process of going deeper into a particular local scenario does not diminish complexity, however this work is a particular situation where I need to increase the availability of qualitative and quantitative local data to improve my understanding of the system chosen and enhance local anticipative policy making capabilities. This approach has been followed by different researchers combining official data with fieldwork in different case studies.

Research interests dealing with climate change are varied, but they tend to have a common interest in rural populations, especially vulnerable and located in developing countries. Ziervogel et al.[16] focuses on modeling decision-making and forecasting of farmers in Lesotho, in an scenario where official forecasts, besides poorly done, are not diligently nor appropriately disseminated towards these end-users, making them more vulnerable as loses due to poor information endanger the farmers'survivability. The same research design is also found in Bharwani et al. [17] for smallholder farmers in a village in Vhembe district, Limpopo Province, South Africa. More recent and more comprehensive approaches are found in Kniveton et al. [18] and Hailegiorgis [19]. The former has Burkina Fasso as its case study, investigating the role of the environment in the decision to migrate using scenarios of future demographic, economic, social, political, and climate change in a dry land context. In that work, these authors found that change to a drier environment produces the largest total and international migration fluxes when combined with changes to inclusive and connected social and political governance, while the lowest international migration flows are produced under a wetter climate with exclusive and diverse governance scenarios. And the latter focuses on the South Omo zone in southern Ethiopia, modeling how the current surge in large-scale land acquisition might affect rural livelihood. In his work, Hailegiorgis found that (i) the occurrence of drought exceeds their adaptive capacity and forces migration; (ii) increasing the magnitude of expansion of large-scale land acquisition aggravate dispossession and increase migration of rural households; and (iii) capacity building and relief support in the time of extreme events minimizes migration. All of these studies made use of agent-based models using diverse platforms (Netlogo [20], Mason [21], and AnyLogic [22]).

As it is clear so far, climate change stresses the place where human activities are carried out, thus deteriorating the quality of the environment of these populations forcing them to make different decisions, which, as Hirschmann proposes [23], can be categorized as exit, voice and loyalty. The previous cases speak of exit, as people emigrate looking for better conditions as the climate damages their well-being; but, the confrontational and loyalty dimensions in social complexity issues also need to be analyzed under climate change effects.

However, loyalty and voice seem to be less treated from the global computational social science community, which should be considered quite shocking as reports related to climate change and conflicts are abundant [24–26]. Related to conflict and climate change, Piontek [27] studies the Nile River, which serves 10 countries in Africa, seeking to understand, via computational modeling, how the interaction between humans and the environment may lead to conflict or cooperation. In this work, the author found that climate change can alter conditions for conflict and cooperation, but is very unlikely it is the immediate cause for those issues. Nevertheless, the outstanding work related to climate change and the emergence of conflicts can be found in the works produced at the Center for Social Complexity at George Mason University the projects funded by the Multidisciplinary University Research Initiative (MURI) and Cyber-Enabled Discovery and Innovation (CDI) programs [28–30]. The former focuses on the complex interaction of pastoral groups with their environment and other emerging external actors in east Africa. It finds that increased seasonal rainfall variability and droughts create tremendous stress on pastoralists groups and challenges their long-term resilience and adaptive response mechanisms, thus concluding the population's relation to the carrying capacity seems to be the major factor affecting cooperation and conflict. The latter, the *Mason-Smithsonian Joint Project on Climate Change and Societal Dynamics*[3] (where I collaborated), focuses on how human communities in Africa and the northern hemisphere respond to changing climate. This has served as the main benchmark for this work.

My research complements the current studies in many directions:

- First, the object of study is not a particular kind of population (as it is the case in most studies) but it studies simultaneously vulnerable but not marginal rural populations, and an urban population of the close metropolitan area; so the water issues will be of concern to two different kind of groups with different necessities on water, which may be the starting point for inter-group conflict [31].

- Second, this agent based model will include the effect of a glacier in the water supply

[3]https://socialcomplexity.gmu.edu/projects/climatesociety/

for the social system, facilitating the analysis of similar systems by separating the precipitation (rainfall and snow melt). This separation, as far as I know, has not previously been done in an model of this kind, which is a particularly important, considering that I am dealing with a tropical mountain glacier, the ones more prone to irreversible melting [32].

- Third, the watershed under analysis may be a representative case for the whole Andes chain, as it is at the center, among the dry biggest cities on the west and the sparsely inhabited Amazon jungle to the east.

- Fourth, it will integrate and harmonize current modeling efforts on the glacier melting trend, the hydrology dynamics and the social behavior; making my work more challenging as these systems have never been integrated before bringing into question the validity of my results.

- Fifth, and related to the previous point, the issue is not of particular concern neither to the majority of the population nor to the political authorities; it looks as though nobody wants to touch the situation as it may collide with the current way people live and benefit. This work also continued with the best practices in computational social science (CSS) research used by the previous studies, as it integrated the complex adaptive systems approach [33], the CSS consolidated techniques [34], and ethnographic work [12].

- Finally, this work particularly complements the current research agenda at my home institution, the Center for Social Complexity (CSC) at George Mason University, where the model Northlands [35] is being developed, and whose preliminary results demonstrate causal processes relating ambient and soil temperature increases to measurable social impacts, mediated by biophysical effects of climate change on the built environment. My results allow for comparissons between different and distant parts of the world where climate change is endangering societies.

1.4 Organization of the research

1.4.1 Computational tools and workflow

During the planing process of this work, I realized I will need not only to code the model, but to collect and organize data, produce files, and compute simple and advanced statistics from those files. Besides, I will need to create documents and send version of my documents for revision. For that, I have tried to automate the whole workflow using different free computational tools.

I decided to use NetLogo[4], but this tool, as all modeling tools I reviewed, does not have all the statistical analysis tools that I needed. Fortunately, R[5] offers all the data analysis support I needed, which in my case included mapping, survival analysis, network analysis, regression models as well as many visualization libraries. I used R from RStudio[6] to take advantage of several other reason to automate my work. RStudio can compile Latex code using the *sweave* library and can connect with NetLogo via the *RNetlogo* library[7]. This allowed me to produce Latex code that embedded R code that was reading NetLogo output. As any modeling process goes through a series of versions, I decided to connect my working directory in RStudio with Github[8]. A next step was sharing my versions to my Advisor, Committee and collaborators. For this need, *Sharelatex*[9] proved to be a perfect companion, as it allowed me to share clean versions of my work using a *pdf* visualization. Finally, during the last stage of my work, *Dropbox*[10] proved very useful to store the files with the multiple simulations created by NetLogo with its tool *BehaviorSpace*. This allowed me use NetLogo to produce and store files in a computer at the Center for Social Complexity in Fairfax Campus, and then have RStudio read those files from Dropbox at home. These elements are represented in Figure 1.3.

[4] This decision is explained in Chapter 4.
[5] https://cran.r-project.org/
[6] https://www.rstudio.com/products/RStudio/
[7] http://rnetlogo.r-forge.r-project.org/
[8] https://github.com/
[9] https://www.sharelatex.com/
[10] https://www.dropbox.com

Figure 1.3: Computational workflow

The combination of all this tools allowed me to finish this work timely. Any correction done in the model, or in the analysis using R was immediately reflected in the final version of the dissertation[11].

1.4.2 Overview and building blocks

This work has the general goal of producing a base case interdisciplinary model to represent *a possible* future for Huancayo as the water balance becomes insufficient to satisfy the population's needs. I consider this model as a coupled human-natural system, where the model keeps the current trends in both systems and sees whether it is possible to see emigration and social conflict emerge.

The product of this work is an agent-based model programmed in Netlogo [20], which will follow a complex adaptive systems approach, when needed. The model respects particular characteristics of complex adaptive systems: there are many agents interacting dynamically, the agents have bounded rationality, i.e., only aware of local information, the agents have

[11] Any auditing and data recovery will always be available from the GitHub repository. Any person requesting access can email the author at jmagalla@gmu.edu or jmagallanes@pucp.edu.pe for instructions.

ways to establish networks which helps them get information, and history matters as path dependence emerges from the agent decisions. However, this complexity is well *encapsulated* into the model, so the non-expert user can interact with it and even contribute to its improvement.

As the social and natural systems have huge amounts of components, this agent-based model needs to abstract carefully the more important components to capture the relationships hypothesized while still be useful for policy making. Thus, the social system will basically represent the demographics of the area and the urbanization growth; and the natural system will represent the water balance built form the glacier melting and rainfall trends.

As it is represented in Figure 1.4, I have two interacting systems where basic interactions and components have been abstracted. For each subsystem, I have collected different kinds of data; for the natural system all the official data available has been complemented with data produced by colleagues from Peru, USA, Spain, Germany, and Austria who have been doing research on this area in the recent years. Some of this data has been used for the social system, but most of the facts and assumptions related to modeling the agents in the social system have come from field work. This field work started in August 2014 and ended in April 2015, with the cooperation between the Center for Sociological, Economical, Political and Anthropological Research at Pontificia Universidad Catolica del Peru (Lima), and the Department of Anthropology at Universidad Nacional del Centro (Huancayo).

In the natural system, this work focuses on the water supply, as it is the key trigger factor for the social issues of interest in this work. Due to that importance, much emphasis has been placed in collecting data to feed the model with a credible water balance model. As water balance depends on the supply and demand of water, the natural system is responsible for the water supply, which depends mainly on rainfall and snow melting. As the official reports on water supply consider these dimensions only, I have not dared to include more components. The current trend in the natural system proposes both a decreasing supply of rainfall and forecasts the complete retreat of the glacier, which will affect the balance

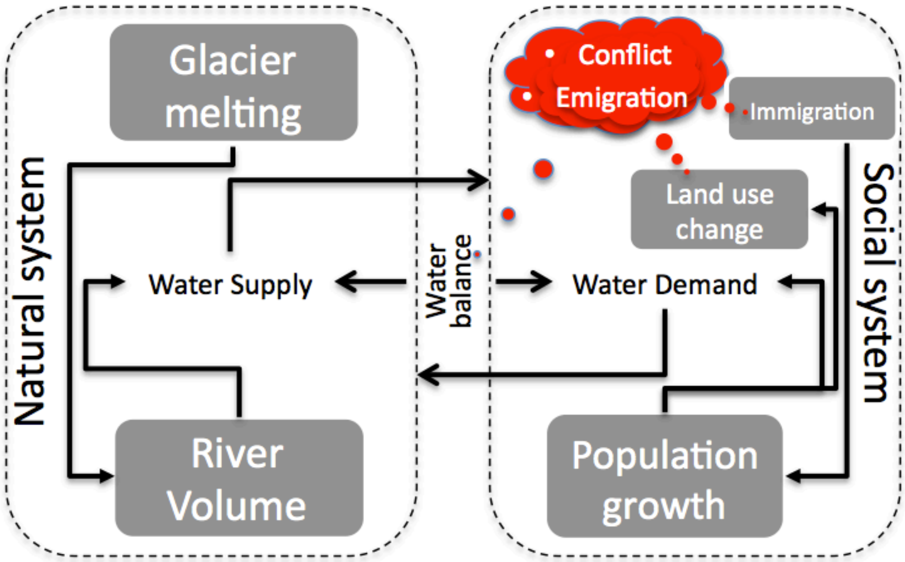


Figure 1.4: Basic model abstraction. The red elements represent the potential outcomes if the other elements keep the current trends

negatively [36, 37]. One obstacle for a more precise model is the lack of information on the snow melt supply, but I will manage to bound that value by eliciting expert opinions and recent measurements available.

On the other hand, water demand comes from the social system, which is represented by two subsystems, rural and urban populations. The basic process in both sub-systems is population growth, that is, eventually there will be not enough water supply for the population's demand. I explore emigration as a particular response (other responses have not been considered at all): there are not many Andean cities having positive population growth but Huancayo metropolis is one of them, so making a case for the opposite phenomenon is politically important. Following the field work on this area, this model tries to give the agent options to avoid migration as water scarcity increases, but the limited local space and agent's satisfaction will eventually leave him no more option than migrate. Another set of demographic variables for the agents are their working, educational and marital status, which are used in the moment the urban agent decide *where* to migrate, that is, those values constrain their free will to chose between moving to the coast or the jungle. I have also considered the immigration parameters in this area, considering that currently Huancayo hosts immigrants from poorer communities nearby, which will be a key factor for conflict to emerge. Precisely speaking, I present a basic heuristic to represent a situation when rural agents are eager to go into conflict due to the presence of *strangers* (the Non-Huancas) in their neighborhood during extreme water scarcity. As it is clear, conflict is a process that can emerge from the urban and rural areas, while migration emerges from the urban area, and not from the rural area, following the results of my field work. However, for a rural agent to migrate, it first needs to have moved to the urban area; and for an urban agent to be perceived as a stranger by a rural one, it needs to have immigrated from another place and established its home in the neighborhood of a rural settler suffering water stress.

This work is comprised of three more chapters. After this one, the second chapter will present the coupled human-natural system where this work takes place.There, I will detail the design of this research, where I will bring in different information so that the place of study can be clearly identified. This will help other researchers decide how this case could be considered in a comparative approach. I assume that Huancayo could be easily compared with similar cities in the Andes (from Venezuela to Chile) if researchers are looking for homogeneous cases. However, other designs may want to stress heterogeneity, and this social system can be a candidate if the phenomena of migration and social conflict are of interest for researchers interested in other tropical glacier areas (Kilimanjaro in Africa) or non-tropical glaciers (i.e. Alps) in Europe or Asia (Himalayas).

For any of these purposes, a comprehensive account of the social situation of the city will be important. I consider relevant demographics and urban growth, as well as cultural and political information on the area. In this chapter, I also present the natural system of the watershed where the city is located. Particularly, I organize the information available on the Huaytapallana glacier, the Shullcas river, the aquifers, and the climate in the area.

The third chapter will explain the implementation of the base model produced in chapter two into an agent-based model, as well as the robustness of the model based on the verification and validation carried out. In the fourth chapter I present the results obtained form the model that answer my research questions and support my hypotheses. In the fifth chapter, I discuss the results from the model in public policy terms, so that political decision makers and stakeholders could find a companion for better decisions, and know how to interpret the results for practical implementation. Finally, I offer a last chapter for summary and conclusions.

Chapter 2: Research Design

This work needs to find answers to the questions:

- Is it possible that extreme migration patterns appear if the current trends in population growth, water balance and glacier melting continue in Huancayo?
- Is the emergence of social conflict in the area possible if the current trends in population growth, water balance and glacier melting continue in Huancayo?

2.1 Hypothesis operationalization

As this work proposes that the research questions have affirmative answers, I propose the following operationalization of variables in the hypothesis, as described in Figure 2.1:

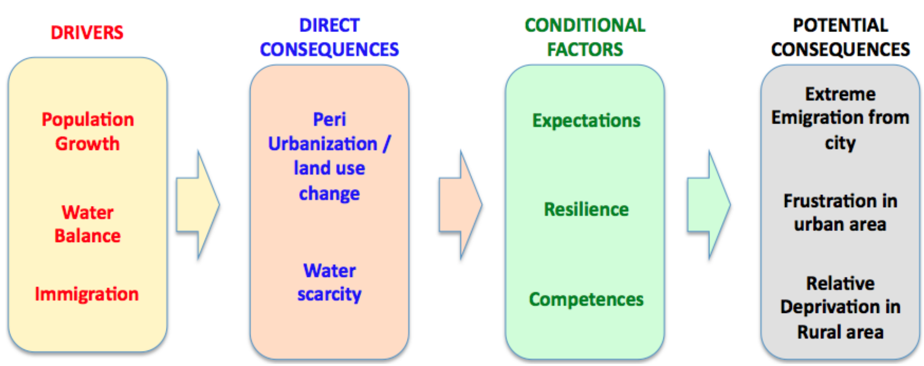


Figure 2.1: Operational variables in hypothesis

The variables present a simple yet comprehensive process to study the potential for conflict and migration:

- The **potential consequences** are chosen as the representation of my framework *exit, voice and loyalty* [23, 38, 39] (previously mentioned and explained later in section 3.4 on page 67). In this case, *exit* is represented by **extreme migration**; *loyalty* by the permanence in Huancayo (not shown); and *voice* by expected reaction from the **frustration** felt by urban people (explained later in section 3.4.2.1 on page 73), or the **relative deprivation** felt by rural people (explained later in section 3.4.2.2 on page 74).

- The **drivers** clearly represent the current trends in Huancayo in the social and natural dimensions [38, 39]. This work proposes a model where these trends are not altered and will show how other factors included explicitly in the model could be managed to prevent the potential outcomes. The assumption that the trends can be extended into the future are based on the historical growth of Huancayo, an example of lack of urban planing since its creation (see section 3.2.2 on page 53). The social trends are population growth and immigration into Huancayo. Population growth already includes the migration balance, but the parameters of immigration into Huancayo will be used explicitly in the model, as the non-Huanca presence is important for the the direct and potential consequences of the model. The water balance trend represents the other important driver, which will be represented by water supply and demand. Water supply will particularly be sensitive to the contribution of the glacier Huayatapallana to the hydrology of the system.

- The **direct consequences** are the clear results of the unaltered trends [38,39]. Based on the dynamics of Huancayo, I have chosen the two most clear direct consequences supported by the literature and field work [40–42]. Water scarcity is a first expected outcome as the water balance and population growth trends remain unaltered. Water scarcity will become a major problem (as explained in [36] and detailed in the next chapter) in the near future, which will combine with population growth and, particularly, immigration to exacerbate peri-urbanization and land use change [40–42].

- The **conditional factors** are processes that work at the individual level, and are the main sources of heterogeneity in the model [38,39]. Every modeled individual will need to find an particular response based on these factors. The factors have been selected from the classical work of Maslow [43] (see Figure 2.2) and its application in agent based modeling to understand conflict situations [44]. According to these individual level factors, I implemented a Bayesian mechanism to compute expectations. Also, I carried out field work to uncover the local resilience and made use of the census data to derive the competences of each individual. The competences closely reflect what determines the potential outcomes [44], that is, of water (physiological needs), work (safety needs), family (belonging needs) and education (for esteem and self-realization needs).

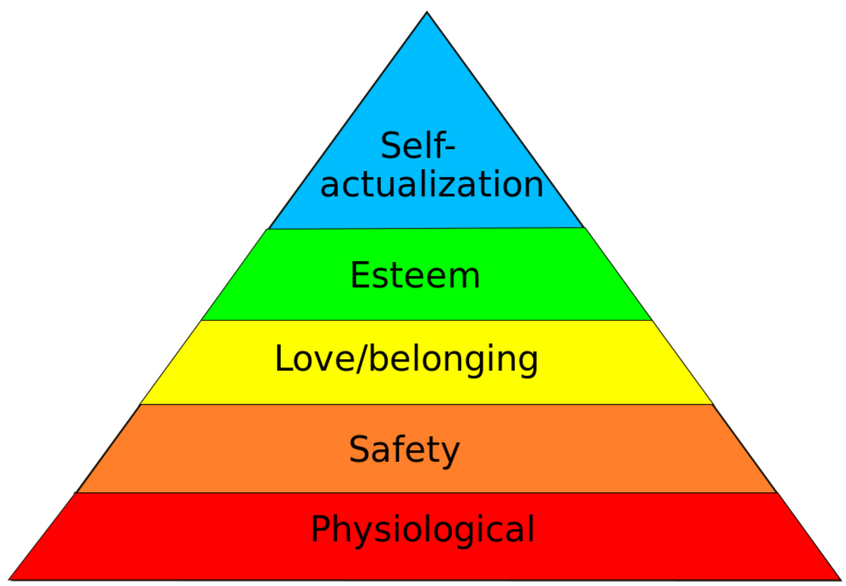


Figure 2.2: Pyramid showing Maslow's hierarchy of needs.
Source: From `http://psychclassics.yorku.ca/Maslow/motivation.htm`

All this information on competences is based on the census data [45] and presented in Table 3.9 on page 69. The data from Table 3.9 reflects the variety of the individuals in the agent based model, but also some restrictions. In the case of this work, no differences are made for *sex*, as the population composition does not reflect a difference in this category. However, the population's age for this model only considers the sub-population for 14 years and older (the age where all the conditioning factors are measured in the official census of Peru) [45].

2.2 Data organization

I collected and organized the following data:

1. Drivers:

   (a) **For Water Supply.** The main data sources are the documents produced by the PRAA[1] project (Proyecto de Adaptacion al Impacto del Retroceso Acelerado de Glaciares en los Andes Tropicales). This project was an initiative of the Andean Community of Nations, which started the study of tropical glaciers in Colombia, Peru, Ecuador and Bolivia. This is the first and only time that information was collected on the Huayatapallana - Shullcas system. This information will be used in section 3.3 on page 61. The data from this project [46, 47] was complemented with other reports from the Ministry of Agriculture [48] and by information publicly available from the local water company of Huancayo (SEDAM Huancayo[2]). As these data was computed only for the years when the PRAA was active (around 2009-2012), the trend in water supply was obtained from the time series organized by Carlos and Grijalva for the period 1995-2011 [36]. The water supply was computed for the whole watershed, and organized into the zones detailed in Table 2.1.

[1] `http://www.comunidadandina.org/cooperacion_praa.aspx`
[2] http://web.sedamhuancayo.com.pe/

Table 2.1: Zones included in the computation of water balance

Districts	Zone type	Zone name	Population (Est. 2011)
El Tambo - Huancayo	Rural	Ucushcancha	0
El Tambo - Huancayo	Rural	Chamiseria	400
Huancayo	Rural	Pacchapata	0
Huancayo	Rural	Ronda	0
El Tambo - Huancayo	Rural	Acopalca	584
El Tambo	Rural	Achapa	0
El Tambo	Urban	1T	23576
El Tambo	Urban	8T	22696
Chilca	Urban	1CH	17235
Chilca	Urban	3CH	21038
El Tambo	Urban	B	0
Huancayo	Rural	Palian	7736
Chilca	Urban	2CH	49170
El Tambo	Urban	3T	30970
El Tambo	Urban	4T	37185
El Tambo	Urban	5T	5512
El Tambo	Urban	7T	12695
Huancayo	Urban	1H	22473
Huancayo	Urban	2H	18873
Huancayo	Urban	3H	12841
Huancayo	Urban	4H	13764
Huancayo	Urban	5H	1827
Huancayo	Urban	7H	4053
Huancayo	Urban	6H	20138
El Tambo	Urban	6T	6001
El Tambo	Urban	2T	16791
Huancayo	Rural	Unas	3000
Huancayo	Rural	Vilcacoto	539
El Tambo	Rural	Cochas-Cullpa	5910

(b) **For Water Demand.** The demand of water was computed following the same sources mentioned above. However, as the demand needs to be computed according to the use of water, this was done for each of the zones in Table 2.1. For each zone, Carlos and Grijalva offered a computation of water demand [36] that was used in this work.

(c) **For Population Growth.** The most important demographic variable for this work is population growth rate per year, which, as computed, includes information on births, mortality, and migration. The official census carried out by the Instituto Nacional de Estadistica del Peru was used [45]. The population growth rate between 1993 and 2007 has been 1.5% yearly, and this values will be used in the simulation (see details in the Table 3.1 on page 57).

(d) **For Immigration.** The last time immigration was computed for Huancayo was 2007 [45] (census). The value at that time was 35%. From the field work (explained later) the immigration present in the peri-urbanizing area is 45%. The average of these (40%) has been used in the simulation to be cautious.

2. Direct consequences:

(a) **Water scarcity** is simply a direct consequence of water trends and population growth. The data has been organized in section 3.3 on page 61.

(b) **Peri-urbanization** is simply a direct consequence of population growth and immigration of non-Huancayo people. As it is explained in [40, 42], the presence of immigrants has increased peri-urbanization. A similar phenomenon has been observed in Lima, where the growth of original population made the city growth vertically (more buildings to stay in the center of the city), but immigration pressure also caused horizontal growth, that is, newcomers inhabited (and some even invaded) lands just outside the city (the peri-urban area).

3. Conditional factors:

(a) **Expectations.** I have agents that use *Bayesian* reasoning to compute expectations. That is, agents will behave differently according to the individual prediction each makes about the scarcity at their current residence. The particular values to be used are 0.5, 0.6 and 0.7, which are expectations as probabilities, which are interpretation from the ethnographic studies carried out during the field work (to be detailed later).

(b) **Resilience.** Resilience represents the times the agent will keep looking for water. An agent starts looking for water when it predicts a particular scarcity (the values from *expectations* mentioned before). The particular values to be used are 4, 5 and 6 (year units), which are an interpretation from the ethnographic studies carried out during the field work (to be detailed later).

   (c) **Competences.** As previously mentioned, these are values that create more heterogeneity in the population of agents. These are computed from the census of 2007 [45] and described in the Table 3.9 on page 69.

4. Potential consequences:

   (a) **Extreme Migration** is an outcome of the model that represents *exit*. It is represents by a series of metrics detailed in Table 4.2 on page 85.

   (b) **Frustration** is an outcome of the model representing the potential to express *voice* in the urban area. It is represents by a series of metrics detailed in Table 4.3 on page 85.

   (c) **Relative Deprivation** is an outcome of the model representing the potential to express *voice* in the rural area. It is also represents by a series of metrics detailed in Table 4.3 on page 85.

2.3 Field work

I decided to organize an ad-hoc collection of information in situ as the model required some information for the agents not available in the literature. I needed to have a clearer idea on how the agents would react as water becomes scarce in the rural and urban areas. For that reason, I organized two research expeditions in each area, which is highlighted in Figure 2.3.

2.3.1 Research on rural area

The rural area represents the largest area of land in this work, but it is much less populated than the urban area. People inhabiting the rural area are very sensitive to the variations of water balance. However, these people are also well trained to survive in these conditions.

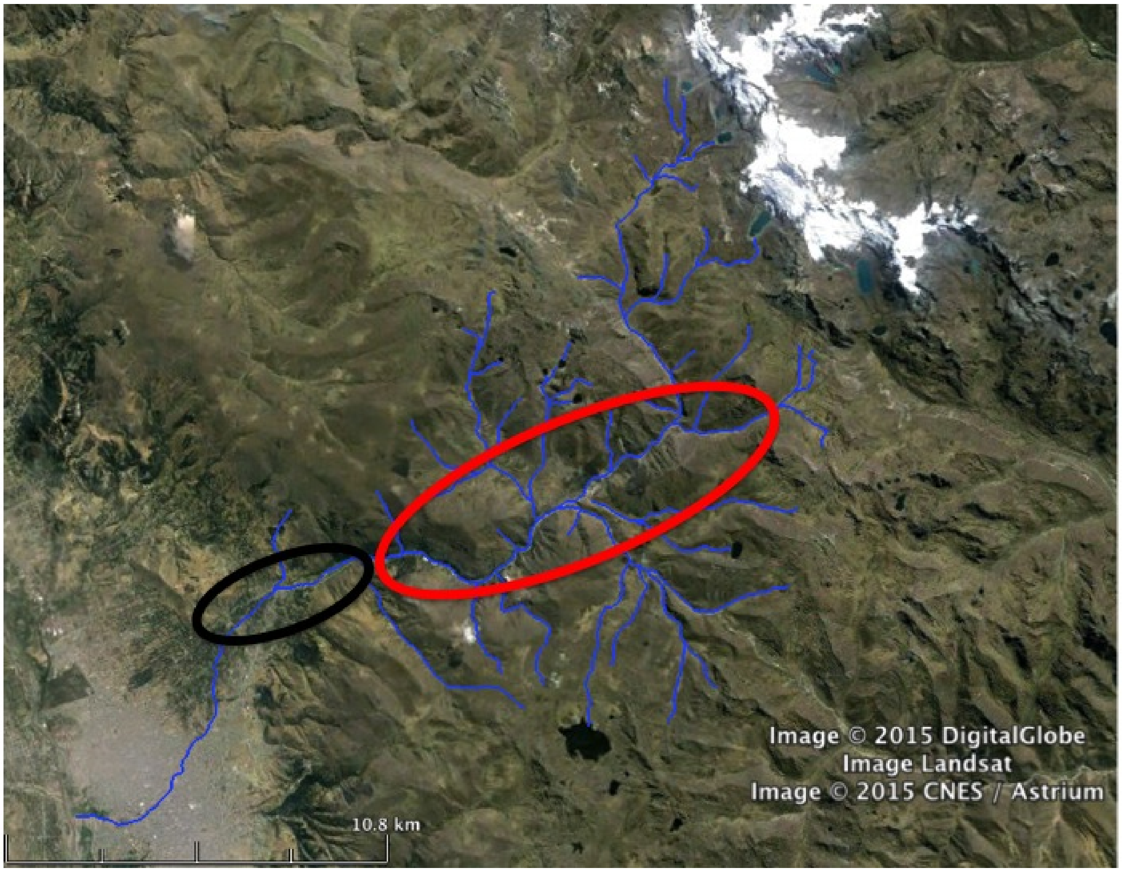


Figure 2.3: Map of field work. The black oval is the area covered by the urban expedition and the red oval the area covered by the rural expedition
Source: Created by the author using Google Maps and ggmaps in R.

As my model has an hypothetical scenario of water scarcity, the team had to be very careful in presenting this scenario to the people they interviewed.

The goal of this expedition (see team in Figure 2.4) was to uncover:

1. *Are urban people aware there might be water issues in the future?*

2. *How long can a rural person stand water scarcity before migrating?*

3. *When would a rural person suffering water scarcity feel relatively deprived?*

The field work in the rural area was carried out during the month of August in 2014, and the team was composed of anthropologists from the Catholic University of Peru (PUCP).

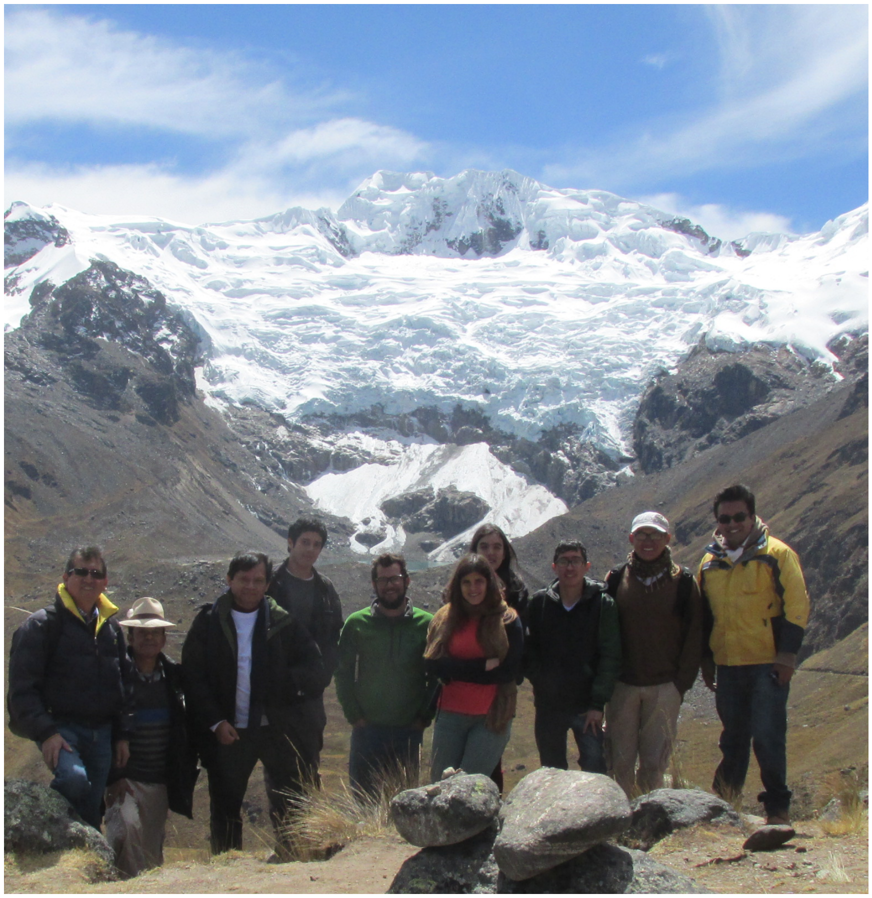


Figure 2.4: Research team for rural area (Huaytapallana is in the background). From left to right: Walter Lopez (Regional Government of Junin), Professor Juan Carlos Condor (UNCP), Jose Magallanes (GMU-PUCP), Alberto Castro (PUCP), Ryam Crumley (Ohio State University), Nicola Espinoza (PUCP), Nurit Matuk (local guide), John Lopez (local guide), Miguel Angel Varillas (local guide) and Jose Ortega (PUCP)

The team was assisted by local guides provided by the Regional Government of Junin and coached by Professor Juan Carlos Condor, appointed by the local university (Universidad Nacional del Centro del Peru -UNCP). I was present during the organization of the team in Huancayo in early August 2014 and assigned the duties and goals of the first part of this visit to the rural area.

The team contacted 57 people from different families. According to previous studies from Milan and Ho [41] the area has around 162 families, so even though this was a non-probabilistic sample, the team managed to interview people from different roles and characteristics, as shown in the Table 2.2:

Table 2.2: Composition of rural sample for this study

Role	Male	Female
Head of family	22	18
Dependant (teenager)	3	3
Dependant (elder)	5	6
Total	30	27

The team was welcome in every visit, due to a couple of fortunate preconditions. First, Prof. Juan Carlos Condor was a very well known and respected person who has done different studies with former students on this area and he introduced the team to the community leaders. Second, before going to Huancayo, I contacted Prof. Bryan Mark from Ohio State University (OSU), who had sent Ryan Crumley, a graduate researcher at OSU to take some samples in the area. Ryan was also very familiar with the people in the rural area as he had spent more than a month taking measurements along the Shullcas. Both of these preconditions facilitated the team get easily accepted in the communities visited.

The rural team lived in the area during the first half of August. They established their center of operations at Acopalca, in a shelter used for tourists (see Figure 2.5). From there, the team visited the herders (higher altitudes) and the farmers (lower altitudes). Each time they visited a family, a team member informed them that they were studying how climate change could impact their environment and asked for permission to accompany them in their daily activities. That is, the main strategy was *participant observation*, a technique chosen to gain better familiarity with the rural people and learn the information needed for the field work goals. The main findings were very surprising. First, person after person affirmed that extreme migration was not an option for them. And second, the increasing presence of non-Huanca urbanizing the rural area represented an undesirable fact. The study also confirmed people were very aware of the progressive diminishing of water, but were also aware that it had not affected them. For sure, they believe this issue will be of more concern in the urban area, but not in theirs.

Figure 2.5: Rural expedition team at shelter. The team lived in this town, Acopalca, to carry out the field work in the rural area. From left to right: Jose Ortega (PUCP), Professor Juan Carlos Condor (UNCP), John Lopez (local guide), Jose Magallanes (GMU-PUCP), Walter Lopez (Regional Government of Junin), Miguel Angel Varillas (local guide), Nicola Espinoza (PUCP), Nurit Matuk (local guide), Carlos Castro (PUCP), and Ryam Crumley (Ohio State University).

A couple of additional important facts were unveiled. First, the rural people were sure that the urban needs of water will collide with the rural needs. They knew there was enough water for rural life, but were not sure how much water will be needed for the growing city in the future. They were not confident local authorities will consider their opinion if the city needs more water. Second, they believed this generation of rural people would do their best effort to make a living in the rural area; but they were not very sure what the reaction of the future generations would be. They considered that the jungle represented an attractive destination for young unemployed people, but were afraid the attraction comes from easy-money and illegal activities.

2.3.2 Research on urban area

The urban expedition started in January 2015. The team for this expedition was composed only of local anthropologists from the Universidad Nacional del Centro del Peru, in Huancayo.

Figure 2.6: Research team for urban area. All members were anthropologists from the Universidad Nacional del Centro del Peru (Huancayo). Raul Arias (standing) was in charge of field work and the coaching and supervision was under the responsibility of Professor Juan Condor (not in picture)

The peri-urban expedition worked between January and March 2015. Considering the amount of blocks in the peri-urban area and the budget constraints, the goal quota was 50 families, which required oversample (the team had to contact 15 extra households) as not every selected household cooperated. The team learned that a *fake* marketing company had once conducted interviews in the area, but they were in fact thieves that used the information to steal cars in the neighborhood. Our data collection followed a different approach. In this case, a survey was designed and applied to 50 families living in the urban settlements located between the city and the rural area. The team designed a polietapic sampling design to include a representative sample of households in the urban settlements located along the peri-urban area (see Table 2.3).

Table 2.3: Composition of urban sample for this study

Urban Settlement	Sample quote
Chorrillos	5
Santa Martha	5
Corona del Fraile	5
Centenario	7
La Floresta II	6
Las colinas de San Antonio	5
La Merced	7
El Remanso	5
Torre Torre	5
Total	50

The goal of this expedition was the similar to the previous one, but included more topics, considering that the urban area will be the one suffering more scarcity. This is detailed in Table 2.4.

Table 2.4: Protocol followed by urban expedition

Guiding questions	Question type	Typical answers obtained
How long can an urban person stand water scarcity before migrating?	Value requested in years	[4,5,6] in years
What would an urban person do when water scarcity is felt at home?	Open question	Look for place nearby or migrate
What would it take for a urban person suffering water scarcity to feel frustrated?	Open question	Difficulty to migrate
What is the origin of the peri-urban settlers?	Boolean question	Huanca or Non-Huanca
How did they end up living in that peri-urban area?	Open question	Looking for a cheaper place

From the table above, I obtained key considerations for the implementation of the model.

First, I confirmed urban people considered migration among their alternatives in case of lack of water with a resilience between 4 and 6 years. This is different from the current position shared by rural settlers. This is perfectly understandable as people in the city and in the peri-urban area were already suffering episodes of water shortage during the dry season. The shortages were during some hours and people (customers) were informed in advanced by the water company (SEDAM Huancayo). Second, if the urban settlers predicted that there will be permanent scarcity in the place they live, they would look for a place in Huancayo to move to. They were aware that they may need to get land closer to the rural area. It is worth noticing that all who said they would never migrate are non-Huancas (see Table 4.1 on page 83) as they already did their investment to come to Huancayo. Third, Huancas or non-Huancas believed that they would feel frustrated if they had to stay in place with water scarcity. Huancas would prefer to migrate, but if they could not, they would feel frustrated. Non-Huancas did not wish to migrate ever, but staying in scarcity conditions would make them feel frustrated too. Fourth, the team found that the current share of non-Huancas in the peri-urban area was 45%.

Finally, I found out that people in the peri-urban area did not start living in that zone but were renting a place downtown, which was expensive, smaller and overcrowded. Progressively, they moved (renting or buying) into the peri-urban area as it represented a cheaper place to live. The strategy they followed to find a better place was to use a system of references, where family and friends were sharing their experience living outside the city, even with lack of public utilities in the beginning. In case of searching for water, they say they will follow the same strategy (referencing system of relatives).

The field work allowed me to complement the quantitative data available with some basic decision making mechanisms that the modeled rural and urban agents should adopt in case of this potential scenario. Besides, the information from the field work helped me introduce heterogeneity in the agents. I consider that within the limitations for this research I have enough information to produce an informative model that will bring sufficient information for policy makers to start anticipatory thinking in the problem this model presents.

2.4 Model constraints

As every model, this study had several limitations and had to assume a series of facts. However, I am making these explicit in this section to facilitate future improvements of the model.

2.4.1 Limitations of the study

As it is clear, answering the research questions depended on how well these limitations have been managed.

- *Official Data.* The data for this study has to be collected via direct inquiries to the different institutions involved in the hydrology and climatology of the area. The time for their response was far from immediate (around six months) and complete, so it also affected the time dedicated to modeling and coding. As mentioned before, the PRAA funded data collection, but that was done only during the time PRAA was active (around 2009-2012). Considering this limitation, I decided to find every researcher that was currently doing some research in this same area. I managed to find at least one other researcher for each dimension of this work. The trends offered in this model for the Shullcas river would not have been possible without the sharing of data by Mr. Guillermo Carlos, a local researcher in Huancayo, and Prof. Mark Bryan, a researcher from Ohio State University. The trend from Huaytapallana would not have been complete without the collaboration from Prof. Ignacio Lopez from Instituto Pirenaico de Ecologia (Spain) and Mr. Jacinto Arroyo, a local researcher at Universidad del Centro and Universidad Continental. For the future improvement of this work, we are all involved in looking for funds to create a long term interdisciplinary research program.

- *Field work sampling.* The census data offered many important information on the demographics of the region under study, however, the political division of the census did not offered information for the peri-urban area and the particular rural settlements along the Shullcas river. This weakness had an obvious problem, the lack of a sampling frame for the peri-urban and rural area of interest in the study, which made probability-based sampling unfeasible. In these cases, the field work had to follow a qualitative design. For the rural area, the research design had to follow an ethnographic approach, conducting *participant observation* while the team lived in the rural area. However, to avoid gender and/or age biases, the team included different categories of people in the study (see Table 2.2 on page 25). As mentioned before, I had key contacts that facilitated this work in the rural area. For the peri-urban area, the team organized the research in such a way that the nine peri-urban settlements could be included (see Table 2.3). For each settlement, the team computed a representative quota. Given the homogeneous distribution of blocks per settlements, the quota was between 5 and 7 per interviewer. However, the next stages used convenience sampling, and there was a need to replace the block assign when no one wished to be interviewed in a particular block with over sampling. In this way, I secured a minimum level of representativeness for this zone, as every settlement was represented. Besides the coaching from local researchers in the field work, the collaboration from Mr. Andrea Milan, a researcher from Institute for Environment and Security Studies at United Nations University (Germany), was very relevant due to his previous work in this same rural area. This work also profited from the collaboration of Mr. Andreas Haller from the Institute for Interdisciplinary Mountain Research (Austria), who shared many insights on the peri-urbanization process in Huancayo.

2.4.2 Assumptions of the study

- *Decision making of agents.* To answer the research questions, I needed to know if migration and conflict were possible, for each case particular assumptions were made.
  - For migration, the assumption was that agents reach a resilience limit and then need to exit the system. This limit is reached as the agent keeps looking within

Huancayo for a place with enough water. Related to that, the search for water within the system is guided by the prediction an agent makes of the water scarcity in the place the agent is living. Both of these processes were modeled based on the reasoning unveiled by the interviews during the field work. This model, by following closely the Maslow hierarchy mentioned before, considers lack of water a sufficient cause to drive the decisions the agent needs to make. Other factors, like education, economy and family (which belong to higher levels in the Maslow hierarchy) are not involved when deciding where to live in Huancayo, but are considered during the decision making process when the agent faces the migration decision.

  - For conflict, the assumption was that agents get frustrated or relatively deprived. Urban agents get frustrated because they could not exit when their resilience limit was reached; and rural agents get relatively deprived when they start having urban neighbors that are non-Huancas and are better off. Again, these dynamics were unveiled by the field work.

- *Representation of the environment.* The representation of the environment was organized to reflect proportionally the real area where action takes place. The area was modeled as a lattice that does not wrap any of the borders. The model does not compute distances, as they are not needed in any decision making process; but the position of the areas were created so as to help the visual analysis of the model dynamics. For this case, the rural area is located to the right of the urban area. An alternative choice could have been the rural area on top of the urban one. In either case, the peri-urbanization process should take place, as it occurs in the model presented in this work. It is worth mentioning that the code in this model has been organized so that a future version could use real maps. Each cell or patch is a place where the agent lives, and it is the source of water of the agent. However, these patches have an *scarcity level* attribute, which will determine what zone in the urban area will suffer droughts.

- *Social interaction among agents.* The interaction of agents have been based on the findings of the field work. In general, a system of reference via family or friendship networks seems to be, for people in Huancayo, the safest way to get information. In the hypothetical situation presented to the urban or rural people, they simply confirmed that finding a better place to live, or organizing to express their frustration would follow a social network approach. Using their networks to find a better place to live was a strategy they used in the past, so my expectations are stronger in this case. Organizing for voicing their frustration was not a familiar situation, but for them it was obvious to think that "it would be very easy to connect among people suffering water scarcity in my neighborhood". In this situation, the assumption included in the model is that voice would be expressed following a *neighborhood* approach. However, I have extended that assumption, considering that once a social tie for *voice* exists among neighbors, it will be persistent even after the neighbor had to move. This assumption is based on theoretical grounds: if the network among people suffering water scarcity determines an homophilic relationship, then according to Lazarsfeld and Merton [49] these homophilous network ties are more sustainable over time (see also [50–52]).

In summary, from the previous sections, I have made clear the process I have followed to integrate the different sources of data and knowledge into my model. Quantitative and qualitative work has been done to reflect system trends and individual reactions as these trends are kept. As every model, several assumptions have to be made, and I have made them explicit so that future improvements are possible.

As it is shown along this work, this research comes in a time when actual strategic decisions are needed to anticipate undesirable situations. Since the year 2015, Huancayo has new political authorities that have requested collaboration on this issue, considering that the former local authorities did not include this issue in their political agenda. An implicit agreement among the researchers that collaborated with this work was presenting their findings integrated into my model to the authorities in July 2015, when the Regional Plan for Environmental Issues would be discussed. It was done so on July 17 at the conference room of the Regional government of Junin. The next chapters deal with the modeling and implementations details that followed from the methodology I employed to gain the acceptance of this work in the Huancayo decision makers community.

Chapter 3: The Coupled System

This chapter is the key element in this work. Here I present a narrative for my model, presenting it as a coupled system, [53] (see also [54, 55]),according to the needs of my hypothesis: *drastic emigration and the emergence of social conflict are potential outcomes of the interaction of population growth, the decreasing proximity among urban and rural area, glacier retreat, and decreasing water supply.* In this chapter, these elements are connected logically to support this hypothesis.

In the first section, I will describe the natural system, so that its peculiarities are highlighted. I will follow a general-to-specific description: I will briefly explain what is the current situation of the Andes, and particularly the Andes in Peru; and only after that I will organize the information available for the Central Andes of Peru, where the Huaytapallana glacier and the Shullcas river, the locus of my research, are located. I end this section offering the current situation of both this river and this glacier, which will be used in my model (described in the next chapter).

In the second section, the science of climate change is reviewed from a sociological and anthropological point of view. First, I briefly describe the *prototype* of the people in Huancayo as proud descendants of the Huanca culture, who astonishingly have legends that make sense of the terrible consequences of the melting of the Huaytapallana [56], which contrasts with other cultures whose mythology does not fit with climate change [12]. Second, I present the emergence of Huancayo from a series of events, which made the Huancas populated the urban and rural area, so that, sociologically speaking, the urban and the rural developed into a network of mutual cooperation, ties that allowed the region to become so prominent and attractive, that the city became a pulling factor for poorer inhabitants from nearby towns, keeping the population immigration and growth rate positive [45, 57, 58]. In this situation, the attractiveness of the city will endanger its livability, as the water supply will be not enough for the water demand, *ceteris paribus*.

The last section gives full support to the hypothesis of this work, as qualitative and quantitative evidence, built on the previous sections, suggest migration may occur only in the most stressful situations, thus making it worse; and that social conflict may arise, not precisely among Huanca people, but from the increasing presence of non-Huanca in the peri urban area.

3.1 The natural system

Peru (see Figure 3.1) is located on western South America and covers 1 285 216 km^2 (496 225 square miles). Its neighbors are Ecuador and Colombia (north), Brazil and Bolivia (east) and Chile (south), having shores on the Pacific Ocean (west). Its population was last measured in the 2007 census [45], resulting in 28 220 764, being the projection for 2015 of 31 151 643[1]. The capital of Peru is Lima, a relatively small urban area (2 672.3 km^2) located in the central coast, and hosting above 8 852 000 inhabitants [45].

One of the major features of Peru that concerns this study is the presence of the Andes mountain chain. The Andes cross Peru from north to south in parallel to the Pacific Ocean, creating three basic regions: coast, highlands (sierra) and jungle (see Figure 3.2). The coast is arid, with scattered valleys created by the *seasonal* rivers born in the highlands, where the Andes are located. To the east, the jungle, where the Amazon river is born, represents the lowest densely populated area but the largest land extension in the country. The Andes, combined with Peru's tropical latitude, topography variations, and both El Niño or *ENSO* (**E**l **N**iño **S**outhern **O**scillation) and the Humboldt ocean currents allow the presence of lots of micro climates, which has contributed to its rich biodiversity (21 462 species of plants and animals where 5 855 of them are endemic [59]).

It is well known that the rich biodiversity and sustainability of life depends on the

[1] official data available at Statistics Office (`http://www.inei.gob.pe/`)

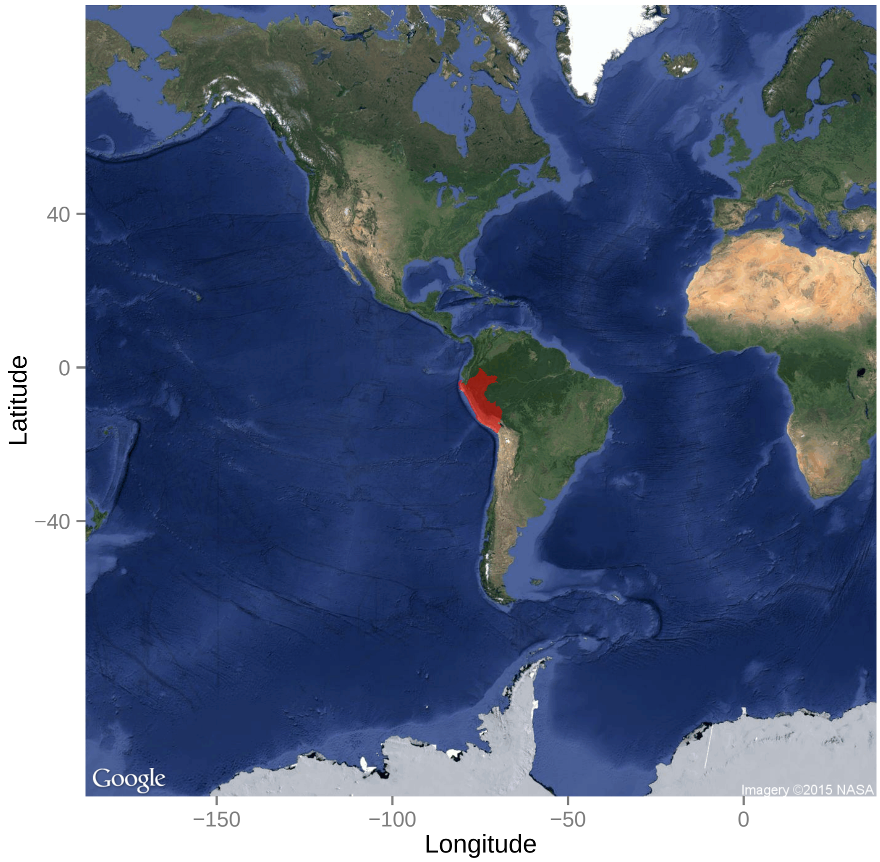


Figure 3.1: Location of Peru
Source: Created by the author using Google Maps and ggmaps in R

availability of *fresh* water. Particularly, the Andes represent that source of fresh water for the Andean countries. Andean glaciers are the natural storage of water, and their gradual release of water from ice and snow melt contributes to the life in the arid coast and in the Amazon rain forest.

As previously mentioned, The Andes glaciers are categorized as *tropical* glaciers (located between the Tropic of Cancer and the Tropic of Capricorn), and most of all tropical glaciers are located in the Andes [60][2]. These glaciers are very sensitive to global warming. They are

[2]Around 99.64% of tropical glaciers are in Andean mountains of South America, 0.25% on the African glaciers of Rwenzori, Mount Kenya and Kilimanjaro, and 0.11% in the Irian Jaya region in New Guinea.

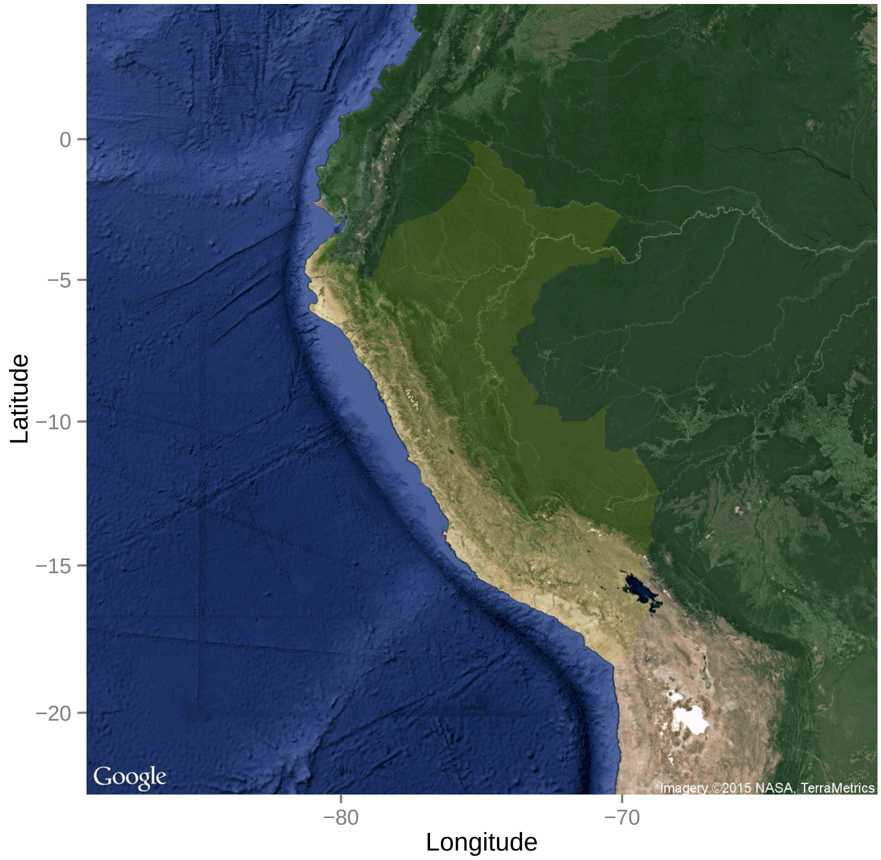


Figure 3.2: Peruvian Andes
Source: Created by the author using Google Maps and ggmaps in R

constantly melting due to the regional temperature. So, water shortage and droughts would start affecting the life in the region with unexpected and currently unknown consequences, as the global warming trends continue.

Peru, particularly, contains the largest fraction of the Andes tropical glaciers (around 70%), and, as expected, its glaciers are melting. From a research done at Peru's Cordillera Blanca, the world’s most extensively glacier-covered tropical mountain range, located in northern Peru, (Figure 3.3) Vuille et al. [61] inform that these glaciers reached their maximum extent between years 1630 and 1680, and significant glacier retreat started in the middle of the 19^{th} century; that is, since the maximum extent of Little Ice Age[3] up to the beginning of the 20^{th} century, glaciers in the Cordillera Blanca retreated a distance of about 1 000 m (around 30% of their length).

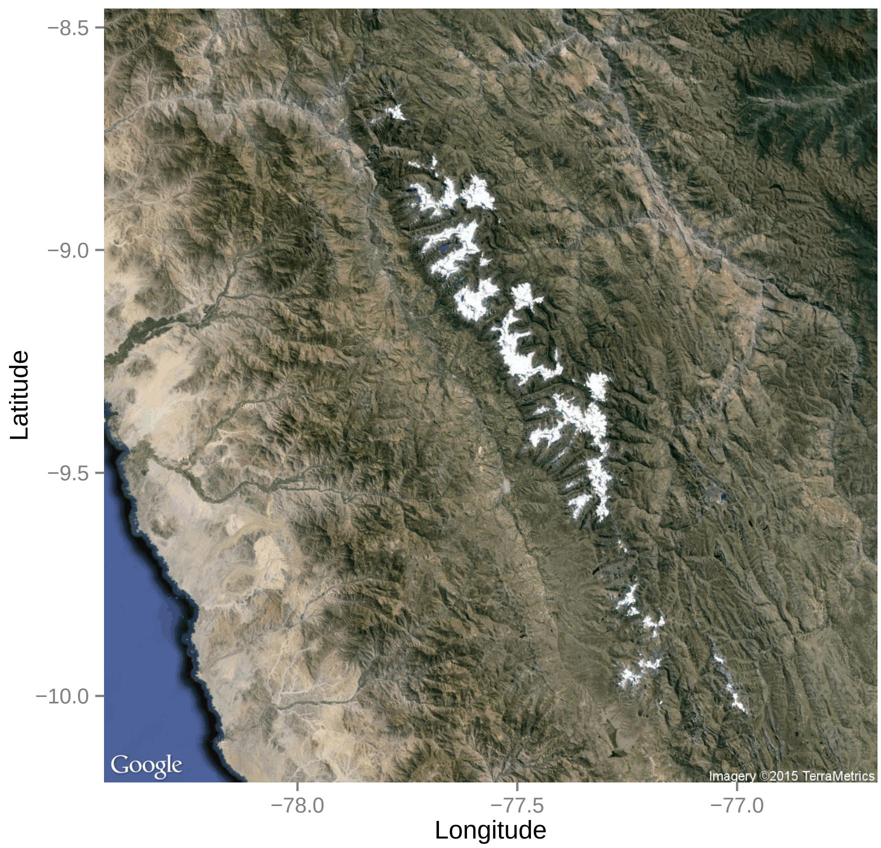


Figure 3.3: Cordillera Blanca
Source: Created by the author using Google Maps and ggmaps in R

Paying closer attention to the snowline (also known as ELA - Equilibrium line altitude separating the accumulation from the ablation zone), much of the glacier shrinkage during the 20^{th} century in the Cordillera Blanca may have occurred between 1930 and 1950 [60].

[3]The Little Ice Age is a period between about 1300 and 1870 during which Europe and North America were subjected to much colder winters than during the 20^{th} century.

It is also reported that there were short-lived advances in the mid 1920s [62] [60], one in the late 1970s [63], and another at the end of the 20^{th} century [64]; however, they did not stop the general trend of retreat. This retreat has also been present in glaciers in Ecuador and Bolivia, making a concrete case for concern for the whole Andean region, as over the last few years the retreat seems to again have gained momentum, as can be seen in Figure 3.4.

Besides the well-studied Cordillera Blanca glaciers, researchers have also paid attention to glaciers in other regions in Peru such as in the Cordillera Vilcanota [65] (eastern Andes) and the Cordillera Ampato [66] (western Andes). Each of these Andes sections are key elements for the local biodiversity, hydrology, and also a key component for the energy of the neighboring regions. However, this work focuses on a glacier and a hydrological system which have been, surprisingly, comparatively much less studied.

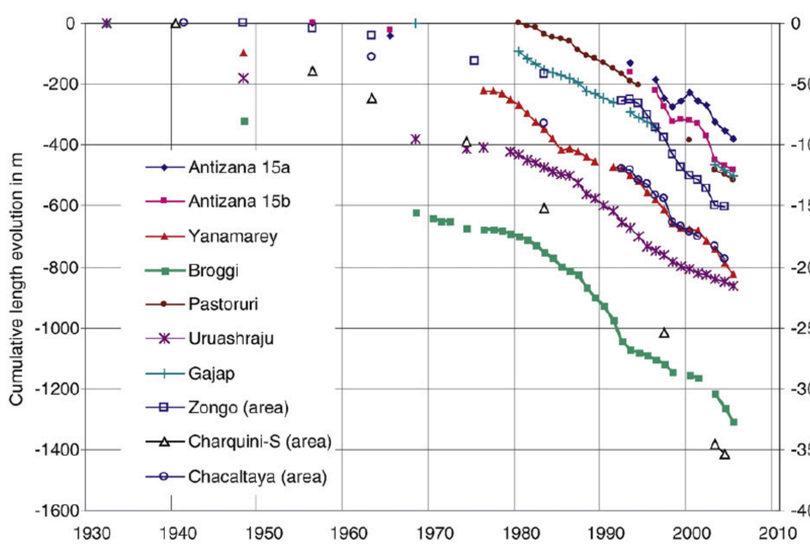


Figure 3.4: Glacier retreat in the Andes. Change in length and surface area of 10 tropical Andean glaciers from Ecuador (Antizana 15a and 15b), Peru (Yanamarey, Broggi, Pastoruri, Uruashraju, Gajap) and Bolivia (Zongo, Charquini, Chacaltaya) between 1930 and 2005. Source: Vuille et al. [61]

3.1.1 Central Peru

The system I have chosen to model in this work is part of a macro system in the central region of Peru. Broadly speaking, Central Peru is composed of the Central Jungle, the Central Coast and the Central Highlands. Arguably, the political areas[4] represented in this macro region are Lima (whose main city is the capital of Peru), Junin (whose capital city is Huancayo), Pasco (whose capital city is Cerro de Pasco) and Ucayali (whose capital city is Pucallpa), which can be identified in Figure 3.5. The geographical and economic characteristics of this region allows these political units to complement each other in mutual benefit, but that complementarity can be endangered as the ecosystem, and particularly the water, threatens the current conditions seriously.

The *highlands* (Andes) differentiate territories to the east and the west, allowing different climates in both directions. The central Andes are the main source of fresh water from the snow melt and contribute to the regulation of the temperature and humidity, thus influencing the whole hydrological cycle; most of the water collected from the Andes, approximately 85%, melts into the jungle, and the rest into the coast. The coast is the most arid land in Peru, but the most most populated cities, including the capital of the country, are located here.

Lima represents the central coast sub region, and from a natural systems point of view, this location makes Lima, especially the metropolitan areas, a very vulnerable area. Lima is the second largest desert city in the world, after Cairo in Egypt. Lima's local mountains are not high enough to be a source of water or ice, but have been instead a source of cheap housing for poor immigrants who dared to stay there even without basic services (water and electricity). As a city in the desert, it is highly dependent on external sources of food, which is currently coming from the highlands and jungle, and from foreign countries. Lima's climate conditions constrain rainfall, so local river recharge is not significant and neither is it possible to consider the water table as an important source of water as Lima is densely

[4] Peru is politically divided into Regions, Provinces and Districts, which is comparable to States, Counties and Townships in the USA.

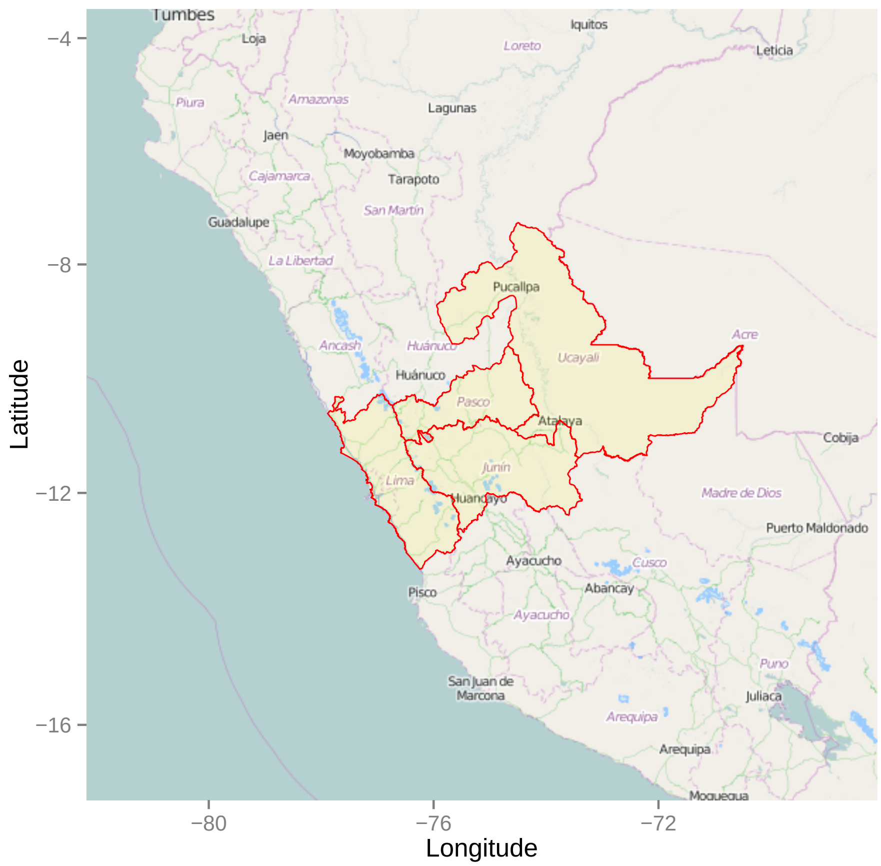


Figure 3.5: Central Peru, political division
Source: Google Maps and the Author

urbanized. This situation makes the central Andes glaciers and rivers its unique source of freshwater.

On the other side, to the east, the *jungle* is the least populated region in the central zone (and in the whole country). It is a regional source of wood, coffee, coca and tropical fruit. As a natural system, this area enjoys the benefit of being located to the east of the Andes, so there is high availability of water due to the local conditions. Nevertheless, the jungle represents also a place where illegal activities, such as illegal logging, coca cultivation and cocaine processing, are easily carried out as the Peruvian state has less presence there.

3.1.2 The Huancayo natural system

Huancayo is located in the Mantaro valley, which hosts the homonymous river that starts at approximately 4 100 masl (meters above sea level) near Lake Junin and flows southeast passing Huancayo. The Mantaro basin is composed of many sub-basins (see Figure 3.6), and in this work, I pay attention to one of them, the Shullcas Basin.

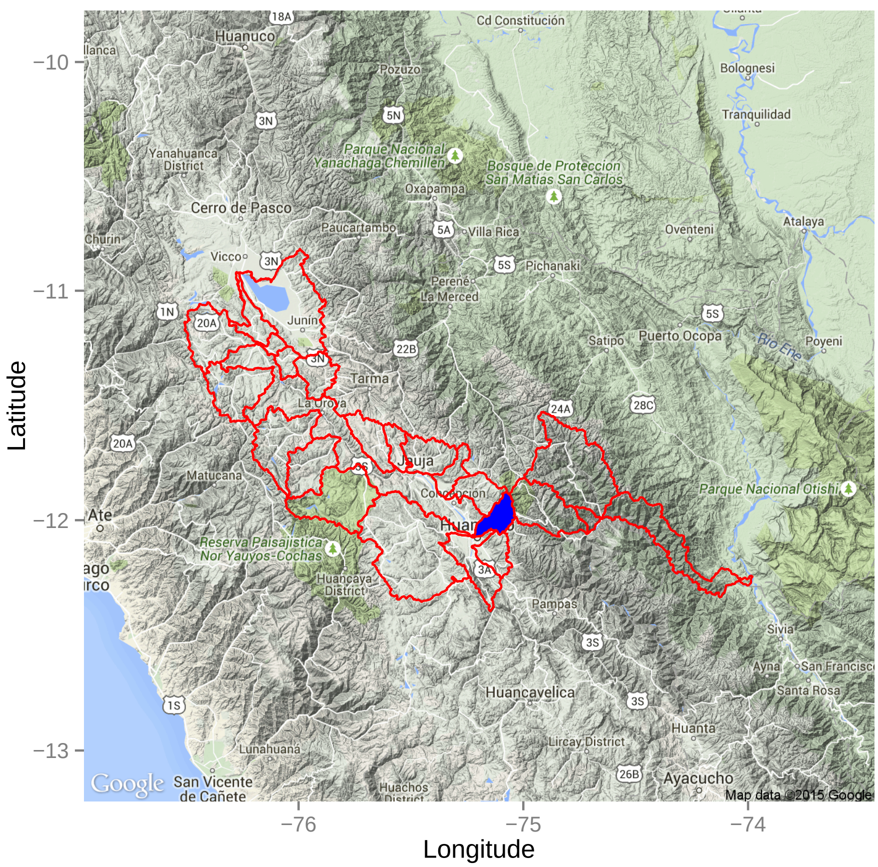


Figure 3.6: System of sub-basins in the Central Andes of Peru. The system is known as the Mantaro Basin. Notice the Shullcas sub basin in blue, where Huancayo is located
Source: Created by the author using OpenStreetMaps and ggmaps in R

Huancayo urban area is situated 20 km southwest of the Huaytapallana mountain range at an altitude of 3 260 masl. Huancayo represents the Mantaro valley's most extended and most populated mountain city in the Central Peru. Huancayo is approximately 200 km east of Lima. In terms of temperature, the climate is typically diurnal (the diurnal temperature variation is higher than the seasonal one). Measurements at 3 302 m above sea level between January and December 2010 show a daily maximum of 25.2 °C (September 28) and a daily minimum of 4.6 °C on (August 7). The multiannual average (1960–2000) of annual precipitation around Huancayo reached approximately 750 mm [67]. The city center has been built on the alluvial fan of the Shullcas River, a tributary of the Mantaro River with its source at the nearby Cordillera Huaytapallana, 20 km northeast of Huancayo, and represents the main source of drinking water for the entire agglomeration.

Along the Shullcas river, between the Huaytapallana glacier and the city, the rural area of Huancayo hosts many settlements called "anexos" or "populated centers". Rural life is dedicated to farming and herding, and they are sparsely populated. Further details on the rural area, based on altitude, are given following [46]:

- From 3 300 to 3 400 masl, the rural area represents 14.42% of the total area of study. Rainfall is around 500 to 700 mm yearly, and the mean temperature is between 15°C and 12°C.
- From 3 400 to 3 900 masl, the rural area represents 18.84% of the total area of study. Rainfall is around 700 to 900 mm yearly, and the mean temperature is between 19°C and 9°C.
- From 4 500 to 4 800 masl, the rural area represents 10.30% of the total area of study. Rainfall is above 10 000 mm yearly, and the mean temperature is between 3°C and 1.5°C.
- Above 4 800 masl, the rural area represents 3.16% of the total area of study. Rainfall is is around 500 to 1 000 mm yearly, and the mean temperature is around 1°C.

3.1.3 The Huaytapallana glacier

What is known today about tropical glaciers is due in great share to the glaciers of Peru. However, these studies have not covered every glacier in the country (see Figure 3.4 on page 40), and the Huaytapallana chain is precisely one of those cases not considered. The Cordillera Huaytapallana is in the eastern part of the Central Andes of Peru, northeastern of the city of Huancayo (see Figure 3.7).

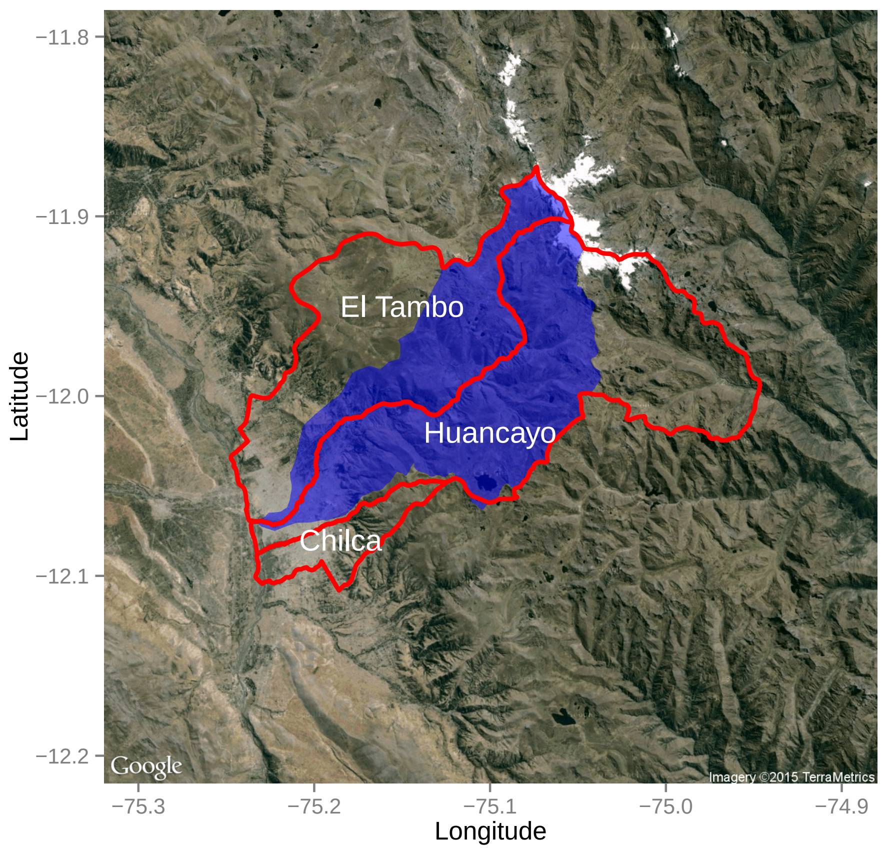


Figure 3.7: Huancayo and its districts (El Tambo, Chilca and Huancayo) delimited by a red line. The urban area appears on the southwest. The Shullcas river sub basin is in Blue. The Huaytapallana glacier appears on the northeast

Source: Created by the author using Google earth and ggmaps in R

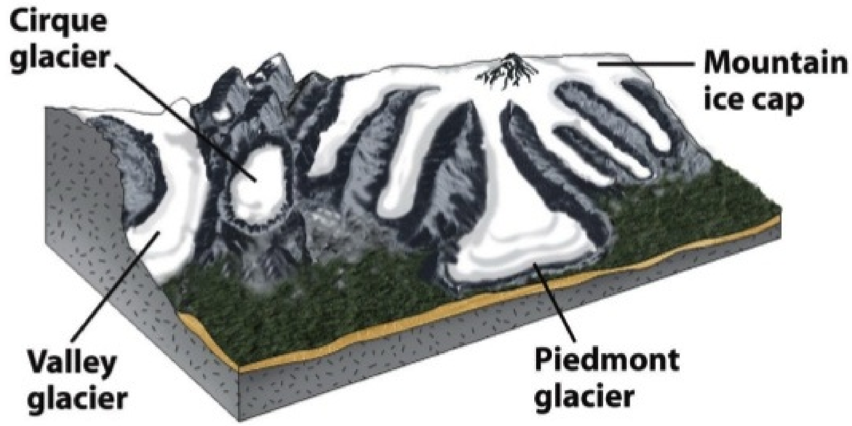


Figure 3.8: Type of glaciers.
Source: Adapted from `http://www.slideshare.net/geology-lecture-20`

The chain or *Cordillera* drains into the Mantaro and Perene rivers, the latter draining into the Amazon basin. The Huaytapallana area contains 30 peaks from 4 850 masl to 5 572 masl, and my glacier of interest, the *Huaytapallana*, is precisely the glacier with highest altitude. Glaciers in Huaytapallana are typically of the cirque type (glacier that fill mountain top bowls as shown in Figure 3.8), and many are hanging glaciers and heavily crevassed because of the steepness.

In the region there are many lakes, particularly the Lasuntay and Cuspicocha, the glacier lakes that belong to the Shullcas watershed. However, many more have been formed in recent decades due to the rapid glacier retreat in this area. In general, the glaciers are the main source of freshwater for domestic and agricultural uses in the Mantaro River Basin and particularly in the Shullcas river basin.

Besides being a source of water, the Huaytapallana glacier is also a potential source of disasters. The Huaytapallana fault [68] is a source of seismic activity. Recent structural changes have also provoked in recent decades *glacial lake outburst floods* due to the the accelerated melting of glaciers. The last one registered in the Shullcas river in was in December 1990, which destroyed hundreds of houses in the rural area and caused many fatalities in the city of Huancayo.

In 2014, the most updated report on the situation of the Cordillera Huaytapallana was published by Lopez et al. [37], a group of researchers from the Pirineic Institute of Ecology (Spain) and from the National Meteorological and Hydrological Service (Peru), producing key information for the modeling purposes of this work:

- This region exhibit climatic conditions typical of tropical mountains, with a wet season from October to April and a dry season from May to September.
- The dry season only receives about 10% of the annual precipitation.
- Due to the proximity of this region to the equator ($\sim$ 11 °S latitude), the temperature (especially the maximal) has very low annual variability.
- The minimum temperature has moderate annual variability, and July is the coldest month. At 4 475 masl (Tunelcero observatory), the minimum temperature is below freezing during the dry season, but the mean maximum temperature exceeds 10 °C throughout the year.
- The most optimistic scenario does not prevent Huaytapallana from melting.

In that work, Lopez et al. [37] reviewed all available Landsat-Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images from the archives of the United States Geological Survey (USGS) (as most studies based on Landsat data consider ETM+ and TM radiometry to be comparable, they used TM data from 1984 and, switched to ETM+ data when it became available because of the better calibration and switched back to TM due to the ETM+SLC failure in 2003). They recovered a total of 19 images, which were processed for analysis of ice-covered areas and the locations of snowlines for the period from 1984 to 2011. The images were taken during the dry season (from June to August) because of the low cloud cover and minimal snow cover during that season to reduce misclassification of ice-covered areas and provides a better classification of the snowlines (for some years, they could not select some images because the presence of a significant cloud cover or an anomalous snow accumulation, which prevented discrimination of glaciated surfaces from seasonal snow cover). They processed these images using Standard Terrain Correction (level 1 T), which provides systematic radiometric and geometric accuracy by incorporating ground control points while employing a Digital Elevation Model (DEM) for topographic accuracy. Their final database was processed by use of calibration and cross calibration of the TM and ETM+ images. The data can be visualized in Figure 3.9

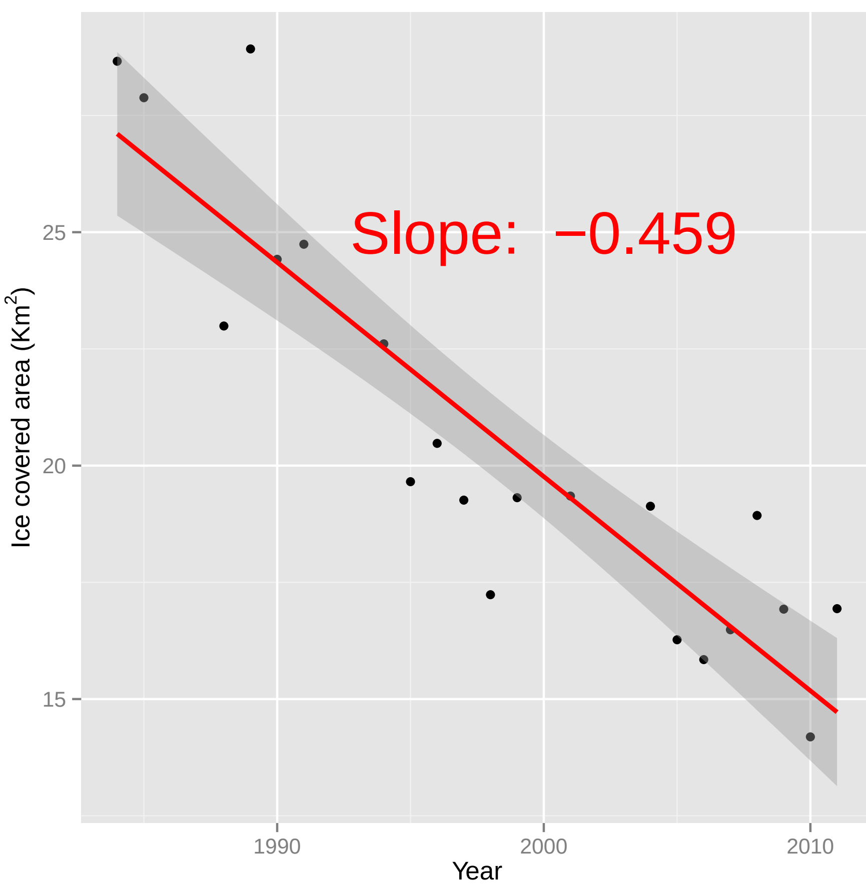


Figure 3.9: Huaytapallana melting trend. The slope I will use in the model is originated from this data

Source: Created by the author using ggplot2 in R. Data has been shared by Dr. Ignacio Lopez from Instituto Pirineico de Ecologia in Zaragoza from his work in the zone.

From the data in their study, Lopez et al. [37] concluded that:

- Between 1984 to 2011 there was a 56% decrease in the area covered by glaciers.

- Glaciers at the lowest elevations, and the ones receiving the most solar radiation underwent faster melting. Glaciers in summit areas also lost ice cover, despite of their altitude.

- The rate of glacier retreat in Huaytapallana is twice the rate of Cordillera Blanca [69] probably because of the lower elevation of the Cordillera Huaytapallana, as tropical glaciers at elevations lower than 5 400 masl are very unstable.

- The warming rate for their period 1965 to 2011 reached 0.22° C per decade.

- Precipitation increased during the wet season, but during the same period, the glacier retreated in this region:a temperature-induced change from snow to rain can increase glacier decline, because glacial ablation is greater in a warmer climate.

3.1.4 The Shullcas river

Shullcas River is a sub-basin of the Mantaro basin. The sub-basin covers an area of 218.82 km^2 in the Huancayo Province. The Shullcas River runs for 35.9 km from the Chuspicocha and Lazuntay glacier lakes, which receive water from the Huaytapallana glacier. Current water use in the Shullcas River sub-basin consists of water for the needs of people in urban and rural area of Huancayo, which include agricultural, hydroenergetical, and business uses. The Shullcas basin is depicted in Figure 3.10.

The Shullcas River sub-basin can be divided, from a geodynamic point of view, into three levels: the **upper** level, where the river is born and has the highest dependence on the glacier lakes Lazuntay and Chuspicocha and the presence of the Huaytapallana glacier; the **middle** level, where the River is met by some streams (Ucushcancha and Ronda) and feeds the locality of Vilcacoto community; and the **lowest** level, which mainly feeds the urban area of Huancayo. Each level has a complex relationship with the micro environment, as the temperature, precipitation, mountain slopes and ground infiltration capacity and human presence and use change. It is also worth keeping in mind that even though the river crosses two districts (Huancayo and El Tambo), the water used in the District of Chilca also comes

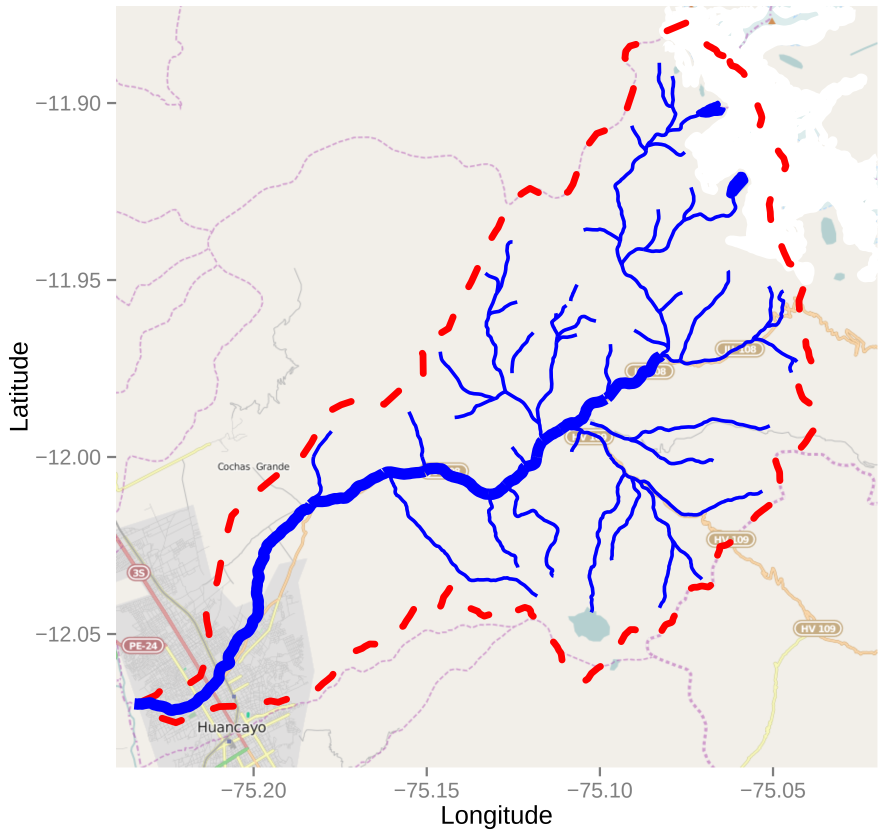


Figure 3.10: Shullcas river sub basin (in thicker blue), including its tributary lakes and tributary and drain streams. Red dotted line represents the geographic limit of the watershed. Notice the Huaytapallana on the Northeast (white)

Source: Created by the author using OpenStreet Maps and ggplot2 in R.

from the Shullcas, as the local water company, SEDAM, manages water for these three districts.

3.2 The social system

People and places, since ancestral times, have a toponymic character, which is generally preserved by culture. In the case of the Andes, the Quechua and other languages are very useful sources of the meaning of place names. As it is known today, the Mantaro valley, where the Shullcas watershed is located was an immense lake that drained during a cataclysmic earthquake; so now, huge stones are dispersed along the valley and embedded in the mountainsides [70]. In Quechua, the language of the Incas, *huanca* or *wanka* means stone, and *yok* means having or possessing, so both terms, *huancayok* means the one that possesses stones (the 'k' was dropped as time passed by).

3.2.1 Culture and climate: a people ready for disasters

History and mythology can complement and ease the understanding on how local people are psychologically ready, or not, to face disasters. Susan Crate [12] presents the case of the Sakha people in Siberian Russia, who are facing huge alterations to their habitat; in this case, the whole culture seems in shock as the strong winter they used to have is languishing. This strong winter is named *Jyl Oghuha* (Bull of Winter) and its weakness is making this climate transition more painful and difficult to bear, as suddenly the whole worldview is falling, while also shaking their identity foundations. The case of Huancayo is different.

In Andean cosmology, *Wiracocha* is the almighty god and creator of everything. He left in the world many *Apus* (gods in human form), who take care of people and whose abode is a particular mountain. In the land of the Huancas, there were two neighboring Apus, *Huallallo Carhuincho* and *Pariacaca*. Each one fell in love and had children that populated their respective lands, but many events caused them to become rivals. The first born of Huallallo Carhuincho was a girl named *Huaytapallana* who was so beautiful that this Apu decided to hide her away from the men in a mountain. Pariacaca had a son named *Amaru*, who loved to travel and who had the power to take any animal form as an Apu's son. Amaru had a wife and a daughter. One unexpected day, while Amaru was flying over some mountains, he saw a beautiful garden in a mountain far from the kingdom of his father. He landed there and met Huaytapallana, whose beauty made him fall in love, forgetting about his wife and daughter. They fell in love of each other and had five children. When Huallallo Carhuincho found out what happened, he killed Amaru; and in revenge, Pariacaca killed Huaytapallana and the five children. Since that moment, both Apus started a terrible fight destroying everything on their way (people, land, cattle, villages, etc.), which explains the peaks and abysses of the valley. When Wiracocha realized what they were doing, he stopped them. He imprisoned Pariacaca and buried him in the highest glacier (which has his name now), and Huallallo suffered the same fate in the mountains where once lived Huaytapallana. The legends ends saying that once the prison of ice retreats, both Apus will be free and the terrible fight will start again. Huanca people have made sense of their past and future fate. Different from the Sakha people, they still find meaning in climate change; and they know this will affect Huancayo and Lima (see in the Figure 3.11).

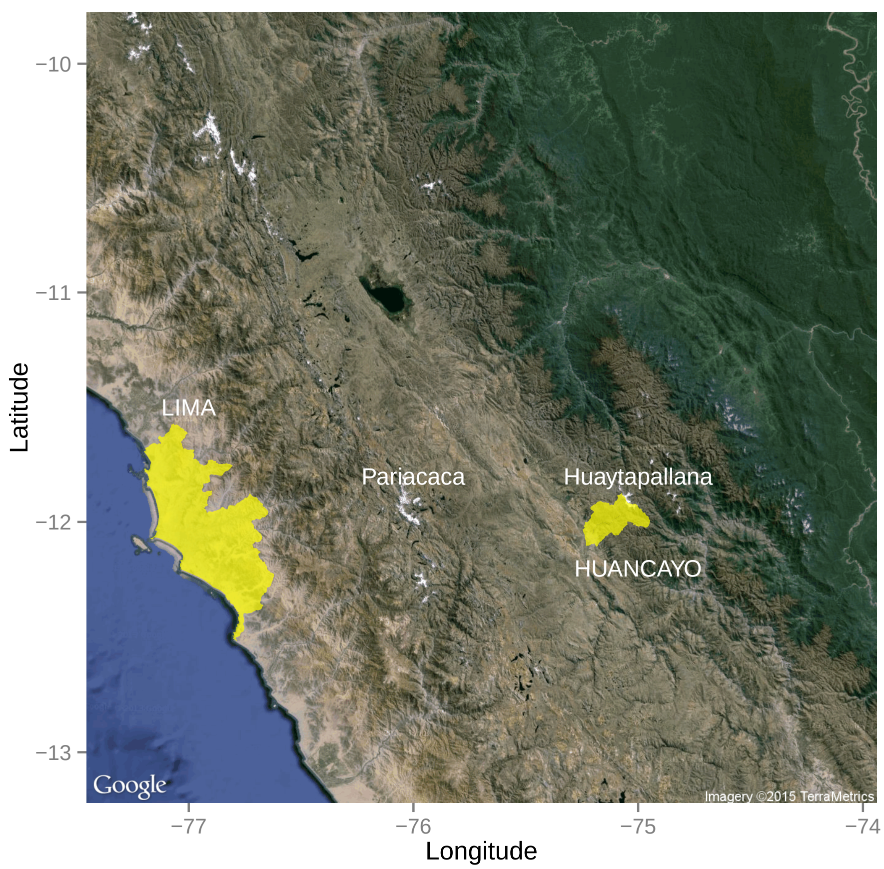


Figure 3.11: Huaytapallana (Huancayo) and Pariacaca (Lima) glaciers.
Source: Created by the author using Google Maps and ggmaps in R.

3.2.2 Immigration to Huancayo: a historical overview

As Aquilino Vasquez explains, the Huanca populated the valley thousands of years BC [56]. The main cultural influence was gained from the Wari, a pre-Incan empire. Their *paqarina* (mythical place of origin) is located in the south in a sanctuary known as Warivilca, whose fame, increased as time passed by, turning itself into an oracle where visitors from different regions came to ask about their fate; since then, the Central Andes has been a pulling place of destination, as it continues until today.

Collective behavior has always been part of their social structure. Before the Incas conquered the Huanca, the basic social organization has been open kinship communities known as *Ayllus*, a *social network* that exists up to date, which collectively gave origin to a Huanca nation. These Huancas will be known as a community known of great pride, warrior spirit, and a salient history of cruelty toward their enemies. In "The Royal Commentaries of the Incas", Garcilazo de la Vega [71] noted, "They scalped their prisoners of war, kept the burnt skins in their temples as trophies of their deeds, and used human flesh as material for their tambourines."

A particular good summary that reflects this long-standing character of the Huancayo people is found in Gutierrez [72], who mentions:

- The Huancas were brought under control by the Incas with great resistance, and their territory became an important center of operations.
- The Huancas took revenge against the Incas by helping with the Spaniards during the conquest.
- In 1820, the Peruvian independence was proclaimed first in this land.
- In 1852, Huancayo was also the place from where President Ramon Castilla signed the law abolishing slavery in Peru.

Huancayo's current situation is a combination of policy decisions and emergent conditions that turned it from a site of 6 000 scattered people by the end of the 19^{th} century into a city of nearly 400 000 (387 966 according to 2007 census [45]). The central government decided that the railway reached Huancayo by 1908 (see Figure 3.12) and the Central Highway, Peru's only highway from Lima to the Central Jungle, by 1930 (see Figure 3.13). These events were sufficient conditions for increasing movement of goods and people that allowed for the gradual presence of a small elite associated with commerce. As a result of this growth, the Province of Huancayo was declared as the capital of the Junin Region in 1931 and since then it has gradually become the most important city of the central Peru Highlands (or *Sierra*) whose growth has been focused in at least 3 Districts (El Tambo, Huancayo and Chilca).

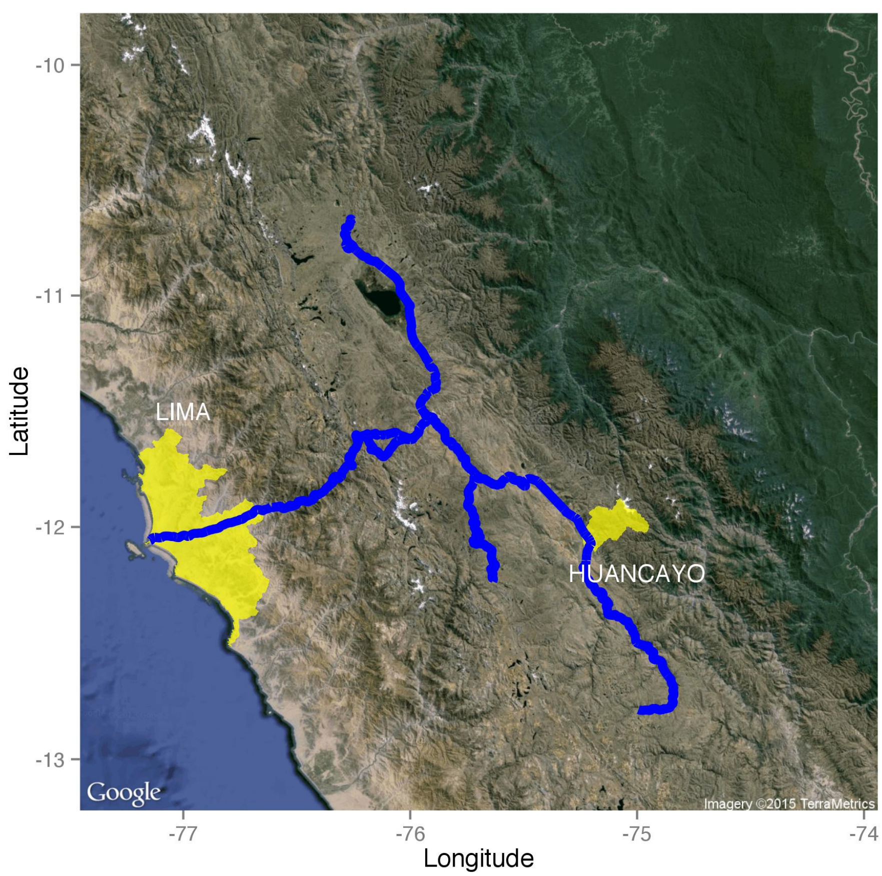


Figure 3.12: Central Peru railway
Source: Created by the author using Google Maps and ggmaps in R.

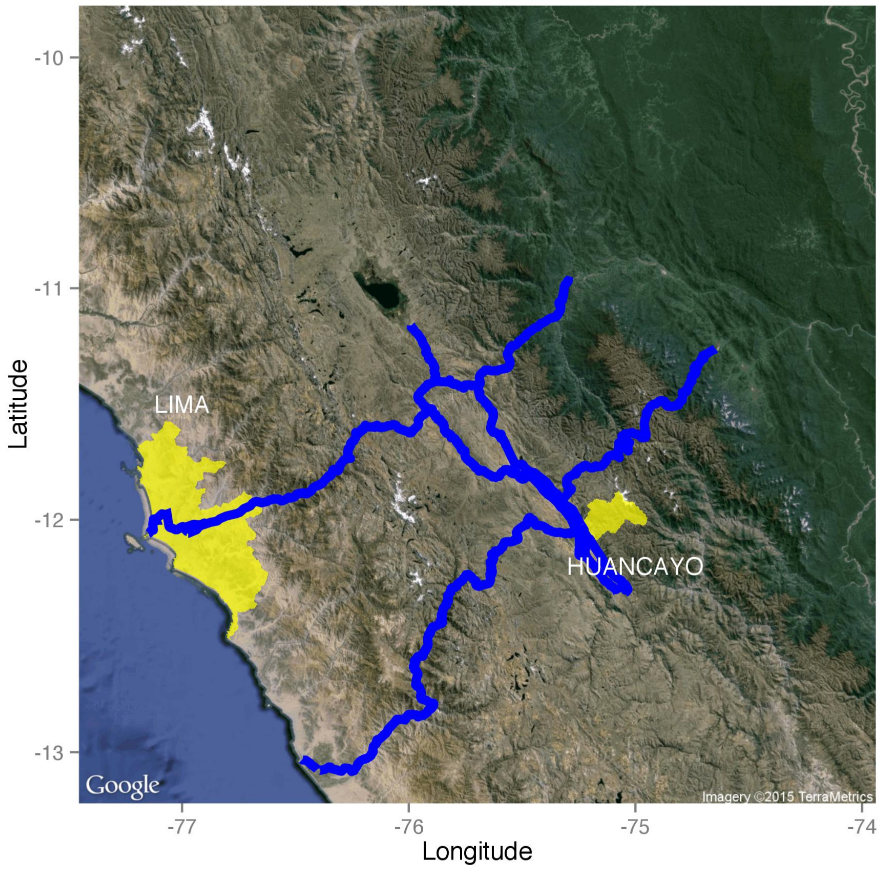


Figure 3.13: Central Peru highway
Source: Created by the author using Google Maps and ggmaps in R.

Huancayo was not a planned city, as explained before, so its growth can be explained in terms of migration events. As De La Cadena [57] explains, Huancayo has been shaped by the particular migration processes of rural families moving into the city during most part of the 20^{th} century. This process was gradual, first exploring the conditions of the city and later exploiting the benefits obtained. That is, one generation of families started visiting and doing trading in the city. Then, the next generation established a urban domicile in the city while keeping their land. Another generation may have sold its land and become a permanent resident of the city, while some other families keep their land managed by the older relatives while their young ones reside in the city getting education and having city jobs. Despite this varied process, this made Huancayo a homogeneous community.

However, the 1980-decade signaled a different meaning for migration. During that time, the internal armed conflict between the State and the guerrilla organizations of *Shining Path* and *Tupac Amaru* made some rural sites unsafe for living, particularly in the poorest regions (which correspond to rural areas). As Diez-Hurtado [58] reports, migrants from the highlands as well as from the Amazonian lowlands sought refuge in Huancayo, and between 1985 and 1994 they developed new livelihoods there. In that period, Huancayo received 19 250 migrants from its own Region (Junin), 13 800 from Huancavelica (the poorest Region in Peru) and even 8 850 from Lima who mainly increase the informal jobs sector. As a result, the growth of city increased above the previous average trend, the urban area expanded, and, unfortunately, the urban planning was left behind.

3.2.3 City growth and urbanization

The most important cities of Peru are in the coast (Lima, Arequipa and Trujillo), all of them big and very traditional rich cities since colonial times. However, as Haller and Borsdoff [40] report, it is becoming of more interest the study of "intermediate cities", especially in rural regions as their political prominence turned them into metropolitan areas offering government and non-government facilities that locally allow means to commercialize agriculture, create off-farm employment opportunities, diversify rural economies and increase the access of rural people to town-based services and facilities [73].

Huancayo is one of these intermediate cities in Peru, and a very interesting to understand; different from the intermediate city of Cajamarca, Huancayo does not have important mining industry; different from the intermediate cities of Ica and Chiclayo, Huancayo is not on the coast and has no extensive farming industry; and different from any other intermediate or big city, Huancayo is the closest one to Lima. Huancayo does not even have an airport with the characteristics of any of the big cities mentioned. What Huancayo offers is a hub between the central jungle and Lima, a place for great food and entertainment during traditional folklore celebrations, as well as "community-based manufacturing and commerce of agricultural and animal products, such as wheat and potatoes, milk, textiles and leather" [40]. A fact I need to highlight regarding this study, is that Huancayo is growing. Huancayo keeps a positive population growth [45], as all of its most important Districts are growing in population. Permanent population has been increasing according to the last three censuses (see Table 3.1 below):

Table 3.1: Population counts of the districts of Huancayo City - last 3 censuses

District	Census 1981	Census 1993	Census 2007	Growth Rate (2007-1993)
Huancayo	88,634	100,116	112,054	0.8
ElTambo	59,533	112,284	146,847	1.9
Chilca	36,918	60,466	77,392	1.7
Average				1.5

Source: Adapted from [45]

The spread of businesses and higher education institutions is another sign of this population growth. In particular, an "establishment index" (EI) was computed in 2013 [40] using the most recent census data [45], as the rate between number of establishments (E) and population (P) multiplied by 1000 (establishments per 1000 people).

$$EI = \frac{E}{P * 1000} \tag{3.1}$$

From Equation 3.1, Lima (including Callao - Peru's most important harbor) gets an EI of 43.4 and Huancayo reaches an astonishing 58.6. This gives a clear idea that Huancayo is growing, and also that the floating population is at least keeping constant. Does this growth represent a positive sign for Huancayo? The fact that the city is growing is in fact a positive sing of its economy, but some other factors need to be considered to decide whether this growth is sustainable.

Another key element in this study is the fact that this growth is also affecting the natural system. Two current studies report of the actual effect of the city growth and attractiveness of Huancayo. First, Arroyo informs us that among the different activities that endanger Huaytapallana, tourism and related cultural rites are the most dangerous [74], a fact also noticed by Altamirano [75]. However, Arroyo also presents alarming facts, as it concludes that even the activities that are being done to ensure more water for the Shullcas, are in fact affecting the Shullcas in the long run, as infiltration trenches for capturing rain water, and reforestation are also endangering the glacier, as they limit snow from becoming ice (see Figure 3.14).

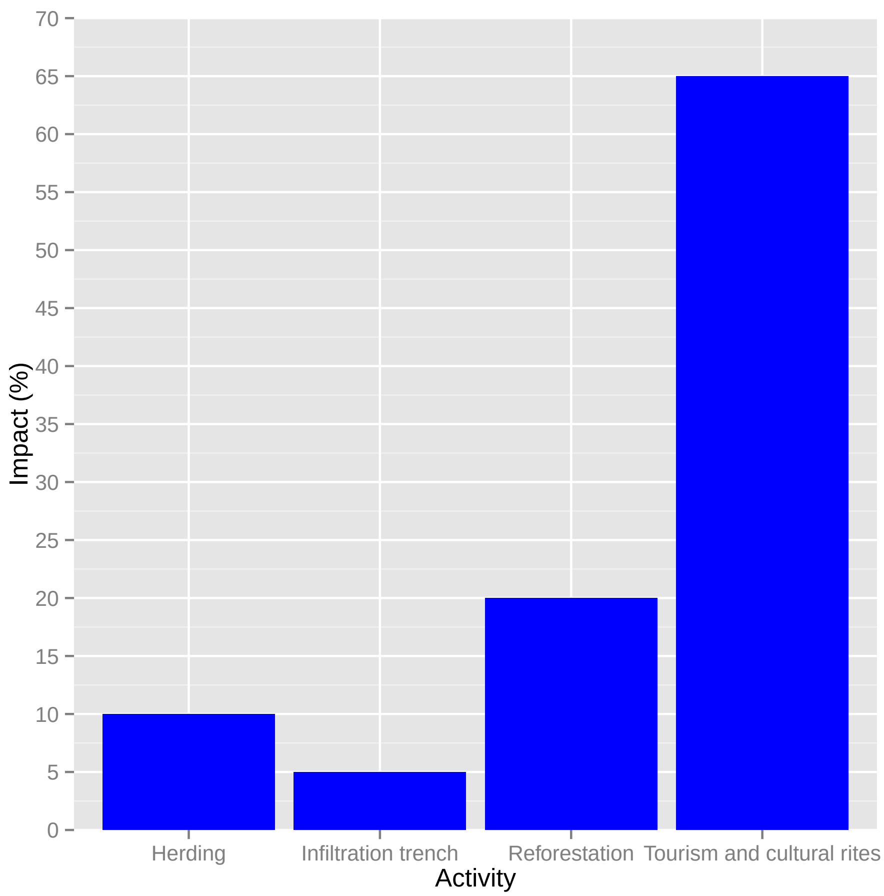


Figure 3.14: Anthropic activities and its negative effects on the Huaytapallana
Source: Adapted from [74].

Tourism is for Huancayo a relevant source of income for different people, as there are many small companies that offer these services to locals and visitors; even taxi drivers offer visits to Huaytapallana. As it is clear now, Huaytapallana is a cultural icon that attracts visitors not only for tourism as usual, but also for religious reasons. However, these activities are poorly regulated, and as a consequence, tourists become polluters representing a negative issue for Huaytapallana and Shullcas.

A second study emphasizes land use change. Following the recent migration events in Huancayo since the 1980s, Haller [42] and Haller and Borsdoff [40] have been doing research on peri-urbanization in Huancayo in recent years. They have obtained Landsat 5 TM satellite images (path 6, row 68) from 1988 (August 7), 1998 (August 3) and 2008 (July 13) at an output scale of 1:100,000. These images were acquired during the dry season, so almost no cloud cover occurred. Then, the effect of urban heat islands was well pronounced, allowing them to differentiate urban settlements from bare rock in mountain regions. That data was classified according to Table 3.2.

Table 3.2: Changes in land cover classification in Huancayo

Name	ID	Explanation
Wood or shrubland	WSL	Non-cultivated woody plants; cultivated wood crops
Ichu grassland or cereal crops	IGC	Natural herbaceous vegetation; graminoids cultivated for grains
Champa vegetable or pasture crops	CVP	Several plant species cultivated for leaves, buds, roots or tubers
Bare soil areas	BSA	Damp moist or wet bare soil
Settlements	SET	Buildings inside the continuous built-up area
Other	OTHER	Rocks and river bars; dry bare soil; rivers, lakes and wetlands

Source: Adapted from [42].

Haller and Borsdoff present the land changes Huancayo has experimented in the last three decades in Table 3.3. These colleagues also managed to organize this information into trajectories, as presented in the Figure 3.15. Form that plot, one knows, for instance, that (the smallest circle on the right) 1 ha changed from class BSA (in 1988) via IGC (in 1998) to SET (in 2008). As it is clear so far, population is growing and also changing the landscape in Huancayo. And this growth is not only endogenous, but also promoted by the immigration of non Huancas into the watershed. In the next section, I will combine the natural and social information to computed the waster balance in the watershed.

Table 3.3: Changes of land cover in Huancayo

	1988		1998		2008	
	Area [ha]	Area [%]	Area [ha]	Area [%]	Area [ha]	Area [%]
WSL	1916	3	2723	4	3936	5
IGC	26225	35	25841	34	23756	32
CVP	18450	24	19129	25	27341	36
BSA	4743	6	5124	7	3439	5
SET	3661	5	4994	7	5266	7
Other	20054	27	17238	23	11310	15
Total	75049	100	75049	100	75049	100

Source: Adapted from [42].

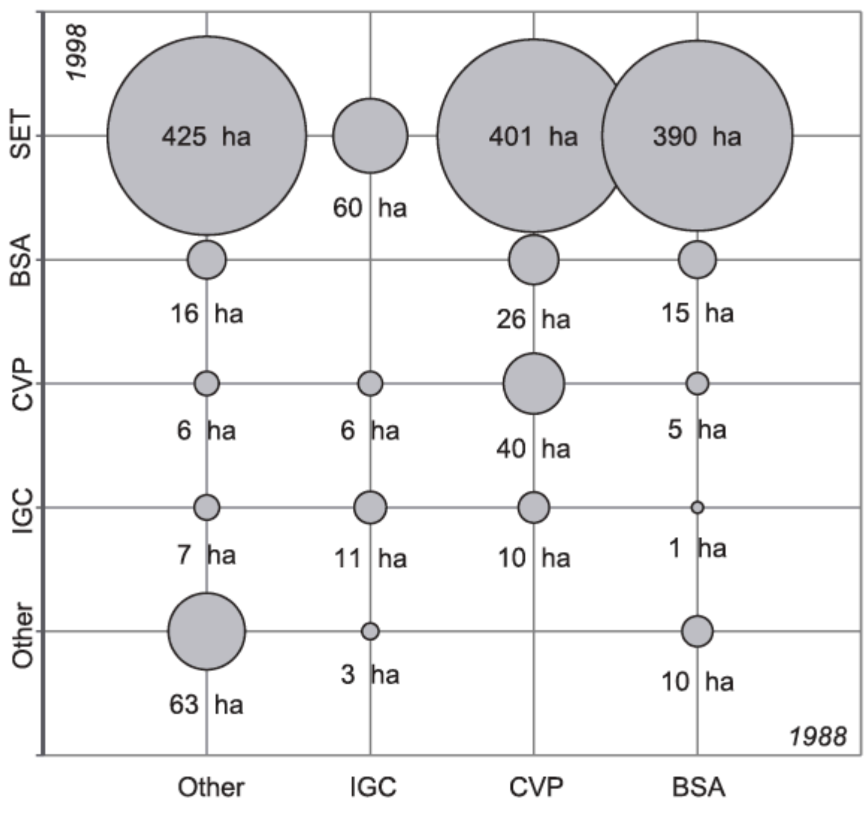


Figure 3.15: Trajectory of land use 1988-1998-2008
Source: Adapted from [42].

3.3 Water balance of the coupled systems

The water balance[5] in this watershed depends on rain and snow melt, both of which generate superficial and underground water, allowed by local runoff and infiltration factors. Both of these sources provide water to the rural areas of El Tambo and Huancayo, and to the urban areas of El Tambo, Huancayo and Chilca.

The information obtained has been organized into *zones*, for both the rural and the urban areas. I delimited the urban zones based on information from the local water company website[6] and previous studies [36]. To delimit the rural zones, I made use of many official sources [48] [76] [77], and a report privately prepared for the government during the project PRAA (Proyecto de Adaptacion al Impacto del Retroceso Acelerado de Glaciares en los Andes Tropicales[7]) [46]. The next paragraphs details the process followed to compute supply and demand of water per zone in m^3, based on information organized for 2011.

One concern of this work is knowledge of the water supply in this region. Following the studies mentioned above, I have produced that knowledge. First, I am computing water supply for the watershed using Equation 3.2:

$$Supply_{water_i} = Supply_{river_i} + Supply_{spring_i} + Supply_{well_i}, \tag{3.2}$$

where, for each zone i, $Supply_{water_i}$ is the total water supply (in m^3); $Supply_{river}$ is the river flow supply (in m^3); $Supply_{spring_i}$ is the supply via springs (in m^3), where available, and $Supply_{well_i}$ is the supply via wells (in m^3), where available. The result can be visualized in Figure 3.16.

The demand is an information badly needed to think in better policy terms, as without a good measure of water demand whatever policy implemented will only get ineffective

[5] As I mentioned before, this area has not been studied extensively and most of the official records are not fully updated. However, all information available on water balance from Shullcas has been organized in this section.

[6] see web.sedamhuancayo.com.pe

[7] Adaptation to the Impact of Rapid Glacier Retreat in the Tropical Andes Project

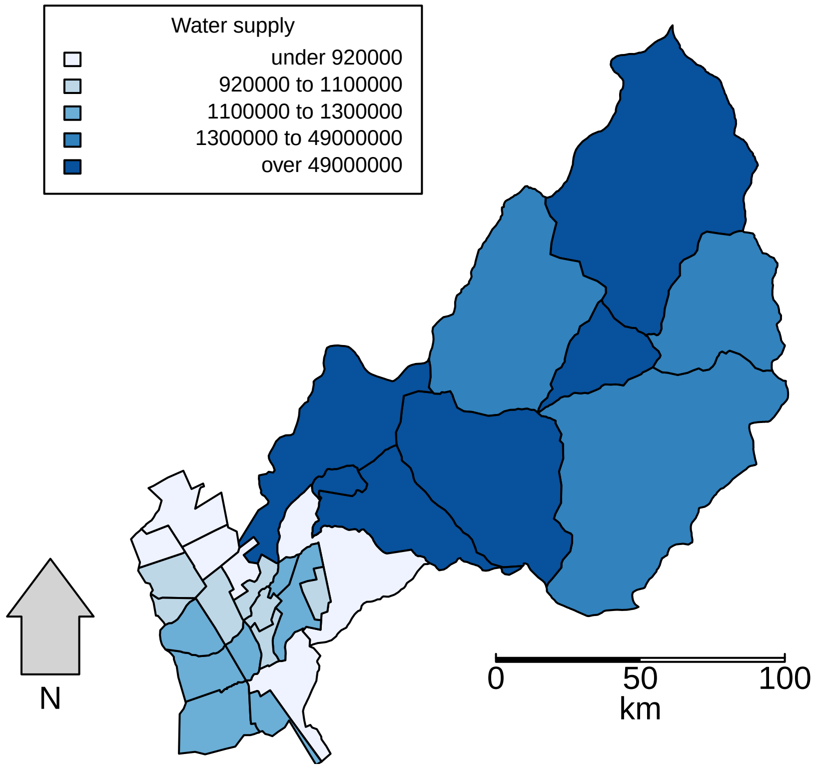


Figure 3.16: Distribution of yearly water supply
Source: Adapted from [36, 46, 48, 77].

outcomes, at best. From the sources cited, and specially from the works of local researchers [36], I offer a measure of water demand for the watershed, using the equations below.

$$Demand_{water_i} = Demand_{water_{A_i}} + Demand_{water_{P_i}}, \tag{3.3}$$

where $Demand_{water}$ is the sum of total water demand in zone i (in m^3), $Demand_{water_{A_i}}$ is the demand for agricultural use in zone i (in m^3) and $Demand_{water_{P_i}}$ is the demand for population uses [8] (see details in Table 3.4). $Demand_{water_{A_i}}$ is the product of average

[8] These include *commercial* (fresh water for motels, hotels, restaurants, office buildings, other commercial

hectares requirement for agriculture use in $\frac{m^3}{ha}$ times total area for agricultural purposes in ha (see Table 3.5).

Table 3.4: Estimation of water demand for population needs (in m^3 per year), as computed for this work

Districts	Zone type	Zone name	Population (Est. 2011)	Demand
El Tambo - Huancayo	Rural	Ucushcancha	0	0
El Tambo - Huancayo	Rural	Chamiseria	400	13140
Huancayo	Rural	Pacchapata	0	0
Huancayo	Rural	Ronda	0	0
El Tambo - Huancayo	Rural	Acopalca	584	19184
El Tambo	Rural	Achapa	0	0
El Tambo	Urbana	1T	23576	1273712
El Tambo	Urbana	8T	22696	1617312
Chilca	Urbana	1CH	17235	1044883
Chilca	Urbana	3CH	21038	1174797
El Tambo	Urbana	B	0	0
Huancayo	Rural	Palian	7736	496961
Chilca	Urbana	2CH	49170	2854798
El Tambo	Urbana	3T	30970	1719455
El Tambo	Urbana	4T	37185	1937275
El Tambo	Urbana	5T	5512	237670
El Tambo	Urbana	7T	12695	621838
Huancayo	Urbana	1H	22473	1344511
Huancayo	Urbana	2H	18873	1209336
Huancayo	Urbana	3H	12841	867596
Huancayo	Urbana	4H	13764	999389
Huancayo	Urbana	5H	1827	122759
Huancayo	Urbana	7H	4053	326177
Huancayo	Urbana	6H	20138	1346856
El Tambo	Urbana	6T	6001	258747
El Tambo	Urbana	2T	16791	886471
Huancayo	Rural	Unas	3000	109500
Huancayo	Rural	Vilcacoto	539	19674
El Tambo	Rural	Cochas-Cullpa	5910	776574

Source: Adapted from [36, 46, 48, 77].

The water demand for population use $Demand_{water_{P_i}}$ is the average demand per person (in liters per person) computed for each zone in [36] times the population per zone, time 0.365, a factor to transform the data from liters into cubic meters per year. The total demand can be visualized in Figure 3.17.

Finally, the statistics for demand and supply are offered in Table 3.6.

This information gives an starting point for the model, and it is the base its initialization.

facilities, and civilian and military institutions; and *domestic* (drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens)

Table 3.5: Estimation of water demand for agriculture needs (in m^3 per year), as computed for this work (omitting zones with no demand)

N^o	Zone name	Area for agriculture (ha)	Demand
1	Acopalca	13.8	188496
2	Chamiseria	172	1376000
3	Pacchapata	517.4	7037184
4	Unas	414.6	4976040
5	Vilcacoto	94	1222000
6	Palian	165	1980000
7	Cochas-Cullpa	763	7630000

Source: Adapted from [36, 46, 48, 77].

Table 3.6: Statistics of demand of water for agricultural and population needs (in $\frac{m^3}{ha}$)

Statistics	Agricultural Demand	Population demand
Mean:	841714.48	733745.39
StdDev:	2028218.24	720928.71
Sum:	24409720	21278616.35

Source: Adapted from [36, 46, 48, 77].

However, to represent this dynamic I still need to know how the trend in supply of water has been recently. For this, I made use of the work by Carlos and Grijalva on the Shullcas supply in the recent years[36] (1985-2011) to obtain the slope needed for the simulation. This behavior of the water supply is summarized in the regression results in Table 3.7.The negative slope obtained suggests a slowly decreasing river capacity. Although the variability is high, I will use this slope in the model to decrease the yearly amount of water since 2011 (the last year the data was collected in [36]). A plot of the data can be seen in Figure 3.18.

Table 3.7: Average water supply trend

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	40.1151	43.3709	0.92	0.3638
YEAR	-0.0185	0.0217	-0.85	0.4025

Source: Adapted by author from [36].

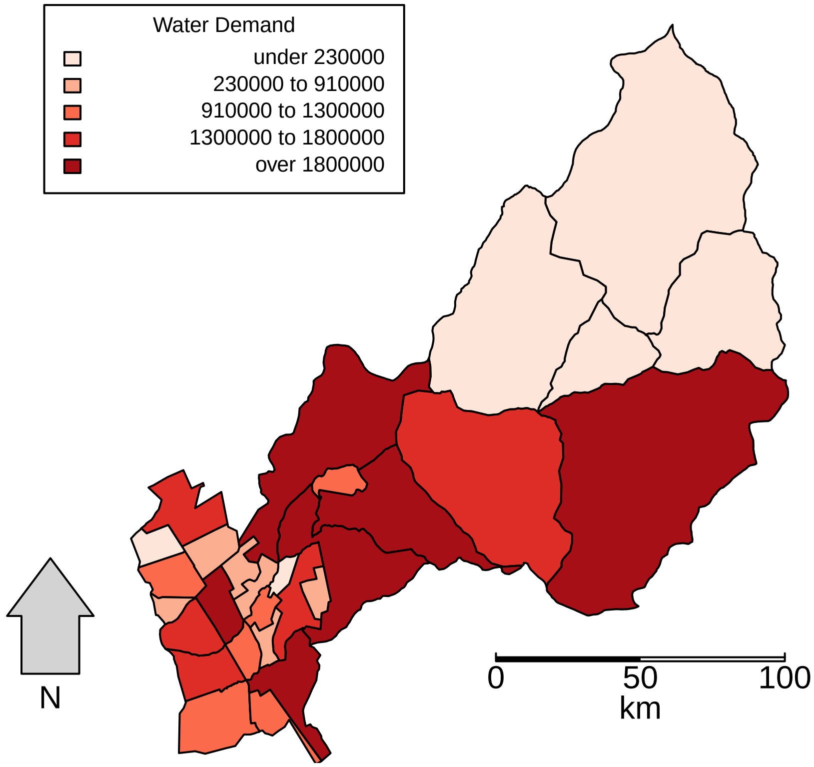


Figure 3.17: Distribution of yearly water demand
Source: Adapted from [36, 46, 48, 77].

As the water supply decreases, the major sources of precipitation are diminishing in the area. However, as the glacier is still present, the current decrease is mostly attributed to rainfall. Besides, according to the opinion of Bryan Mark and Ignacio Lopez [78, 79] there would be a moment of high snow melt in the Huaytapallana during its last stage of retreat. From the knowledge obtained and integrated, the panorama of the water supply is pessimistic, and the “tropical” nature of the glacier complicates things even more, as one can think that glaciers melt in summer and recover in winter yearly. In the Andes that is not case, tropical glaciers are unlike the Swiss Alps, as the period of rainfall in the central Andes coincides with summer, so there is no season during which the glacier could recover [39].

But, how much would the total retreat of the Huaytapallana affect the Shullcas water

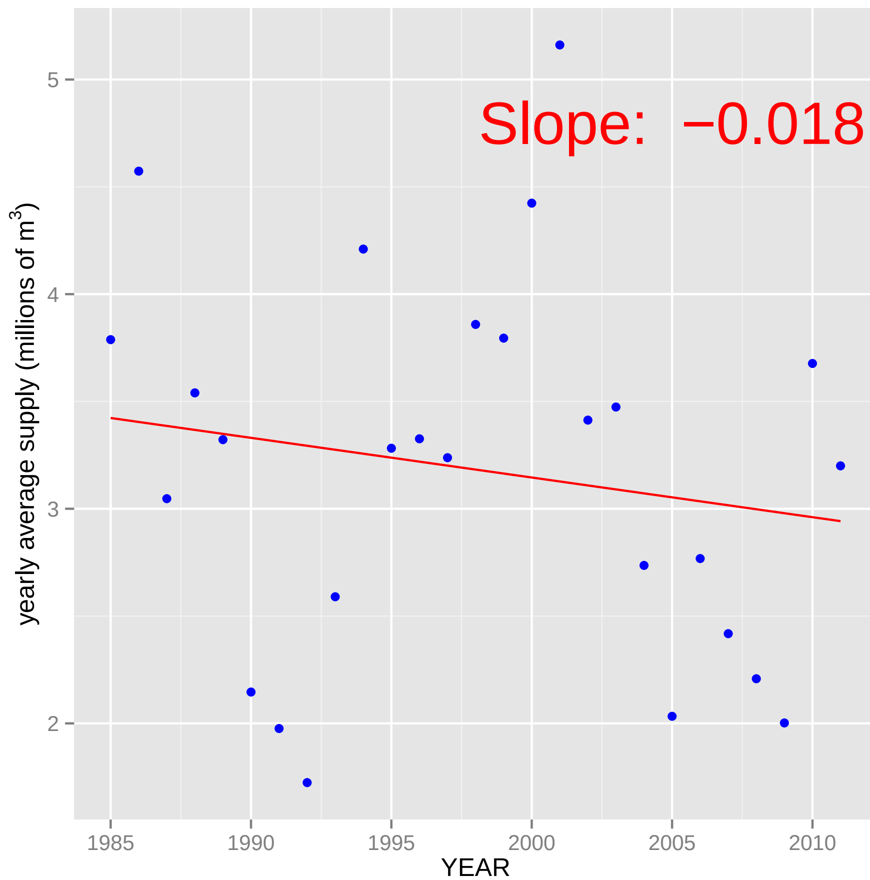


Figure 3.18: water supply trend
Source: Adapted by author from [36].

supply The official reports have no idea [46]. However, from personal communication with experts and their very recent measurements [**?**, 78, 80], the effect during the dry season is expected to be at least 15% but no more than 20. From here, and following the same strategy of the river and glacier modelers [36, 37], I will use the slopes from the linear behavior of both in the model developed in the next chapter. What is left to know in order to sustain the hypothesis is how can migration and conflict be an outcome out of negative water balance, population growth and land use change. In the next section, I will propose that narrative, guided by a theoretical framework and insights from the field work.

3.4 Potential social effects in the coupled system

Apparently, Huancas can get in trouble. Now, I need to know what their individual responses could be, keeping in mind that responses are not going to be homogeneous but diverse, and that the response is at the individual level. This is starting point that needs a basic framework.

Albert O. Hirschmann offers that framework, with his related concepts of *exit*, *voice*, and *loyalty* [23]. According to Hirschmann, one should not expect all agents to disengage from problematic situations by simply moving away, but one should expect a variety of reactions. That is, in the face of any problem, some people will simply stay and adapt to new conditions (loyalty), some people will complain explicitly to have their context reinstated (voice), and some people will find that getting away from the problem is the best option (exit). The basic abstraction of this work follows these three concepts. I apply this framework to understand the decisions of people as the natural system suffers water scarcity in Huancayo, as water supply keeps decreasing and water demand keeps increasing.

3.4.1 Migration

Migration can arguably be considered an exit; however, not always as an expression of free will. Reuveny understood this phenomenon very well [81], as he proposes that under stressing climate conditions, it is more likely that people feel *forced* to migrate. The Table 3.8 organizes the information he collected to support his thesis that water scarcity is highly related to migration, which also highlights the catalytic role climate change have with political and economical factors, thus revealing a series of structural weaknesses in the social systems in affects, reinforcing the idea that developed countries are less affected than developing countries [12].

From Table 3.8 I observe that (i) water scarcity *pushes* huge migration movements; different from other migration needs, the lack of basic natural resources provokes not only individuals but also whole communities to migrate; (ii) climate change reveals social and

Table 3.8: Recent migration processes related to water scarcity (number of people migrating in millions).

Country	Conflict	Overpopulation	Economic Factor	Ethnic Factor	Governance	Decade start	Decade end	Quantity migrating
Bangladesh	1	1	1	0	1	1970	1990	0.60
Ethiopia	1	1	1	0	1	1980	1980	0.60
Rwanda	1	1	1	1	1	1990	1990	1.70
Mexico	1	0	1	0	1	1960	1990	0.28
Bangladesh	1	1	0	0	1	1950	2010	17.00
El Salvador	1	1	1	0	1	1950	1980	0.80
Ethiopia	1	0	1	1	0	1960	1980	1.10
Mauritania	1	1	0	1	1	1980	1990	0.07
Somalia	1	1	1	1	1	1970	1970	0.40
Haiti	1	1	1	0	1	1970	1990	1.30
Philippines	1	1	1	0	1	1970	1990	4.30
South Africa	1	1	1	0	1	1970	1980	10.00
Sahel	1	0	1	0	0	1960	1980	10.00
Brazil	1	1	1	0	1	1960	2010	8.00
Sudan	1	1	1	1	1	1970	1980	4.00
US	1	0	1	0	0	1930	1930	2.50
Ethiopia	1	1	1	1	0	1970	1970	0.45
Nigeria	1	1	1	0	0	1970	1990	
Pakistan	1	1	1	1	1	1980	1990	
Bangladesh	0	1	1	0	0	1970	1990	
China	0	0	1	0	1	1980	1990	30.00
Ecuador	0	0	1	1	1	1970	1990	
North Korea	0	0	1	1	1	1995	2000	0.40
Somalia	0	1	0	1	1	1990	1990	2.80
Guatemala	0	1	1	0	1	1950	1980	0.10
Dominican Republic	0	0	1	1	0	1940	1980	0.10
Canada	0	0	0	0	1	1930	1930	0.30
Mexico	0	1	1	0	0	1990	2000	3.00
Kenya	0	1	1	1	0	1960	1990	0.20
Uzbekistan	0	0	1	1	0	1970	2000	1.50
Russia	0	0	1	1	0	1990	1990	2.00
Russia	0	0	0	0	1	1990	1990	
Burkina Fasso	0	1	1	0	0	1960	2000	
India	0	0	1	0	0	1970	1980	
Zimbabwe	0	0	1	0	1	1980	1980	
Thailand	0	0	1	0	0	1980	1990	
Russia	0	0	1	0	0	1990	1990	0.07
Tanzania	0	1	1	0	1	1950	1990	0.84

Source: Adapted from [81].

economic vulnerability of people, as, globally, developed countries have less cases of migration than poor countries. There, rural people, in particular, depend on self consumption and trading in local markets; so, people migrating needs to look for destinations that have particular *pulling* conditions that fit their weakened competences; (iii) The complexity of situations like this will have no immediate political and policy solution, while the people affected bears long lasting consequences; (iv) population growth in systems vulnerable to water scarcity and underdevelopment represents an explosive combination, as in countries with these characteristics, social conflict emerged and was catastrophic.

Related to what I just observed, I consider that I can relate conflict and migration with climate change in my work, as the current evidence suggest so. With that in mind I consider that the following facts support my hypothesis:

- Huancayo is in a system gradually becoming more vulnerable to water scarcity, yet the population keeps growing (see Table 3.1 on page 57) and the land use keeps turning from rural to urban (see Figure 3.15 on page 60).

- People migrating will not go anywhere they wish, but to a place they could do better according to their economic, educational and family condition. In the situation of Huancayo, the possible destinations, according to the field work, can be Lima or the jungle (or even foreign countries); so, policy makers need to be aware of the competences and constraints the demographic composition of Huancayo has, which I present in Table 3.9.

Table 3.9: Key demographic indicators (% rural and urban)

MARRIED	WORKING	COLLEGE	RURAL	URBAN
0	0	0	29	24
0	0	1	4	9
0	1	0	13	9
0	1	1	4	8
1	0	0	30	22
1	0	1	3	6
1	1	0	14	10
1	1	1	3	12
Total			100	100

Source: Adapted from [45]

- There is a considerable number of people who have moved into Huancayo and who would have no intention to leave Huancayo. From the field work carried out, rural wankas are not satisfied with the growing presence of non-Huancas in the peri-urban area. From the field work, a qualitative sample of fifty families gave a 45% of families in this area are not Huancas (keep in mind that the non-Huanca share in the last census was 35%).

- Urban people are currently suffering some water shortages during the dry season, but the idea of moving has not crossed their minds yet. From the local interviews conducted, they will believe there is a serious scarcity if this phenomenon is present for 4 years (but they will definitely leave if it reaches 6 events).

- Finally, from the field work I carried out in this area, urban people are more likely to migrate than rural people. In fact, every rural person interviewed has no intention of migrating in case of water scarcity, as they believe the situation would not be any better somewhere else. Most rural residents told me: "*If we do not have water here near the Huaytapallana, that means the city and the coast will be worse than us.*" This is very important as authorities need to understand where might people go. Even though some rural people have family in Lima (or in foreign countries), there are people in the rural area less eager to migrate and prefer to develop different strategies, as found by Raul Ho and Andrea Milan [41] (see Figure 3.19). This last behavior has also historical references in Peru. Peruvians in the highlands have deep roots and do not move but prefer their situation be improved in situ. The worst natural disaster in Peru, the 1970 earthquake, provoked an snow avalanche in the "Cordillera Blanca" killing 70 000 people; and spite of that, the survivors refused to leave their place [82].

But what about the people that are staying? According to my field work, the people less likely to migrate are the rural ones (poorest) and the recent immigrants living in the peri-urban area. In the next section, I will deal with these people whose *loyalty* may turn into a conflictive *voice*.

3.4.2 Social conflict

Is it possible that conflict emerges and escalates in the central Andes of Peru? Can peaceful people turn violent after suffering so many climate issues? I consider here that social conflict is possible, if the individuals a social system become frustrated, an hypothesis also supported by modelers at *Los Alamos National Laboratory* [44] and in agreement with social psychology of conflict. I relate as an initial cause, the difficult situation that the people

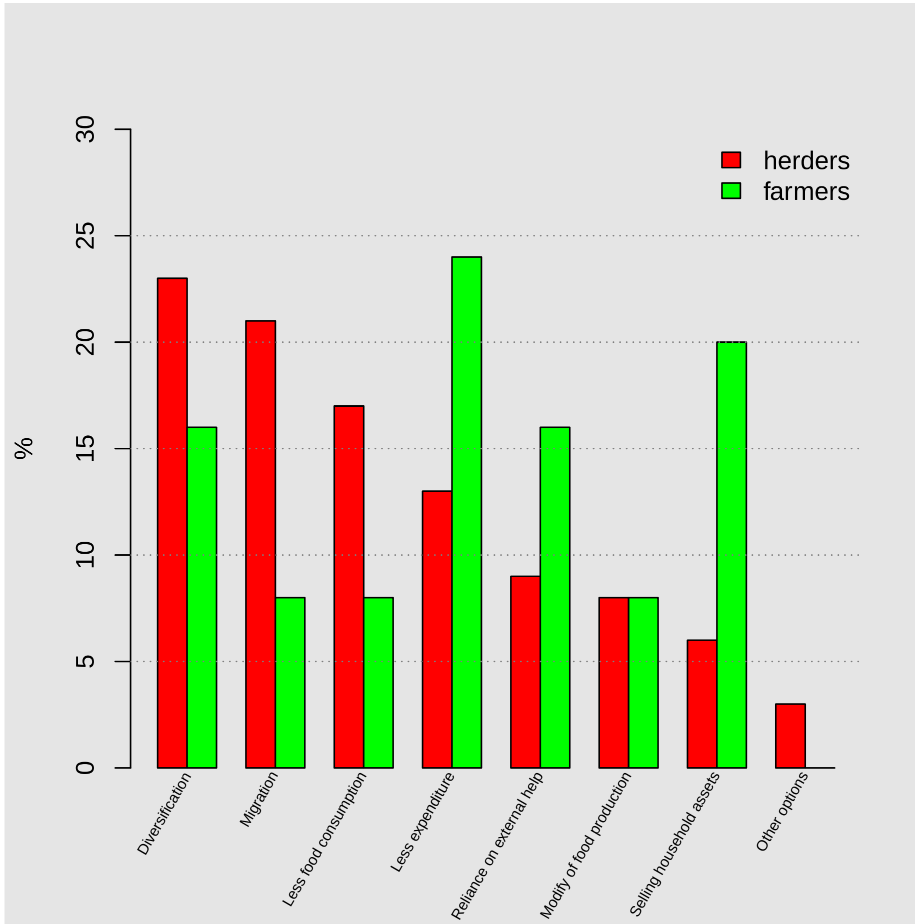


Figure 3.19: Strategies adopted in rural area. Migration is not a relevant option for rural people, specially for farmers (lower altitudes)
Source: Adapted from [41].

that can not escape have to bear with. For this group, two theories of psychological processes apply to explain the potential for conflict, namely *frustration-aggression* and *relative deprivation*, which I will introduce later.

How likely is that Huancas not migrating turn their frustration into social conflict? This work has not modeled this question, but the current situation in Peru shows that the social conflicts related to environmental issues have been the most frequent [83] (see Figure 3.20), and have occurred between communities over scarce resources, between a community and an extractive company, and between a community and the local/central government [83].

In most of these cases, there have been huge protests, lost of millions of dollars, political repression, and worst of all, many lives were lost [83].

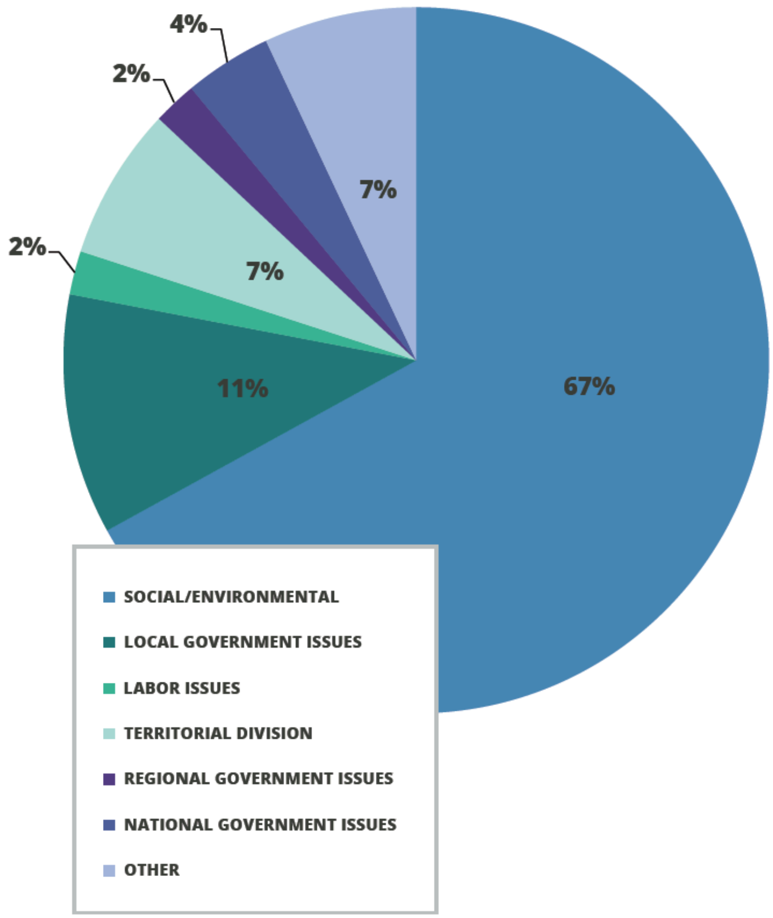


Figure 3.20: Nature of conflicts in Peru, related to oil and mining
Source: Based on [83]

Evidently, the metropolitan area of Huancayo is the engine that makes this province show a positive economy. According to the official records, gross domestic product has been increasing on average 0.5% per year the last two decades[84]. However, nowadays, 6.4% of the population lives in extreme poverty and 22% are yet in relative poverty[84]. That is, there will be some people that will have no option but to leave Huancayo, and their strong *loyalty* to the land can pave the way to violent behavior.

There are antecedents in previous studies that economic disadvantage is a significant factor for children to become aggressive [85]. That is, it is important to keep in mind that the current generation may be submissive under economic stress but not necessarily the next one. In either case, the fact that economy is seriously affected determines a change in the quality of life that every family generation will face with a different strategy.

3.4.2.1 The emergence of aggressiveness

Frustration-aggression hypothesis helps us understand why we need someone to blame [86]. The theory says that frustration causes aggression, but when the source of the frustration cannot be challenged, the aggression gets displaced onto an innocent target. In this case, I can not expect a rural person to blame the weather or the Huaytapallana for his or her condition. However, blaming the urban neighbor or the rural community nearby are possible targets, as long as they see them as *strangers*.

Rural communities in Huancayo depend strongly on family farming for survival, and in trading for a better living. When water scarcity affects Huancayo seriously, the income of these people will be seriously compromised as their lands become less productive and as the local market for their products may not be as profitable as before, because the city may have less visitors or their regular costumers migrated. As expressed by Nielsen [87], frustration-aggression theory is also used to explain riots and revolutions, as both are caused by poorer and more deprived sections of society who have bottled up frustration and anger through generations.

In this context, this and the next generations are prone to experience frustration as their goals are interfered by the scarcity of resources caused by the lack of water. However, aggression is not always the response to frustration [88]. In this stage, I care more for the inner feeling of frustration than the act of violence itself; and in fact, this frustration may be finding his way towards their own families, as rural communities in Peru are currently the ones facing the higher indices of domestic violence [83, 89].

3.4.2.2 The feeling of deprivation

The inner feeling of frustration might not develop into a concrete cause of violence without the ingredient of relative deprivation theory [90]. Relative deprivation is felt when a person lacks the resources to sustain the expected lifestyle in his/her society. Relative deprivation is directly correlated to social exclusion and the feeling that you have been left behind. From my own experience, it is not a matter of feeling envy, but to believe life is unfair. Relative deprivation has important consequences for both behavior and attitudes, including political attitudes, and participation in collective action [91]. As Ted Gurr already explained [92], relative deprivation can lead in extreme situations to political violence such as rioting, terrorism, civil wars and crime. Understanding relative deprivation is key for social policy effectiveness.

Then, how can frustration and relative deprivation come into play in the case of Huancayo? Arguably, conflict will have a different pah in the urban and the rural area.

1. In the urban area

    - People that could not migrate become frustrated. Urban people not migrating will feel angry as they can not move and they keep suffering scarcity.
    - Frustrated non Huanca urban people will be less likely to migrate. Field work revealed that non Huancas made their life investment to move to Huancayo; so, they will stay, and their population share will increase. Following [40], non Huancas will be prominent in the new urbanized areas closer to the rural area.
    - The emergence of organization for conflict. Frustration is not enough. Urban people need to organize to fight for change politically. If frustrated people find a way to network, the potential for conflict increases.

2. In the rural area

    - Neighborhood effect. From field work, I know that relative deprivation will take place when a poor rural that could not exit, finds that the nearby zone has been urbanized and that his/her closest urban neighbors are non Huancas, who are better off than he/she is. This finding has also been supported during an interview to Andreas Haller, who is currently studying peri-urbanization in Huancayo [40, 42].

- Family effect. It is expected that if a relatively deprived rural individual decides to start some kind of conflict, its family may be involved, increasing the actual number of people in conflict.

By integrating different kinds of knowledge (glaciological, hydrological, anthropological, sociological, urbanistic and psychological) that I have enough elements to believe that migration and social conflict are potential outcomes of the current trends in climate change (less water supply), and city growth (population growth and land use change). The possibility of integrating this interdisciplinary knowledge using a computational social science approach will answer questions that the simple qualitative combination of these facts can not, as well as facilitating the exploration of different scenarios for different initial conditions, as Herbert Simon proposes [93]. In the next chapter, I will describe this approach.

Chapter 4: Modeling and Implementing the coupled system

In Figure 1.4 on page 13, I made the effort to abstract to its basic components the coupled system I am working on. Using the same scheme, I collected data and evidence for both the social and natural system components in the previous chapter to support the hypothesis that it is possible for Huancayo to experience a drastic alteration in emigration patterns and the emergence of conflict if the current trend in glacier melting, river volume, immigration, population growth and land use are kept. So far, I have organized the following:

- It is possible that drastic emigration events occur in Huancayo, in the urban area, if population growth keeps the current trend (see Table 3.1 in page 57) and water balance becomes negative as the natural system will keep reducing water supply (see table 3.7 on page 64 based on [36]), the glacier keeps melting (see figure 3.9 on page 48 based on [37]), which will impact negatively the Shullcas water supply in around 15%-20% based on recent measurements [78] and on expert judgement [80].

- It is possible that conflict emerges in Huancayo, both in the urban and rural area. In the urban area, theoretically, conflict is possible if people who suffer excessive water scarcity can not migrate and become frustrated and aggressive (see section 3.4.2.1). However the conflict emergence will depend on the capacity of people to organize. In the rural area, theoretically, conflict may emerge as frustrated rural people find that their neighborhood has not only change but has brought non-Huancas who are even doing better [40,42], thus feeling relatively deprived (see section 3.4.2.2). This is supported by the ad-hoc field work carried out in the area and interviews with experts [94].

Up to this point, I successfully connected different facts and built a logical narrative of current conditions (premises) from which I have proposed logical conclusions.

4.1 Modeling paradigm

Nevertheless, even though narratives are needed for good modeling, they may not be good enough for making better decisions. Even if I added more details to my current narratives, those would be more details to the premises which increase the complexity of the narrative while maintaining or reducing the usefulness of my modelling efforts; as more assumptions will be needed the inferences will weaken, then this logical system will experience the Bonini's Paradox [95].

This is when Computational Social Science comes into play in modern science, as Herbert Simon says:

> *"The obvious point is that, even when we have correct premises, it may be very difficult to discover what they imply. All correct reasoning is a grand system of tautologies, but only God can make direct use of that fact. The rest of us must painstakingly and fallibly tease out the consequences of our assumptions... Greatly oversimplified, the idea is that we already know the correct basic assumptions,..., but we need the computer to work out the implications of the interactions of... variables.... For it is typical of many kinds of design problems that the inner system consists of components whose fundamental laws of behavior mechanical, electrical, or chemical are well known. The difficulty of the design problem often resides in predicting how an assemblage of such components will behave"*[93].

Complexity is not a new concept, but the use of computers has allowed me to find better ways to understand emerging properties of complex systems [93]. There are certainly many computational modeling approaches—e.g. system dynamics or discrete systems simulations—that deal with organizational complexity. However, key concepts such as learning and emergence can only be modeled, arguably, through the use of agent-based models (ABM) [33, 34, 96, 97]. As with all modeling techniques, ABMs need to capture the most basic variables and processes that could explain a particular phenomenon, while making all building assumptions explicit and transparent, and producing outcomes valid and of interest to the scientific and policy community. In contrast to other techniques, agent-based models are virtual laboratories that allow their components to have different behaviors, reactions, and to be aware of only limited information. In particular, ABMs are useful in the social sciences when a particular social theory can be enacted through coding. We all can then see how the model behaves as the building parameters of the theory are manipulated [33, 97]. Besides, ABM allows for the inclusion of complementary theories and models to carefully enrich the original theory, allowing the creation of different scenarios.

4.2 Implementation tool

Currently, there are many agent-based modeling tools available to implement this model. In a Wikipedia on ABM, 87 toolkits are identified[1] worlwide. Most of them are freely available (71), but only the following are multiplatform, have documentation, support Geographical Information Systems (GIS) applications and have 3D capabilities (besides being free):

- Behaviour Composer
- Brahms
- FLAME
- FLAME GPU
- Framsticks
- GAMA
- MASON
- NetLogo
- Repast

[1] https://en.wikipedia.org/wiki/Comparison_of_agent-based_modeling_software

- SeSAm

- TerraME

However, NetLogo is the only one from the lost above which has at least two complete books that explicitly make use of it, one by Wilensky and Rand [20] and another by Railsback and Grimm [98], very recent works that gave more detailed references on how to conduct agent-based modeling. This was the starting point to select NetLogo.

Our particular problem had some constraints that also pushed the selection in a path dependent way. First, this model started as a class project at George Mason University, and although it was a simpler version without real data, the complexity was similar. That first version was done using NetLogo and was made out of the combination of some of models in the NetLogo library. A second consideration was the analysis tools NetLogo included, such as profiling, networking, GIS and especially behavior space. A third consideration was the time needed to complete the model, knowing NetLogo offered a series of functions that will reduce the programming time, as compared with the Java-based toolkits. Speaking of the Java-based ABM toolkits, these were ruled out as the the model was conceived since the beginning as an stylized model of middle coding complexity. I prepared a basic version in Python but NetLogo proved to be faster. NetLogo is not the best platform, but it was perfect for this work, considering the elements just mentioned, some experts opinion [99] and one more: I could integrate R and NetLogo for analysis, and I could integrate R and Latex. In this case, the versatility of R also contributed to keep using NetLogo, whose interaction with R has made the production of this document easier.

The model presented was implemented in NetLogo (version 5.1, released July 2014) [20] for Mac Operating Systems (OS)(see dashboard in Figure 4.1).

The computer used has been a MacBook Pro (OS 10.8.5). I carried out three different runs reported in this work:

- The *base* simulation, which was run once with all the default values, as presented later in Table 4.5 on page 98. The outcomes (discussed in the next Chapter) are considered

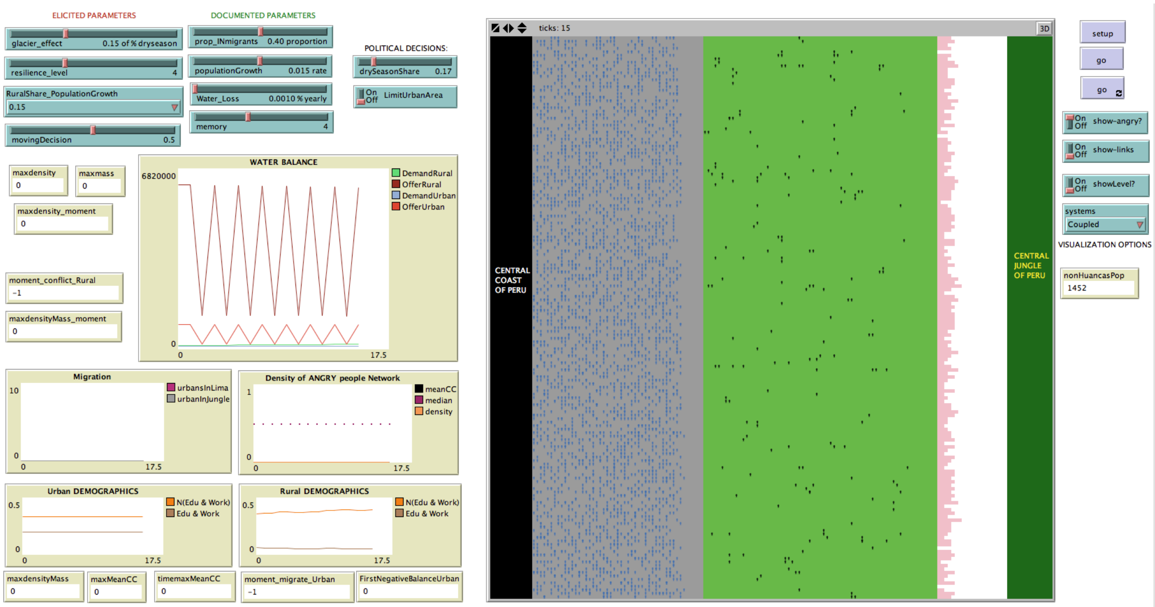


Figure 4.1: The AndeanLab dashboard. The grey area represents the urban area and the green the rural. The glacier is the white area and the pink patches are the melted glacier zone. Notice the reference to Lima (left) and the Jungle (right)

the result of the simulation, which is also validated by the narrative presented in Chapter Two. This run took 4.5 minutes.

- The *verification* run, where the *base* run was run 100 times, to see the consistency of results, considering there were several sections containing random processes affecting agents decisions. This run took eight hours.

- The *policy* run, where all the parameters of interest from the base model were varied or swept (those parameters are described later in section 4.4.3.2 on page 98). For each combination or scenario, I carried out 100 runs, which produced 64 800 simulation outputs for all this combinations, each, *base* run was run 100 times, to see the consistency of results, considering there were several sections containing random processes affecting agents decisions. This run took 79 hours and 58 minutes.

As already mentioned, the simulation has included the use of the network extension (for building and analyzing network data), the tool *Behavior Space* of NetLogo (to produce the different kinds of runs), R (for data analysis) and Gephi (for network visualization).

4.3 Model calibration

As seen in this chapter, there are many input and output variables and I needed to be sure the parameter space was adequate while avoiding over fitting. For the input variables in the social system, a careful selection was made of their values, usually via the interviews with the local population and with colleagues who are experts on the matter. Official data was also used for the precise values of immigration, emigration, births and deaths, all of them combined into a single value of population growth. The demographic composition of the population (see Table 3.9) was reconstructed from the 2007 census [45]. The population modeled has been selected from the same source, but reduced to include only people older than 14 years old. Due to the limitations of the space in NetLogo grid, the population was modeled at 1/100 of the original size. Given this, the supply and demand of water has been modeled in the same proportion.

Two particular parameters from the natural system have to be calibrated in order for our model to resemble the actual behavior of the water supply and the speed of the glacier melting. In the first case, Mr. Guillermo Carlos shared the data he collected to estimated the risk of water scarcity in Huancayo [36], which is depicted in Figure 3.18. Thus the value of the slope of that linear function (0.018) will be used to decrease the amount of water supply in the system, yearly.

In the second case, the data shared by Dr. Ignacio Lopez from his research at glacier Huaytapallana [37] was used to calibrate the number of patches that needed to be melted yearly, so that the behavior resembles his findings. The initial value for the area in the simulation 17 km^2 (the area for 2011), and the slope of the linear model (0.4587) will be applied to reduce it yearly.

4.4 Model description

Here I coded an ABM based on the information organized in the previous chapter to explore further the consequences of the facts collected and integrated. In the next pages, I will introduce this model, which I have named **AndesLab**, following the standard ABM description proposed by Grimm et al. [100, 101].

4.4.1 Overview

4.4.1.1 Purpose

AndesLab is an stylized agent-based model designed to explore the effects of integrating the current trends in water balance with the current trends in population growth and land use change. As these trends continue, decision mechanisms are implemented at individual level to represent the likely reaction local people will have when facing the challenge both systems present simultaneously. AndesLab is an abstract model designed for theoretical interdisciplinary exploration, policy reflection and political awareness.

Effectively, AndesLab functions as a platform that combines current knowledge on the *Huancayo-Shullcas-Huaytapallana* coupled system and uses the *exit-voice-loyalty* social framework to represent the options the inhabitants of this region will have. AndesLab makes use of quantitative data to represent the glacier, river, and the demographics of the coupled system, and also makes use of qualitative information, obtained *ad-hoc* and *in situ*, to represent how people will react as the trends continue. AndesLab includes a *Bayesian* approach to represent how the urbanites update their beliefs on water scarcity locally. The model also includes a basic use of social networks and social psychology models to support the mechanism of conflict emergence.

From the previous chapter, I have enough elements to support the central hypothesis that migration and social conflict are expected outcomes of the current trends in climate change (less water supply), and city growth (population growth and land use change). This hypothesis is falsifiable if the city changes its growth trend, there is no more land use change or if for some reason the climate in the zone behaves in such a way that it allows the glacier to recover and/or the rainfall to increase and be more predictable.

The use of an ABM complements the current holistic hypothesis mentioned, with a methodological-individualism approach, as I can consider causal connections between individual and natural conditions:

- *Memory*: In a recent thesis in Computational Social Science, Hailegiorgis [19] used a four year memory of the past events in the modeled population for forecasting the climate. This work will follow that approach but including a Bayesian mechanism to combine memory and belief updating (more details in section 4.4.2.6 on page 93). In my case, besides using four in the *base* run, I will include five and six during the *policy* run.

- *Scarcity Belief*: As I am using Bayesian updating, I need a forecasted value to represent people's belief that scarcity is becoming a real possibility. Scarcity belief will represent those values as a probability (between zero and one). For the base run I will use 0.6. In the policy run, this value will go from 0.5 up to 0.8 (more details in section 4.4.2.6 on page 93). These values have been selected to represent the Huanca *a priori* decision to stay in Huancayo despite difficult conditions.

- *Resilience*: During the ad-hoc interviews in the area, I wanted to know how many years of scarcity people in the urban area will wait until they decide to migrate, the answers are shown in Table 4.1:

Table 4.1: Resilience of urban people

Seasons without water	**frequency**	**share**	**share Huanca**	**share non-Huanca**
4	12	0.24	0.16	0.08
5	13	0.26	0.18	0.08
6	15	0.3	0.2	0.08
never leave	10	0.2	0	0.2
Total	50	1	0.54	0.44

I will use the mode (6) for the base run, and all the other numerical values during the policy run, as explained before.

- *glacier effect*: Glacier effect is a key contribution as nobody knows this real value. My colleague Bryan Mark from Ohio State University [78] has done the first measurement ever on the Shullcas river to approximate how much the Huaytapallana glacier contributes to the river flow. The value he has given is 15%, which will be used in the base run. As other researchers believe it may be higher (up to 20%)[**?**, 80], I will use that interval during policy run.

As for policy making, I have consider a sensitivity analysis of the amount of water available during the dry season. The base simulation is run with the current value of 0.17, but I will analyze if migration and conflict are sensitive to this value, adding higher values of 0.2, 0.25 and 0.3 during the policy run to give the policy maker the amount of water that should be saved to avoid conflict and/or migration.

Other important elements that AndesLab considers at individual level, but are not considered in hypotheses are:

- *Social Conditions*: Migration in Peru is related to an individual level education status, employment, marital status, gender, and age. These study will use the first three and will not consider gender nor age, following [44].

- *Origin*: It is important to differentiate in the model whether the agent is representing an urban or rural person, and whether it is Huanca or Non Huanca. That difference is a key factor during the emergence of conflict in the rural area (see the Algorithm 8 on page 107 in section 4.4.3.3), and is also among the restrictions to emigration (see Algorithm 4 on page 102).

From the hypothesis, the dependent variables are:

- **Migration**: It involves urban people, as they are the most severely affected by water balance. I measure the moment and the amount of people related to migration, among others:

Table 4.2: Migration-related variables

Variable	Variable Name
People that moved to the Jungle	movedtojungle
People that moved to Lima	movedtolima
Rural people that moved to urban area	movedtohyo
Season when Migration started	season-migrate-urban
Max number that emigrated in a year to the Jungle	maxjungle
Max number that emigrated in a year to Lima	maxlima
Max number that emigrated in a year	maxmove
Season when Max number that emigrated in a year was reached	maxtimemove
Season when Max number that emigrated in a year to the Jungle was reached	maxtimejungle
Season when Max number that emigrated in a year to Lima was reached	maxtimelima

Migration is not straightforward, it has many conditions and is affected by random events (see algorithms 1 on page 90, 4 on page 102 and 6 on page 105).

- **Conflict**: Properly speaking, the model represent people *frustrated* or *frustrated* (urban), and people *relatively deprived* (rural), but *not* violent actions. I measure this in different ways:

Table 4.3: Conflict-related variables

Variable	Variable Name
Max number of angry people reached	maxmass
Density of Angry Network when max number of angry people reached	maxdensitymass
Average clustering coefficient of Angry Network when max number of angry people reached	maxmeancc
Number of network components when Max number of angry people reached	maxcomp
Season when Max number of angry people reached	maxmassangrytime
Rural population when max number of angry people reached	maxmasspoprural
Urban population when max number of angry people reached	maxmasspopurban
Season when first rural started feeling relatively deprived	season-conflict-rural

4.4.1.2 State variables and scales

All the variables are described in the appendix (on page 162). These have been organized according to the entities each represents, and for each case I indicate the scale of measurement and also give references to the particular researcher that produced that value or the relationship to other variables for its computation. In the appendix, there is a table for agents (or turtles in NetLogo jargon), and a table for *patches* (also NetLogo jargon for the square piece of ”ground” over which turtles can move). In the Figure 4.2, I show the variables for urban agents, patches and rural agents, as recorded in NetLogo.

The global variables have been organized in two tables, for the natural and for the social system. For the natural system the variables are shown in the appendix (on page 164), and the social system variables are also on page on page 165 in the appendix. As it is shown in the appendix, all the variables have support from different studies and ad-hoc fieldwork conducted by myself or research partners in Huancayo, Peru.

(a) an urban agent and its variables

(b) a patch and its variables

(c) a rural agent and its variables

Figure 4.2: Variables for patches and agents

4.4.1.3 Process overview and scheduling

AndesLab starts in 2011, and simulates the next 50 years of Huancayo. Every time a complete cycle of the simulation is run, the history of Huancayo advances six months. So, this model will only run for 100 cycles. As each cycle represents six months, a cycle represents a season, which is either the *dry season* (that goes from May to September) or the *rainy season* (that goes from October to April); so, the reasoning does not follow the January - December calendar. Figure 4.3 reflects the flow of the code each cycle or season, a figure that also represents the translation of the concepts represented in the scheme 1.4 on page 13 into computer logic.

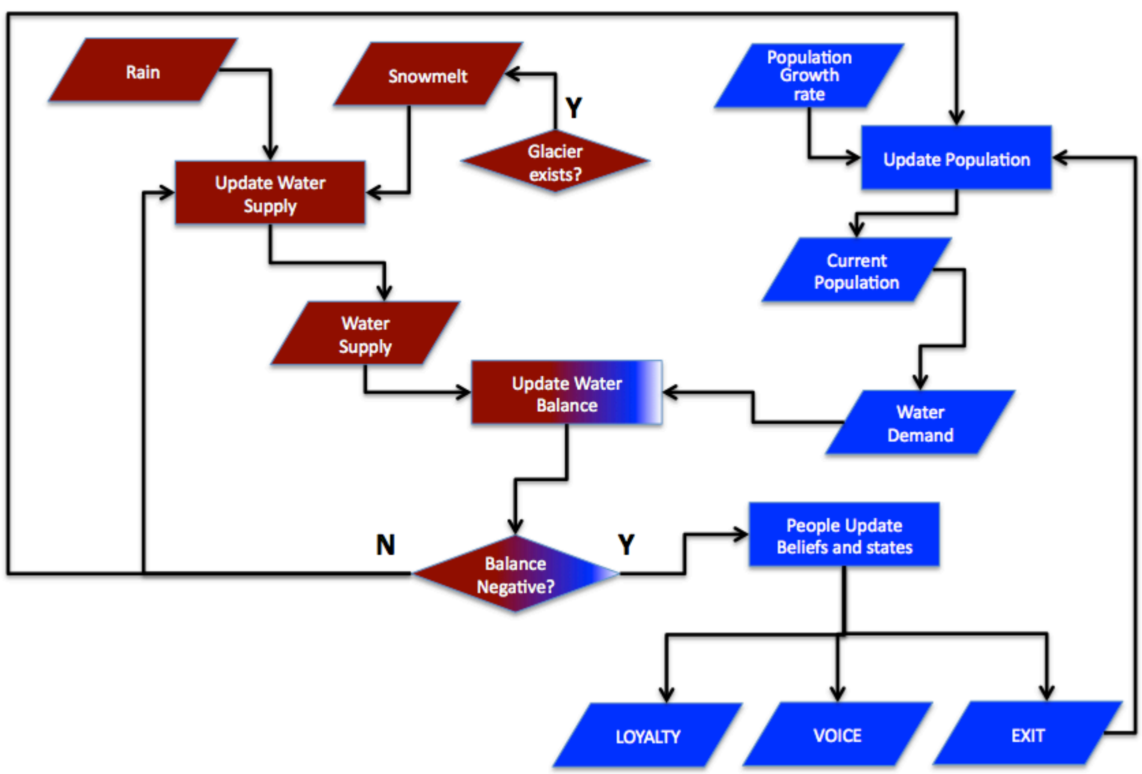


Figure 4.3: Process overview. Color differentiates type of system (blue for *Social* and red for *Natural*. A pass through this chart represents a six month *season*.

From figure 4.3, it is clear that there are two systems interacting based on the water balance, and this water balance will trigger migration and conflict. The natural system means the hydrology of the area, supplying water that needs to meet the demand of the population. The social system is the people needing water. In the computation of the demand, farming and population needs have been considered for the rural agents, but only population needs for the urban agents. The data for supply and demand is by far the most updated data available for this area, but it is just a cross-sectional data, restricting longitudinal analysis. This weakness was overcome as I used the data shared from Carlos and Grijalva on their study on water scarcity risk in the zone [36].

Figure 4.4 is a flowchart representing the decision making of a rural agent. As it is shown in that figure, the decision flow starts when the agent detects scarcity. That detection is a particular computation following a Bayesian approach, which was assumed as the mechanism to update beliefs, that is the agent has to "believe" the future of water is compromised to start looking for a place to live. While the agent believes there is scarcity, it keeps moving. This will end when the agent reaches the resilience limit. If the rural agent meets conditions to migrate, it will migrate to the urban area (to leave Huancayo you have to live in the city). Agents that could not migrate are candidates to feel relatively deprived.

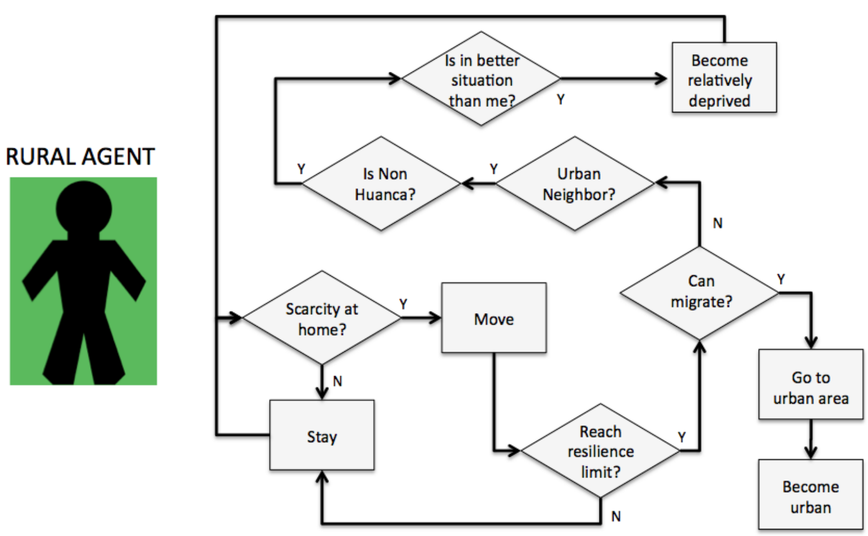


Figure 4.4: Decision making - rural agents

Figure 4.5 is a flowchart representing the decision making of an urban agent. Similar to the previous figure, the decision flow starts when the agent detects scarcity following a Bayesian approach. Once the agent detects scarcity, he will look for a place to move. As long as the agent detects scarcity where the agent is staying, the agent will move. The moving will end when the agent reaches the resilience limit. If the urban agent can migrate, the urban agent will migrate to Lima or the Jungle, depending on the agent's characteristics (employed, educated, marital status). Agents that could not migrate are candidates to feel frustrated. Once the agent is frustrated, the agent will try to connect to other agents in the same situation. These connections make a social network of frustrated or frustrated agents. A link is destroyed when a member of the network of frustrated agents migrates.

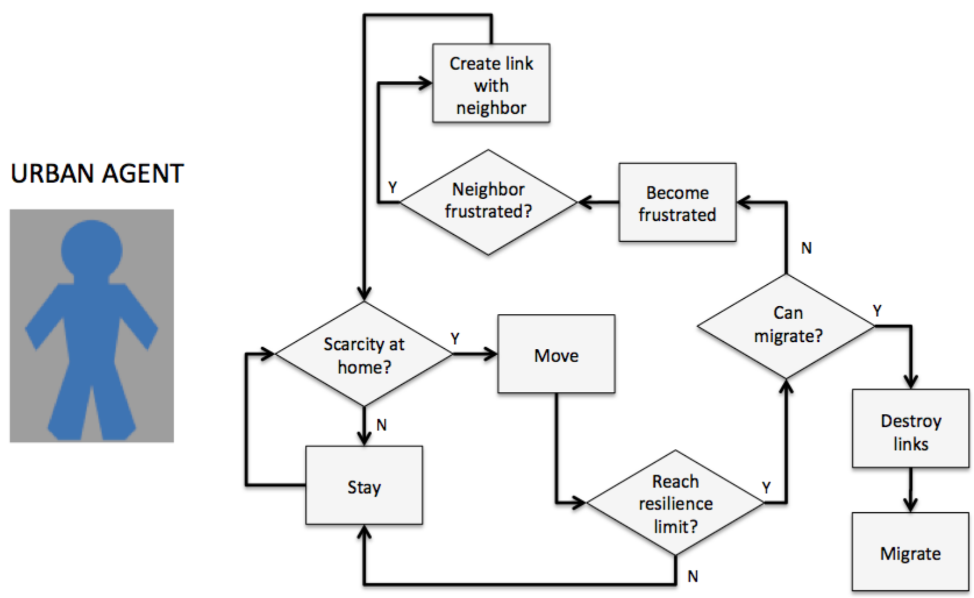


Figure 4.5: Decision making - urban agents

The Algorithm 1 represents an alternative high level abstraction of Figure 4.3 in human-readable style (pseudo code). In this algorithm, it is clear that the code runs 100 seasons, which is controlled by a clock (or tick in NetLogo jargon).

Algorithm 1: Highest level pseudocode

```
Initial Setup;
while clock ≤ 100 do
    get current population;
    get water demand for the current season;
    update glacier;
    get water supply;
    set water balance = water supply - water demand ;
    if water balance < 0 then
        dry patches random per risk zone;
        get people that believe there is scarcity;
        for each people that believes there is scarcity do
            if the resilience of agent has not reached threshold then
                all agents decrease resilience;
                urban agents look for place to live in Huancayo;
            else
                if agent is rural then
                    if  agent has demographic conditions then
                        have agent migrate to urban area;
                    else
                        update relative deprivation of agent not moving to urban area;
                else
                    select an agent randomly with a uniform probability; // only for urban agents
                    if agent selected has demographic conditions then
                        agent migrates;
                        update migration counter;
                    else
                        agent can not migrate;
                        agent gets frustrated;
                        frustrated agent connects with frustrated neighbor(s);
            update resilience;
    update Population;
    change season;
    update clock;
```

In the previous pseudo code, I have colored in **blue** the sub-models I will explain later in subsection 4.4.3.3 on page 100, as each deserves particular attention. Besides, there are a couple of important computations I describe in the next equations (The values of variables in the equation are found in Table 4.5 on page 98):

- The computation of water demand (in the urban area):

$$WaterDemand_{seasonal_{perurban}} = 0.5 * \frac{WaterDemand_{yearly_{urban}}}{Population_{urban}} \tag{4.1}$$

- The computation of water demand (in the rural area):

$$\begin{aligned} WaterDemand_{seasonal_{perrural}} = \\ 0.5 * \frac{WaterDemandNF_{yearly_{rural}} + WaterDemandF_{yearly_{rural}}}{Population_{rural}} \end{aligned} \tag{4.2}$$

In both equations (4.1 and 4.2), the total demand is distributed evenly, assuming that, even though the dry or rainy season have different supply, the agents demand the same amount of water every season. Notice that for the rural agent, the demand considers farming (F) and non-farming (NF) needs.

4.4.2 Design concepts

4.4.2.1 Basic principles

The basic principle guiding this work is the integration of multiple knowledge sources, particularly when the systems I am dealing with are still far from being well known. The flexibility of ABMs to represent different entities and relationships among them has allow me to include entities from different fields of knowledge. However, as I am still facing a poorly understood system, computational simulations will allow me to include relationships currently unknown or poorly documented. This work demonstrates that despite inaccuracies, AndesLab result still represents a valid source of concern to policy makers. These assumptions have followed closely the ideas of Hebert Simon related to poorly understand systems [93]. For Simon, it is clear that simulations are still of use when we do not know very much initially about laws that govern the behavior of the system, and his major advise is to pay attention to the organization of the entities that make up the system, instead of paying attention to its inner characteristics, which is also in agreement with George Box when he states:

> *"Since all models are wrong the scientist cannot obtain a* correct *one by excessive elaboration. On the contrary following William of Occam he should seek an economical description of natural phenomena. Just as the ability to devise simple but evocative models is the signature of the great scientist so over elaboration and overparameterization is often the mark of mediocrity."*[102]

The deep knowledge of each source of knowledge is currently unavailable. Despite that, I have been careful to follow a complex adaptive systems approach that is reflected in the next subsections.

4.4.2.2 Emergence

This ABM does not code how many people should migrate, when a conflict is likely to start or where people should go when migrating. These outcomes would be the result of individual decisions combined with bounded information obtained in the neighborhood of the agent. In that way, I expect that the aggregate results bring interesting insights as the output will emerge from the system's dynamics.

4.4.2.3 Objectives

The objective of the agents is to live in Huancayo as long as possible, making every effort needed to find a suitable place where water has an expectation of availability. When their capacity to live without water security is passed, they may exit the system (migrate) or stay frustrated[2].

4.4.2.4 Adaptation

Agents suffering water scarcity are allowed to look for better places to live, instead of exiting (migrating) the system immediately. These process is related to the information they get from interacting with their networks and with the local environment. However, the agents are not themselves creating different alternatives to migration, as the model is constrained by the *exit-voice-loyalty* framework.

4.4.2.5 Learning

Agents know where they are, they have a memory registering whether there is the water or lack of it, and they learn that the place where they live is not safe of water scarcity according to what they remember. This does not prevent them from coming back to a place they lived before. In the city, some areas are riskier than others (only three in this model). As an agent looks for water, it will tend to go to less risky areas, but can get stuck in the same risky area as the agent does not have information of every patch (they in fact communicate with other agents to get some information, but those agents have to be relatives of the agents to share information - see sections 4.4.2.7 and 4.4.2.8).

4.4.2.6 Prediction

I did not design a study to get information on how people in the area make predictions in the fieldwork, so I decided to assume a Bayesian mechanism. Bayesian updating follows from the use of Bayes's rule to combine a priori knowledge with experiential information to arrive at a subjective assessment about the probability that some event will occur in the future [103]. In practical terms, I express prior information in the form of a probability distribution, which agents combine with events they witness in the simulated world to arrive

[2]When an agent migrates or exits the system, global variables are updated, but the agent, in fact, dies (or more properly said, it is killed by me) in NetLogo

at an estimate of the quality of an unknown parameter, in this case the probability that they will suffer sustained water shortages in the future[3].

I limit the use of the Bayesian approach to what agents live as personal experience. Others have employed a similar approach in the study of animal behavior, suggesting for example that mammals' past experience as the equivalent of a prior distribution on a particular outcome. As McNamara et al. propose:

> *"...animals might take the prior probability that it will rain on a particular day to be the frequency with which previous days have had rain. In practice I can expect that the prior for any animal is typically set by a combination of the environment in which it evolved and its own past experience."* [107]

In this work, I have a population that will decide whether to go for *exit*, *loyalty* or *voice* based on their experience. The experience is constructed as the agent has a limited memory of size m, where it records a sequence of m events (0=water scarcity, 1=water available) in its home. I assume these are Bernoulli events, so a beta-binomial conjugate is used to computed the posterior parameters[103], which will inform the agent of the scarcity it should expect where it lives. As time goes by, if an agent's estimation of scarcity goes above a threshold, the agent will look for a better place to live within the simulated world. The memory of the agent only has the last m events (the agent forgets!); and it has to be so, otherwise the first years full of water will always be present in his beliefs. When the agent moves to a new place, the memory is not emptied. The agent starts with an informative prior, so 0 and 1 are equi-probable in the beginning.

4.4.2.7 Sensing

It is expressed in this way:

[3] The literature on Bayesian updating for decision making is extensive, but particularly scarce for ABM. In the context of ABM, Bayesian inference has mainly been used for topics related to social learning [104] and on methodological topics such as calibration of simulations [105]; particularly, the Bayesian approach is included in the epistemological discussions on social simulations[106].

- An agent is always aware of the situation (*water history* - within memory limits) of its *home patch* (where it is currently living)

- An agent can access the water history of its neighbor patches only when the agent has predicted that its home patch offers no future water security.

- An agent can access the water history of the neighbors [4] of its family network (see subsection 4.4.2.10 on page 96) when the agent has predicted that its home patch offers no future water security.

- An agent ignores the situation of the glacier or the river, i.e., the agent only notices water scarcity when it is affected in its home patch.

- A frustrated agent knows if an immediate neighbor agent is also frustrated, so both can connect (this is another kind of network).

- A rural agent knows when he has non-Huanca immediate neighbors and if their social conditions are better than the rural agent's.

4.4.2.8 Interaction

From the previous subsection, it is clear that:

- Frustrated agents interact among one another. They represent an emerging network of protest, the *frustrated network*.

- Agents interact with their family when the agent is trying to change the place where it lives. This interaction is via the link they share as members of the *family network*

- Agents interact with their environment since they first feel the absence of water at home, and then they start updating their beliefs.

Additional details are given in subsection 4.4.2.10 on page 96.

[4]When I speak of neighbors in this work, I mean the neighbors in a Moore neighborhood, that is, the eight patches surrounding an agent on the two-dimensional square lattice of NetLogo

4.4.2.9 Stochasticity

Stochasticity is explicitly present in four processes:

1. A random uniform process is used to allow an agent to migrate.

2. A random uniform process is used to select which agents will feel water scarcity when water balance turns negative during dry season. This is a process of drying patches per sub region, where each sub region has a different priority to suffer scarcity.

3. A random uniform process selects the amount of agents that will have offspring.

4. A beta-binomial conjugate prior is used to predict water scarcity.

4.4.2.10 Collectives

There are three important collectives, all of them represented by networks:

1. **The family network**. The simulation starts with a population of individuals, but each year (every 2 ticks), some individuals, randomly selected with a uniform distribution, have offspring. The offspring will have the same attributes as the parent, and every time an agent has offspring, this offspring is connected its parent with a link that is part of its own family network. As already seen, family network will be used to provide information about the availability of patches with better water prospects.

2. **The frustrated network**. This is a network that will be built of adjacent frustrated agents, the ones that could not leave, even though they have most of the conditions to exit the system. The frustrated network is helpful in the analysis as it differentiates from the frustrated population (all the frustrated agents). To be part of the frustrated network, an frustrated agent needs to have another frustrated agent as neighbor. Once the link is established, the link persists. The agent can move to anywhere in the urban area and it will keep all the links established. However, as frustrated agents could have more chances to migrate later, the network loses a node when that happens and the link connected to it disappear, possibly creating sub-networks. This network is a key

proxy to represent the possibility of conflict, as a dense network of frustrated agents is assumed to represent a conflict possibility. For the sake of analysis, I compute the network density, the network average clustering coefficient, the number of connected components [108], and record the moment when the maximum value of those measures are achieved.

4.4.2.11 Observation

I observe each of the variables from Table 4.2 on page 85 and Table 4.3 on page 85, and also the one from Table 4.4, below:

Table 4.4: Population-related results

Variable	Variable Name
Final Population	population
Final Rural Population	ruralpopulation
Final Urban Population	urbanpopulation
Final Non Huanca Population	nonhuancaspop
Final number of angry urban people	conflict-mass
Final number of rural families with at least one member feeling relatively deprived	ruralcountangry
Final Network density of angry urbanites	density-angrynetworkurban
Season glacier retreated	timebyeglacier
First season of negative water balance	firstnegativebalanceurban
Final urban water balance	urbanwaterbalance
Final rural water balance	ruralwaterbalance

4.4.3 Detail

In the next paragraphs, I offer different details on the actual implementation of the AndesLab, presenting with more detail relevant sections of the code. At the end, I will present the sections on Verification and Validation.

4.4.3.1 Initialization

In Table 4.5, I present the initialization of the most important variables in AndesLab. *Counters* and *flags* used along the code have been omitted, but, as usual, counters were initialized with zero (0) and, depending on the logic of the code, flags were initialized with either *true or 1* or *false or 0* (there were also some flags that were initialized with -1).

Table 4.5: Initialization of ABM

Variable	Initial Value	Reference	Note
ALPHA-INITIAL	1	[103]	For Bayesian updating
BETA-INITIAL	1	[103]	For Bayesian updating
ruralPopulation	132 agents	[45]	Population scaled to 1/100
urbanPopulation	3230 agents	[45]	Population scaled to 1/100
population	3362 agents	-	computed as $ruralPopulation + urbanPopulation$
glacierArea	17 patches	[37]	scaled to virtual world
MELTING-SPEED	0.4587	[37]	parameter calibrated from data (see model 3.9 on page 48)
glacier-effect	15%	[78]	Percent. Data computed on March 2015.
yearly-WaterOfferedUrban	1872437.2 * 0.6	[36, 46]	In m^3; 0.6 is the current inefficiency [36]
yearly-WaterOfferedRural	7474900.18	[36, 46]	In m^3. Data rescaled to the population in simulations
yearly-WaterDemandUrban	198435.83	[36, 46, 48]	In m^3. Data rescaled to the population in simulations
yearly-WaterDemandRural-notFarming	14350.32	[36, 46, 48]	In m^3. Data rescaled to the population in simulations
yearly-WaterDemandRural-farming	244097.20	[36, 46, 48]	In m^3. Data rescaled to the population in simulations
prop-Immigrants	40%	[45]	percent
resilience-level	4	fieldwork	interval
memory	4	fieldwork	interval
RuralShare-PopulationGrowth	15%	[45]	percent
movingDecision	0.6	fieldwork	probability
populationGrowth	0.015	[45]	rate
Water-Loss	0.018	[36]	rate
drySeasonShare	17%	[36, 46, 48]	percent

The meaning of each variable in Table 4.5 is given in the tables in the appendix on page 162.

4.4.3.2 Input

No external files are used. All the data has been pre processed and the coefficients obtained are used in the model. However, as I will use *behavior space* (see Figure 4.6) for sensitivity analysis, these values will create the input combinations:

- resilience-level: 4, 5, 6
- memory: 4, 5, 6
- drySeasonShare: 0.17, 0.2, 0.25, 0.3
- movingDecision: 0.5, 0.6, 0.8
- glacier-effect: from 0.15 to 0.2

These values correspond to the selected independent variables for the model. Other input variables (parameters) have not been varied.

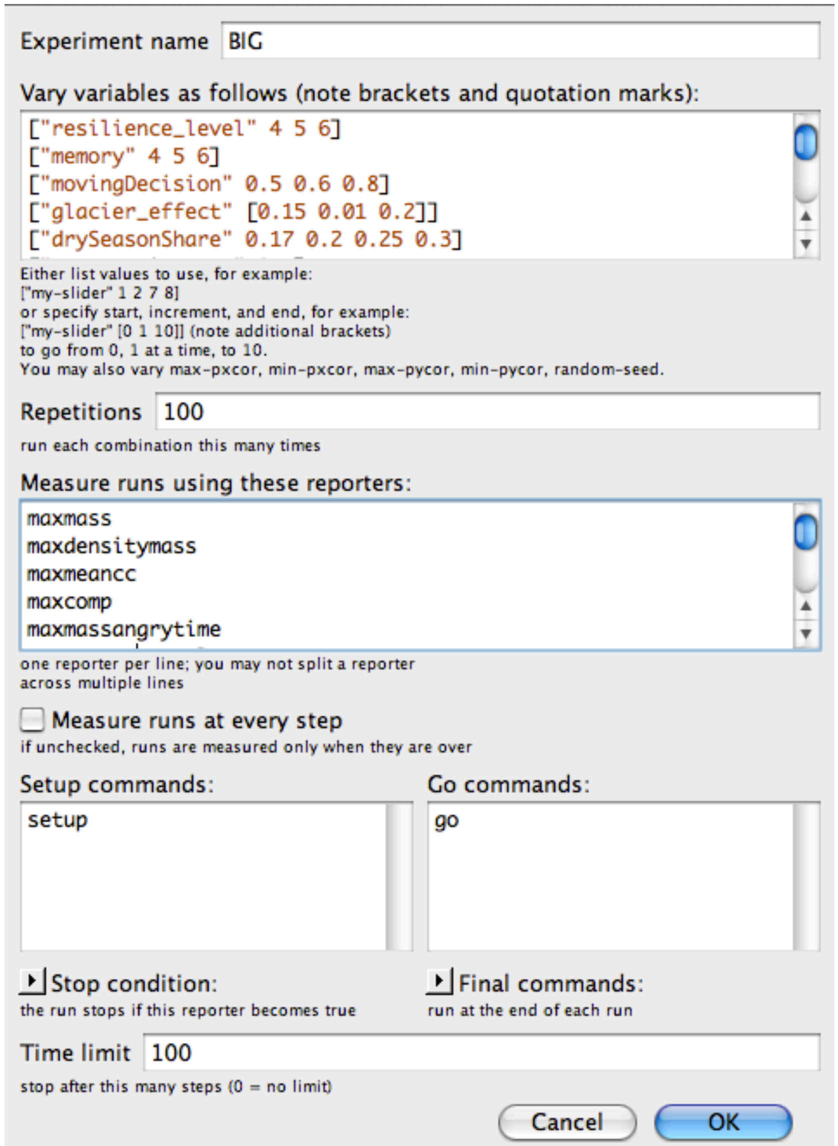


Figure 4.6: Using NetLogo's BehaviorSpace.

4.4.3.3 Sub models

In Algorithm 1 from the section 4.4.1.3, I mentioned the sub models of this ABM, and I will present them in detail here (all the variables names used are described in detail in the Appendix on page 162).

Update glacier: Currently the glacier **volume is unknown**, but I know the trend of the area from the model 3.9 on page 48, which is taking the snow line or border higher, a process represented in Algorithm 2:

Algorithm 2: Updating glacier area

```
Data: Glacier data considered in the study
(from Chapter three
Result: Glacier melted
set glacierArea; // the actual area of the patch
set MELTING-SPEED;// constant number of patches to melt in actual area
while noGlacier? = false do
    set glacierAreaABM;// number of glacier patches
    set patchesMeltingAbm; // number of glacier patches that will melt
    set CurrentGlacierPatches;// number of glacier patches not melted
    set patchesToBeMelted;// glacier patches that are closer to rural patches:  the snow line
    if patchesMeltingAbm < count patchesToBeMelted and CurrentGlacierPatches > 0 then
        ask patchesMeltingAbm from patchesToBeMelted:// only to patches in snow line!
        change color of patch; // glacier patch looks dry
        set retreat? = true; // glacier patch is dry
    else
        for glacier patches remaining do
            change color of patch; // glacier patch looks dry
            set retreat? = true; // glacier patch is dry
    for patches that look dry do
        set newRural? = true;// patch variable
    set glacierArea = glacierArea - MELTING-SPEED;
    if all glacier patches are dry then
        set noGlacier? = true; // global variable
```

Compute water supply for this season: It is a simple algorithm that makes sure each season of the year (rainy or dry) has the respective share of water supply (see Algorithm 3).

Algorithm 3: Computing water supply

```
Data: Hydrological data considered in the study
(from Chapter three
Result: Water supply
set flag1 = true;
set flag2 = true;
set WaterLoss; // constant to decrease water supply yearly
if noGlacier? and flag: then
    // process BELOW is done only ONCE after glacier melted!
    update yearlyWaterOfferedUrban; // water supply in urban area feels effect
        of no glacier
    update yearlyWaterOfferedRural; // water supply in rural area feels effect of
        no glacier
    set flag = false;
if drySeason? then
    // compute supply for rural area using a share of yearlyWaterOfferedRural
    set seasonalWaterOfferPerRuralinPatch;
    // compute supply for urban area using a share of yearlyWaterOfferedUrban
    set seasonalWaterOfferPerUrbaninPatch;
else
    // compute supply for rural area using a share of yearlyWaterOfferedRural
    set seasonalWaterOfferPerRuralinPatch;
    // compute supply for urban area using a share of yearlyWaterOfferedUrban
    set seasonalWaterOfferPerUrbaninPatch;
    // updating water supply for the year
    set yearlyWaterOfferedUrban = yearlyWaterOfferedUrban * (1 - WaterLoss) ;
    set yearlyWaterOfferedRural= yearlyWaterOfferedRural * (1 - WaterLoss) ;
if flag2 then
    // process BELOW is done only ONCE at the beginning
    dry Urban Patches by ScarcityLevel; // calling subroutine
    dryRural Patches by ScarcityLevel; // calling subroutine
    set flag2 = false;
```

Deciding if the agent migrates: The Algorithm 4 is based on the census data and particular studies [109] that highlight that the migrants from Huancayo tend to be college educated. The migration to the jungle is not documented anywhere, but based on the kind of pulling factors the jungle offers (illegal logging, coca cultivation, seasonal jobs, illegal mining), I assumed that jungle represents the place that people unemployed, with no dependents and low qualifications may go. These findings have similar results in other Andean country (Colombia) [110], which partially support my assumptions.In general, the model represents "Lima" as a place that pulls people that has qualifications, can afford moving and would like to bring their families; and "Jungle" represents the destination for risk-taking people, not willing to bring family along. According to the field work, only the Huancas (original from Huancayo) would migrate, so the 40% of the population (the non-Huanca share would have to stay).

Algorithm 4: Deciding if agent able to migrate

```
Data: Demographic characteristics considered in the study
(from Table 3.9 on page 69)
Result: Agent able to migrate or not
if agent is Huanca then
    if agent is urban then
        if agent is working, has college studies and is married then
            agent can migrate to Lima;
        else
            agent can migrate to Jungle;
    if agent is rural then
        if agent is working and (has college studies or is married) then
            agent can migrate to urban area;
        else
            agent has to stay in rural area;
else
    agent can not migrate;
```

Get people that believe there is scarcity: Each Agent updates its belief independent of what the other agents are doing. Agents compute a belief in water scarcity that is compared to the *MovingDecision* value:

- The key value for making decisions is the estimated water scarcity probability the agent computed independently. This computation is based on the agent's experience.
- The experience is recorded in memory.
- Memory is limited (will be varied in the simulation runs). The values allowed in memory are 1 or 0, where 1 means water available, and 0 water scarce.
- Every new event (1 or 0) will erase the oldest event from memory, when memory size limit is reached..
- As the states can only be 1 or 0, the agent will compute the water scarcity probability assuming they are Bernoulli events and that the the probability of water availability can be represented with a binomial distribution. That is, the agent will update its estimation of water scarcity considering its current memory (size <= m), where there are *s* values 1 and *m-s* values zero, and alpha is the number of years remembered with no water scarcity and beta is the number of years remembered with water scarcity. The estimation of water scarcity is computed as:
  - Given $\alpha_{initial} = 1$ and $\beta_{initial} = 1$, so that
  - $\alpha_{current} = \alpha_{initial} + s$ and
  - $\beta_{current} = \beta_{initial} + (m - s)$, then

$$estimatedAvailability = \frac{\alpha_{current}}{\alpha_{current} + \beta_{current}} \tag{4.3}$$

  - So, estimatedScarcity = 1 - estimatedAvailability

The Equation 4.3 is the expected value of posterior beta distribution conjugate to a binomial (m,p), which updated a uniform prior beta($\alpha_{initial} = 1$,$\beta_{initial} = 1$) with the new information as it became available.

The Algorithm 5 represents this process.

Algorithm 5: Bayesian updating

```
Data: Status of water supply in patch while running the model
Result: Updated belief on water scarcity
set ALPHAINITIAL = 1; // initializing alpha
set BETAINITIAL = 1; // initializing beta
set MEMORY SIZE; // initializing beta
for each urban do
    if number of events in history < MEMORY SIZE then
        update history;// start recording events to remember
    else
        // recording and forgetting
        add newest event to history;// 1 for water; 0 for scarcity
        erase oldest event in history;
    compute successes as sum of values in history;
    compute failures as length of history minus successes;
    set alpha = ALPHAINITIAL + successes;
    set beta = BETAINITIAL + failures;
    set estimatedScarcity = 1 - alpha/(alpha+beta);
    if length of history equals sum of values in history then
        // When the agent remembers he always have had water
        set movingCounter = 0;// count towards resilience top is reset
```

---

agent looks for place to live within system (only urbanites): This algorithm allows the urban agents to find a place where to move when the probability the agent predicts of water scarcity is unacceptable for the agent. In this algorithm, the agent combines the search for local information in its neighborhood, as well as information exchange with its relatives (see Algorithm 6.

Algorithm 6: Looking for place where to move within Huancayo

Data: Estimated scarcity and possible destinations
Result: Destination to move in Huancayo

```
// Only for urbans
for urbans whose estimatedScarcity is less than movingDecision do
    get possible Destinations; // all neighbor patches that can be inhabited
    update possible Destinations with information from relatives;
    find best place; // possibleDestinations with lowest estimatedScarcity
    if there is a best place then
        move to this best place;
        increase movingCounter in 1;
```

agent connects with frustrated neighbor(s): An "frustrated" network represents a network of people that should have migrated but could not. For the model assumptions, it is not of much concern having frustrated agents, the problem is when frustrated agents connect. So I have a situation where:

- If a *frustrated* agent **runs into** another frustrated agent they will connect via a network link.
- A frustrated agent will run into another agent if that agent is one of its 8 neighbors.
- Every frustrated agent keeps computing its expected scarcity. If things improve, the agent is not frustrated anymore and will not be part of network; otherwise, the agent keeps frustrated.
- Once an agent reached its top resilience level, it is given the possibility to migrate.
- An the agent migrates weakens the network of frustrated agents, as there is one less node and one less connection. The amount of connectivity in the network is a key emergent outcome in this work (see Algorithm 7).

Algorithm 7: Building the frustrated network

Data: Frustration status of agents

Result: Network of frustrated agents and network statistics

```
for each urban agent that is frustrated do
    find all urbans on my neighborhood who are frustrated;
    make a link with the frustrated agents found; // making frustrated network
for each urban agent that is frustrated do
    destroy links with agents who are not frustrated any more;
// Computing some network statistics
compute network density ;
compute connected components;
compute clustering coefficient;
save network statistics when max number of frustrated agents was reached;
save season when max number of frustrated agents was reached;
update global variables related to this Algorithm;
```

update relative deprivation of agent not moving to urban area: This sub-model (see Algorithm 8) is in charge of monitoring the conditions for conflict emergence in the peri-urban area, as the rural agents may experience *relative deprivation* when these agents are in a poor condition and their urban neighbors:

- have populated the land close to the rural area;
- are non-Huanca and
- have better conditions (employment and education).

This situation will provoke that the rural agent not only feels relatively deprived, but it may also become a family effect. That is, rural families are widespread across the rural area, and a conflict situation between one rural agent and one urban agent, can turn into a dispute between families.

Algorithm 8: Update relative deprivation and detect conflict

```
Data: Status of rural and urban agents
Result: Updated status of rural agents
set flag3 to detect season when first relatively deprived agent appears;
// This is applied to rurals that could not migrate into the city
for each rural who is married but neither employed nor college educated do
    // Agent seeks for foes towards urban region.
    find possible foes in urban neighbors // Agent pays attention only to some
        potential foes
    keep actual foes if they are non-Huanca, have work or have college education;
    if there are actual foes then
        change status of relativeDeprived to true;
        make your self visible in the ABM;
        // highlighting that the conflict will involve the family
        for each relatively deprived rural in this network do
            make your family members visible in the ABM ;
        // saving the season when conflict started
        if flag3 < 0 then
            set moment first rural gets relatively deprived = current season;
```

4.5 Model verification

Verification of a model is the process of confirming it is correctly implemented with respect to the conceptual model [34, 111, 112]. In this case, it is making sure the code matches specifications and assumptions of the model in Chapter 3. In this section, I show the steps followed to test, as well as find and fix errors in the model implementation. For the verification of my model, I have followed the recommendations in Cioffi [34], and in Dam et al. [111]. As suggested in their works, I carried out profiling, recording/tracking agent behavior, testing extremes and parameter sweeps, minimal model testing, and testing model variability.

4.5.1 Profiling

As stated by Cioffi [34], profiling is the counting of the frequency with which key code elements are used to identify possible sources of coding issues. For my model, it means counting the times each function or procedure was called. For that, inside the *GO* function in NetLogo, all the logic was coded into many procedures. The result of profiling is shown in Table 4.6 for a run of 100 seasons:

Table 4.6: Model profiling (100 seasons)

Name	Calls	InclusiveT(ms)	ExclusiveT(ms)	Exclusive/calls
CONFLICT-IN-URBAN-REGION	100	21676.10	21676.10	216.76
GO	99	54692.66	14577.05	147.24
URBANS-COMPUTE-SATISFACTION-AND-SCARCITY	50	5065.86	5065.86	101.32
URBANS-MOVE-BUT-NOT-MIGRATE	100	4086.79	4086.79	40.87
DRY-PATCHES	53	1694.46	1694.46	31.97
MIGRATION-OF-URBANS	100	851.35	1171.03	11.71
UPDATE-SEASONAL-WATER-PATCH	100	4112.20	1165.61	11.66
DRY-URBAN-PATCHES-BY-RISK-LEVEL	100	2409.43	805.46	8.05
CONFLICT-IN-RURAL-REGION	100	470.58	470.58	4.71
DRY-RURAL-PATCHES-BY-RISK-LEVEL	100	537.16	446.67	4.47
POPULATION-GROWTH	100	1437.46	433.80	4.34
UPDATE-GLACIER	100	401.97	401.97	4.02
WANNA-LIMIT-URBAN-GROWTH?	100	247.01	247.01	2.47
UPDATE-POPULATION-COUNT	50	121.13	121.13	2.42
AGENTS-DECIDE-TO-MIGRATE	100	5597.78	181.54	1.81
MIGRATION-OF-RURALS	100	158.42	158.42	1.58
FIND-NEW-SPOT-Rural	446	360.50	360.50	0.81
AGENTS-COMPUTE-SATISFACTION	100	5134.04	68.18	0.68
FIND-NEW-SPOT-Urban	2690	522.03	522.03	0.19
AGENTS-DECIDE-TO-CONFLICT	100	22148.07	1.39	0.01

The profiler table above was computed using NetLogo's Profiler extension. The first column, starting from the left, is the number of times that procedure was “called”. The second is the “Inclusive time” in milliseconds for that procedure, or the total time the model spent within that procedure and the procedures it called (e.g. the inclusive time for “go” is the total run time). The third column is the “Exclusive time”, which is the total time spent just on that procedure without any procedures it called. The last column is the Exclusive time per call (rather than summed over all the calls).

As it is clear from Table 4.6, except from the *GO* procedure, the first and the third procedure have the highest ratio *exclusive/calls*. It is worth mentioning that these two processes are expected to be the more time consuming as they are activated by the urban agents while they decide to migrate and make networks. The last procedure, which presents the lowest ratio *exclusive/calls*, also has a consistent value, as it is activated by the rural agents in case they feel relatively deprived.

Profiling was extensively used to detect possible opportunities for code optimization. As the results show, no procedure in the final implementation presented an inefficient behavior.

Finally, as commented by Cioffi, an ordering of the frequency may represent a Zipfian distribution, which seems to be the case in Figure 4.7.

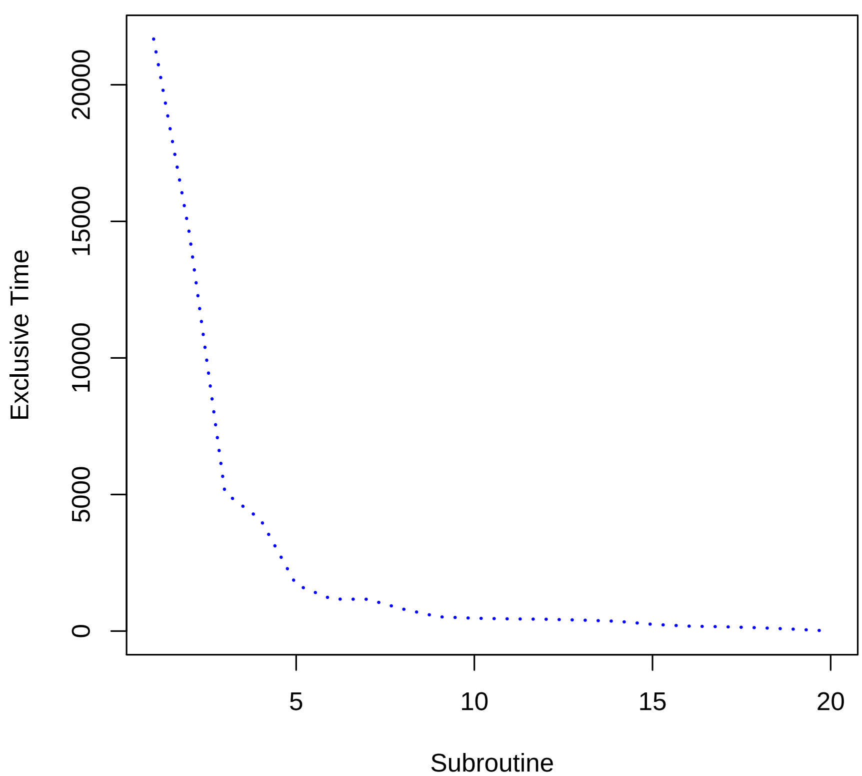
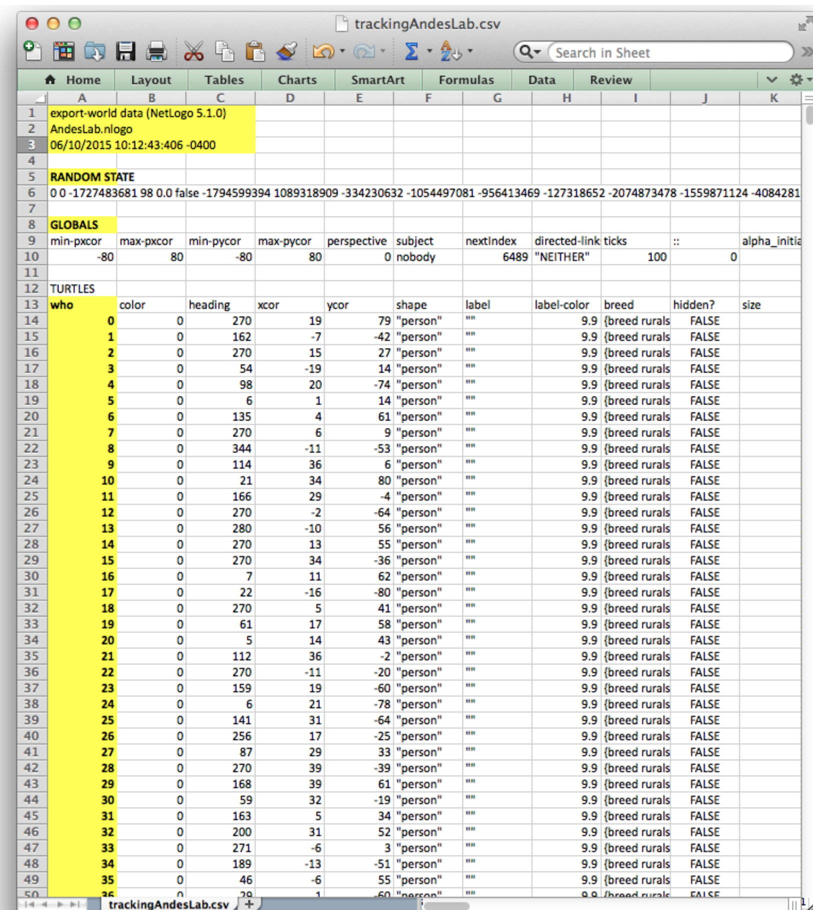


Figure 4.7: Zipfian-like distribution of subroutines

It is worth mentioning that this model was developed following the *spiral* approach suggested by Cioffi [28], which in fact reduces the potential for coding mistakes as the project increases in complexity.

4.5.2 Recording and tracking agent behavior

NetLogo offers a tool to follow particular agents and debug the code. In this case, I recorded the behaviors of the agents in a file (see Figure 4.8) and tracked agents of different kinds and status (see Figure 4.9) to confirm they followed the expected behavior.



trackingAndesLab.csv

	A	B	C	D	E	F	G	H	I	J	K
1	export-world data (NetLogo 5.1.0)										
2	AndesLab.nlogo										
3	06/10/2015 10:12:43:406 -0400										
4											
5	RANDOM STATE										
6	0 0 -1727483681 98 0.0 false -1794599394 1089318909 -334230632 -1054497081 -956413469 -127318652 -2074873478 -1559871124 -4084281										
7											
8	GLOBALS										
9	min-pxcor	max-pxcor	min-pycor	max-pycor	perspective	subject	nextIndex	directed-link	ticks	::	alpha_initia
10	-80	80	-80	80	0	nobody	6489	"NEITHER"	100	0	
11											
12	TURTLES										
13	who	color	heading	xcor	ycor	shape	label	label-color	breed	hidden?	size
14	0	0	270	19	79	"person"	""	9.9	{breed rurals	FALSE	
15	1	0	162	-7	-42	"person"	""	9.9	{breed rurals	FALSE	
16	2	0	270	15	27	"person"	""	9.9	{breed rurals	FALSE	
17	3	0	54	-19	14	"person"	""	9.9	{breed rurals	FALSE	
18	4	0	98	20	-74	"person"	""	9.9	{breed rurals	FALSE	
19	5	0	6	1	14	"person"	""	9.9	{breed rurals	FALSE	
20	6	0	135	4	61	"person"	""	9.9	{breed rurals	FALSE	
21	7	0	270	6	9	"person"	""	9.9	{breed rurals	FALSE	
22	8	0	344	-11	-53	"person"	""	9.9	{breed rurals	FALSE	
23	9	0	114	36	6	"person"	""	9.9	{breed rurals	FALSE	
24	10	0	21	34	80	"person"	""	9.9	{breed rurals	FALSE	
25	11	0	166	29	-4	"person"	""	9.9	{breed rurals	FALSE	
26	12	0	270	-2	-64	"person"	""	9.9	{breed rurals	FALSE	
27	13	0	280	-10	56	"person"	""	9.9	{breed rurals	FALSE	
28	14	0	270	13	55	"person"	""	9.9	{breed rurals	FALSE	
29	15	0	270	34	-36	"person"	""	9.9	{breed rurals	FALSE	
30	16	0	7	11	62	"person"	""	9.9	{breed rurals	FALSE	
31	17	0	22	-16	-80	"person"	""	9.9	{breed rurals	FALSE	
32	18	0	270	5	41	"person"	""	9.9	{breed rurals	FALSE	
33	19	0	61	17	58	"person"	""	9.9	{breed rurals	FALSE	
34	20	0	5	14	43	"person"	""	9.9	{breed rurals	FALSE	
35	21	0	112	36	-2	"person"	""	9.9	{breed rurals	FALSE	
36	22	0	270	-11	-20	"person"	""	9.9	{breed rurals	FALSE	
37	23	0	159	19	-60	"person"	""	9.9	{breed rurals	FALSE	
38	24	0	6	21	-78	"person"	""	9.9	{breed rurals	FALSE	
39	25	0	141	31	-64	"person"	""	9.9	{breed rurals	FALSE	
40	26	0	256	17	-25	"person"	""	9.9	{breed rurals	FALSE	
41	27	0	87	29	33	"person"	""	9.9	{breed rurals	FALSE	
42	28	0	270	39	-39	"person"	""	9.9	{breed rurals	FALSE	
43	29	0	168	39	61	"person"	""	9.9	{breed rurals	FALSE	
44	30	0	59	32	-19	"person"	""	9.9	{breed rurals	FALSE	
45	31	0	163	5	34	"person"	""	9.9	{breed rurals	FALSE	
46	32	0	200	31	52	"person"	""	9.9	{breed rurals	FALSE	
47	33	0	271	-6	3	"person"	""	9.9	{breed rurals	FALSE	
48	34	0	189	-13	-51	"person"	""	9.9	{breed rurals	FALSE	
49	35	0	46	-6	55	"person"	""	9.9	{breed rurals	FALSE	

Figure 4.8: Snapshot of world exported. The output was obtained using NetLogo's *export-world* tool, which writes the values of all variables, both built-in and user-defined, including all observer, turtle (identified with **who**), and patch variables, the drawing, the contents of the output area if one exists, the contents of any plots and the state of the random number generator, all written to an external file.

From the data saved, I could confirm my agents and the world kept their variables within reasonable values. This process was done at different stages during the modeling process, and it allowed me to identify and correct a couple of issues related to the social networks procedure.

Besides, during the coding process, I included several *breakpoints* to debug the code and detailed comments, when needed. And as shown in the section on profiling, I created many procedures to easy understanding of the main function (GO) and the identification of possible errors. As an additional good practice, variable names were very informative, to ease reading of the code.

4.5.3 Testing in a minimal model

It is recommended [111] that models that have different sub systems and agents be tested individually and integrated. Currently, the model can simulate the natural world or the social world independently, or the coupled systems if desired. All the analysis is based on the coupled system. In Figure 4.9, I show this functionality to represent each system or the coupled system.

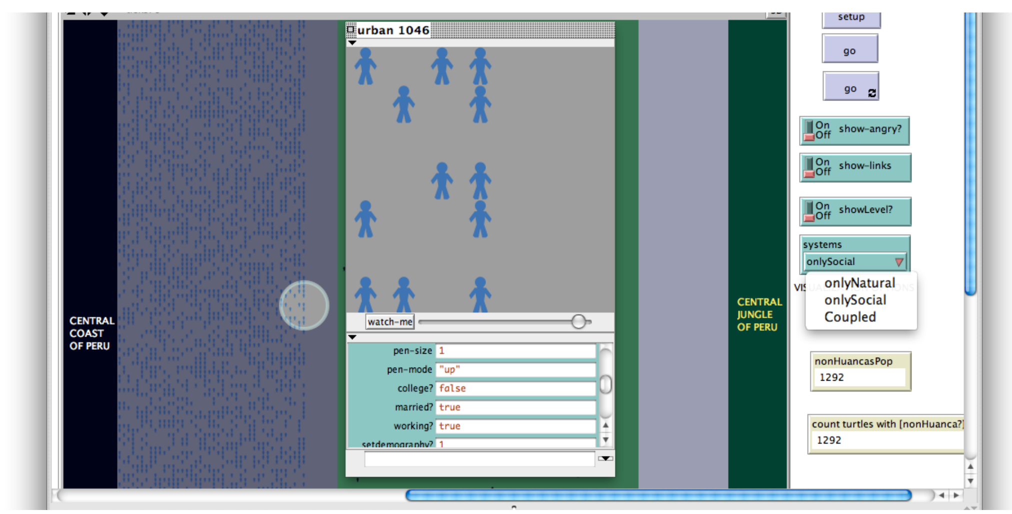


Figure 4.9: Functionality to simulate simpler model. Notice NetLogo's tool to follow particular agent.

Using this testing proved to be useful, as I can clearly test the behavior of each system if the other were not at play. Including this technique allowed me to ease calibration of different components. That was very convenient as I could show each researcher, that shared data with me, the behavior of the sub-system they were interested in. In this way, I could test within and between systems interaction, making sure the model reflected the current knowledge.

4.5.4 Parameter sweeps and variability testing

After processing the quantitative and qualitative data obtained from either literature review and/or field work, the input variables in the model belonged to intervals that reduced the amount of input values. However, before having those values available, it was a common practice at the end of every stage, to vary the input variables to extreme values. This allowed me to identify many processes that dealt with division by zero computations, where I needed conditional statements. High values of input variables gave no particular issues in the model, other than accelerating some final systemic outputs as expected.

To verify variability of the input variables I requested 100 runs. This gave me confidence to produce the scenarios analyzed in the next chapter. The output for the variability test was saved in a file

The variability represents in fact the effect of the different stochastic components in the code, and that output will be further discussed below for the Population, Migration and Conflict variables.

- **Population** and **system** outcomes are important to be known to verify the behavior of the model. The output produced for verification of these outcomes showed an interesting range of values that confirmed my expectations. The first robust statistic is that the maximum and minimum values of all the variables are in the same order of magnitude. Then, the values with the highest variance are the ones related to water balance (last two rows), which was also expected as their variation is very high across time (see Table 4.7).

Table 4.7: Variability of population and system output (100 simulations). See Appendix for variable description.

Statistic	Mean	St. Dev.	Min	Max
population	3,625.35	34.78	3,551	3,732
ruralpopulation	577.25	0.54	576	578
urbanpopulation	3,048.10	34.79	2,974	3,156
nonhuancaspop	2,602.35	33.72	2,532	2,673
conflict-mass	2,443.31	39.86	2,348	2,531
ruralcountangry	1.46	1.97	0	10
density-angrynetworkurban	0.01	0.001	0.01	0.01
timebyeglacier	70.00	0.00	70	70
firstnegativebalanceurban	42.00	0.00	42	42
urbanwaterbalance	282,146.90	1,102.38	279,828.10	284,742.90
ruralwaterbalance	1,917,614.00	527.56	1,916,879.00	1,918,837.00

The other variables have minimal variability and their mean values are also as expected. The variables with zero variability are the ones that were calibrated to represent that behavior, and will keep that results in all cases.

- **Conflict** is a key dependent variable in my hypothesis. The output produced for verification of these outcomes confirmed that the final results were robust. There was some variation due to number of simulations and the random processes present in this experiment, but there were no significant outliers in any variable. The results in this case, shown in Table 4.8, had no relevant dispersion in any variable. It is worth noticing that rows three to five are variables related to network statistics and the variability of the results are within reasonable limits. The last row informs me that there were cases when there was no relatively deprived rural person (the flag '-1' never changed), and that there were cases when this situation happen at the very end of the simulation.

- **Migration** is the second key dependent variable in my hypothesis. There was some variation due to the different combination of input values (see section 4.4.3.2 on page

Table 4.8: Variability of conflict output (100 simulations). See Appendix for variable description.

Statistic	Mean	St. Dev.	Min	Max
maxmass	2,529.220	36.229	2,452	2,619
maxdensitymass	0.007	0.0005	0.006	0.008
maxmeancc	0.376	0.020	0.340	0.420
maxcomp	635.530	75.569	443	778
maxmassangrytime	94.440	0.833	94	96
maxmasspoprural	562.950	3.173	560	569
maxmasspopurban	3,331.960	91.046	3,114	3,475
moment-conflict-rural	56.340	43.222	−1	99

98) and the random process present in this work, but there were no outliers in any variable (there were some outliers in the non-Huanca variable, but still the values were within reasonable boundaries). The value 0 in the third row (movedtohyo) means that there were no rural agents that migrated into the city, which is in fact the typical answer I got from the field work in the rural area (see Table 4.9).

Table 4.9: Variability of migration output (100 simulations). See Appendix for variable description.

Statistic	Mean	St. Dev.	Min	Max
movedtojungle	2,599.05	35.51	2,509	2,670
movedtolima	353.11	18.76	310	414
movedtohyo	0.00	0.00	0	0
moment-migrate-urban	53.44	0.90	52	54
maxjungle	371.80	18.61	339	425
maxlima	51.44	5.69	40	68
maxmove	420.12	20.11	376	472
maxtimemove	64.04	0.28	64	66
maxtimejungle	64.08	0.39	64	66
maxtimelima	65.28	5.74	62	94

My model has been consistently verified. It succesfully integrated all the sources of interdisciplinary knowledge following an spiral approach. Next, I will show how the prospective results have validity.

4.6 Model validation

As Dam et al. indicate [111], if verification answers the question *did we built the thing right?*, validation addresses the question *did we build the right thing?*. However, as these authors affirm, traditional validation methods are not always applicable to agent-based simulation, as validation cannot simply compare computed behaviour to "real" system behaviour if the model is exploring possible future states. For this study, validation focuses on whether the model is useful and convincing in its explanation on how this coupled system works and whether issues can occur. Based on the suggestions of these authors, I have accomplished the steps required to support the validity of this model.

4.6.1 Historic replay and literature review

There are many similarities that give support for this work:

- As a result of the calibration (see section 4.3 on page 81), the season when water balance was negative matches previous findings [36]. That is, the water balance becomes negative in season 42 (after 21 years), considering **2011** as the base year.

- The glacier coincides with the forecast from previous literature [37], disappearing in 70 periods (35 years), again considering 2011 the first year.

- The demographic structure depicted in Table 3.9 on page 69 is kept without much variation along the whole simulation even though the selection of people migrating has different considerations (see Algorithm 4 on page 102). Considering these values were given just once based on the census data, the simulation offers a future scenario without altering drastically this initial setting.

- From the values above, the migration of agents is also kept constant without further alterations; migration does not start immediately after water balance is negative, as the interviews suggested.

- Also, from the fieldwork, the statistical mode of migration in the rural population remained zero in all scenarios.

4.6.2 Expert validation

This is the strongest support I have got for this model, as each of the following experts support the modeling and its findings:

- Juan Ignacio Lopez, glaciologist, researcher from Instituto Pirenaico de Ecologia (IPE) in Zaragoza, who has been adviser to Peruvian glaciologist and he himself gather all the data related to Huaytapallana, which was also shared for this study.

- Andreas Haller, a urban geographer, from the Institute of Geography at University of Innsbruck and from Institute for Interdisciplinary Mountain Research at Austrian Academy of Sciences. He himself conducted research to understand the peri-urbanization of Huancayo 4 years ago. Besides being interviewed, he shared data and maps.

- Guillermo Carlos, forest engineer, from the Universidad Continental in Huancayo, who has conducted research on water balance in the urban area of Huancayo and the risk of scarcity.

- Walter Lopez, the current Environment Manager of the Junin Region. He has recently requested the use of the model to help develop a strategic plan for the region.

- Bryan Mark, Geographer, expert in tropical glaciers, a Professor at Ohio State University and Director of the Glacier Environmental Change Group at that university. He is one of the most respected scholars worldwide on tropical glaciers, he has conducted research in the Andes, particularly in Peru. He has recently started working on the relationship between the Shullcas and Huaytapallana. He also shared data for this dissertation on the impact of glacier retreat in Shullcas.

4.6.3 Micro-macro correspondence

Some historical macro behaviors were replicated indirectly from micro interactions, which makes the validity stronger:

- *Peri-urbanization.* There is no potential for conflict in the rural area if there is no peri-urbanization. So, peri-urbanization is a key validation concept. As it has been extensively studied by Haller [42] and Haller and Borsdorf [40], the expansion of the city into the rural area will bring a series of issues. The peri-urbanization of Huancayo is represented in Figure 4.10.

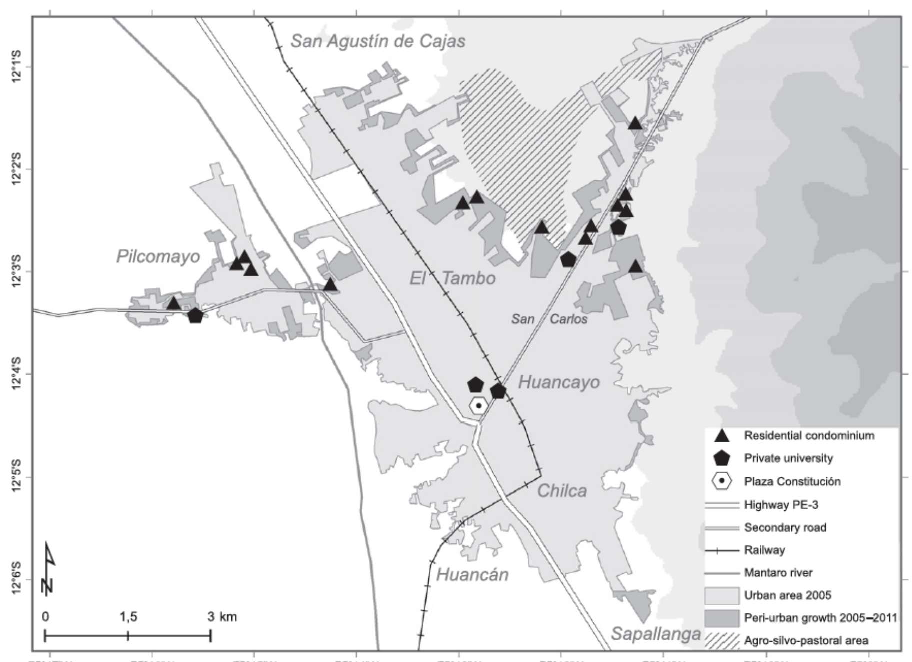


Figure 4.10: Peri-urbanization - actual process.
Source: [42].

This dynamic was able to be replicated out of agents local decisions. The driving mechanism is explained in Algorithms 5 and 6, related to finding a place to live based on a system of references, as discovered in the field work. Figure 4.11 shows clearly the peri-urbanization process *in silico*.

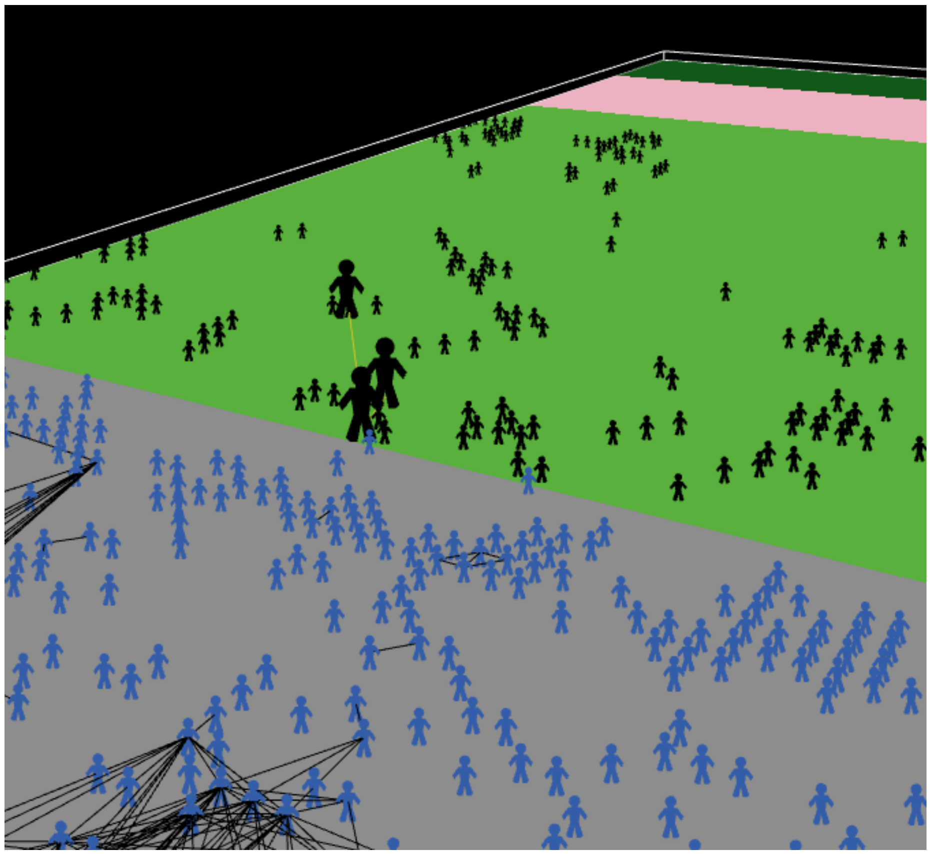


Figure 4.11: Validation of peri-urbanization - model

- *Migration*. The expected trend in migration has been computed based on data from [109, 113]. Coincidentally, the initial values of migration in my model have a closer relation to this trend, but higher water scarcity will change the migration trend in the next periods. The macro trend was the emergent outcome of the micro level decision of the agents, which is a combination of different algorithms in this model (see Algorithms 1 on page 90, 4 on page 102 and 6 on page 105.) That is, the agents migrating fit closely to the historic migration behavior, but after 7 years, the expected trend will be very different. The Figure 4.12 focuses on the periods when the official expected migration is close to the emergent migration from the model.

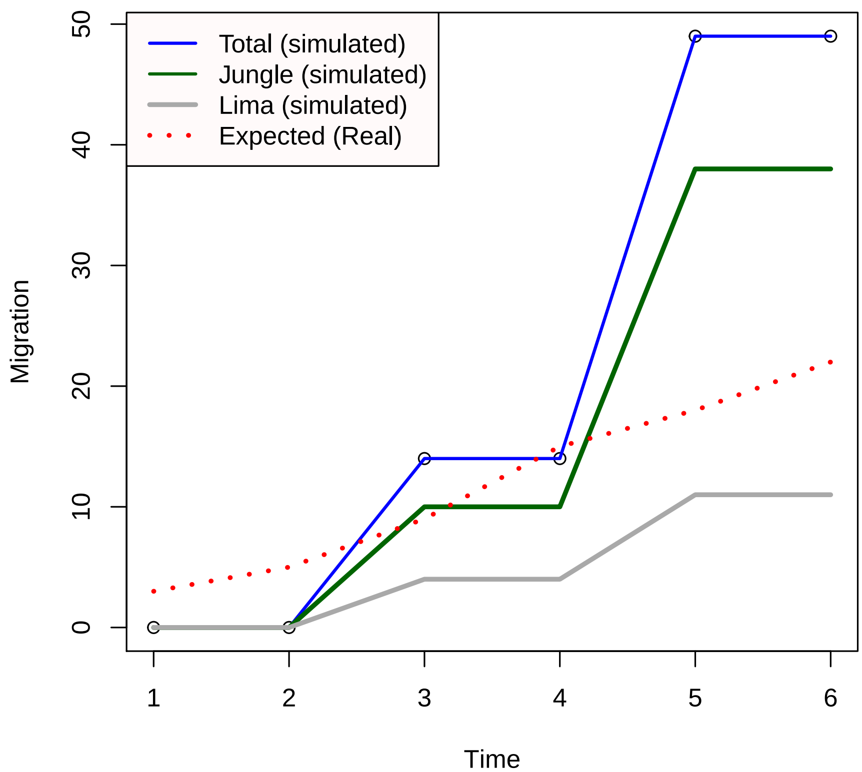


Figure 4.12: Validation of migration from local decisions

This behavior is explained by the restrictions that the code imposes to the agents, that depend on the employment, education and marital status, including a random uniform process and a search for water process.

As it has been seen, I have relied on different criteria to give some level of validation to my model. This stage has been very challenging as the model tries to be a support for actual decision making for events that have no previous history to compare with. That is the main reason I needed to present this work to different experts and stakeholders to gain legitimacy from them, which was accomplish. However, I have also shown how the basic mechanism that were discovered during the field trip could lead to produce the conditions for the potential outcomes of interest in this work. conflict and migration.

Finally, it is worth mentioning the praise this model has obtained when it was presented in the World Congress on Social Simulation in Brazil on November 2014 (it was selected for publication), at the University of Pittsburgh in April 2015, and at the Junin Region in July 2015. In all of the later cases, commentators knowledgeable of the barriers in getting data from different sources in countries like Peru, see this model as a baseline where each expert can later provide more knowledge to get more accurate results. However, all agree that the lack of anticipative policies would bring the scenarios that emerged in this model.

Up to this stage, I consider I have enough ingredients to make the model run, create different scenarios, and produce results. I believe the outcomes obtained will be useful for the communities I want to help. I am sure that the scarcity of data can not be an excuse to not produce a model in these circumstances. Political decision making is characterized by the need to make decision facing high uncertainty with no model in hand, but it always needed to develop consistent arguments to move resources towards the achievement of a vision of future. In the next chapter, I present the results of this model, with the hope it represents a vision that must not become a reality.

Chapter 5: Analysis

> *"Although policymakers cannot draw lessons from events that have yet to occur, they can try to anticipate events. In doing so, they may treat the future as an extension of the present in order to bound speculation by existing knowledge. Theorists can claim future success for their prescriptions on the grounds that predictions follow logically from premises, whether or not their premises are plausible. Politicians can exploit uncertainty about the future by willfully asserting faith in their proposals, which have yet to be proven wrong" (pp.91) [114]*

This quote from Professor Richard Rose[1] has guided the purpose of my research. In his work "*Lesson-Drawing in Public Policy: A Guide to Learning Across Time and Space*" [114], Rose believes anticipation allows policymakers to forgo the necessary rigors of empirical evidence, as anticipation is not a scientific endeavor but in fact a *political tool* that can be used when facing uncertainty and novelty. This is particularly important when questions like *"When will this occur?" "What will be the impact?" "Whom will they impact more?"* and the like, have no clear answer. These same questions are asked by policy makers and stakeholders about Huancayo, but each from his position without integrating the partial data and knowledge they have.

In this situation, the model developed in this work represents the first interdisciplinary tool to ignite the interdisciplinary discussion so badly needed for this situation. As Rose suggested, I just *extended the present*, which allowed me to corroborate the narrative that water supply, population growth and peri-urbanization could lead to drastic migration and social conflict if their current trend is allowed to continue. As uncertainty is the motivation for anticipation, I present the results and analysis from my model in series of snapshots:

[1] Director of the Center for the Study of Public Policy at the University of Strathclyde, Glasgow

- **Take one**. The model has been verified and validated. The population is situated in the year 2011 and the model is ready to run. The population count reflects a proportion of actual population. The areas are also proportional. The Glacier Huaytapallana area in the year 2011 is represented by the zone in white, the rural settlers inhabit the green area and the urban agents are in the gray area. The water balance is not an issue yet, the water supply is enough for the population water needs. However, both the glacier area and the water supply time series have decreasing trends. These trends are not steep so the population does not feel alarmed. Water supply trend will eventually collide with the positive population growth trend.

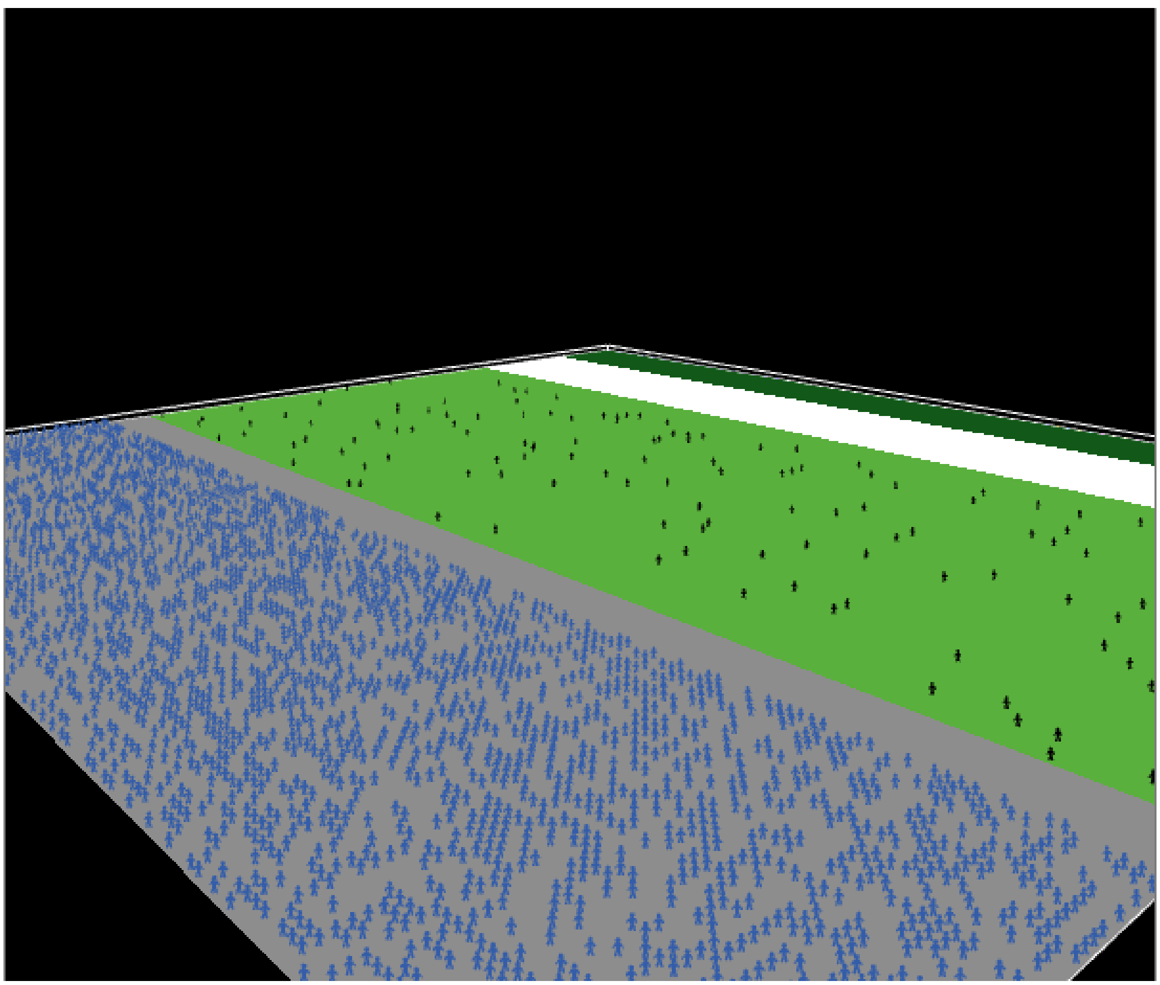


Figure 5.1: Start of the simulation

- **Take two**. The model is already running. As time passes by, the glacier Huaytapallana keeps melting, following the identified trend. The pink patches near the white patches represent the zone retreated, so the glacier presents a higher snow line. In the model, no recovery of glacier area is possible. Even though there are no water issues in this season, people started slowly moving away from the more densely populated area (left gray area) into the peri-urban area. The only driving force for this is the population growth. The urban agents inhabiting the peri-urban area are still far from the rural area, so the rural settlers have no relative deprivation issues yet. Also, as the urban people have no water issues, there are no frustrated people yet.

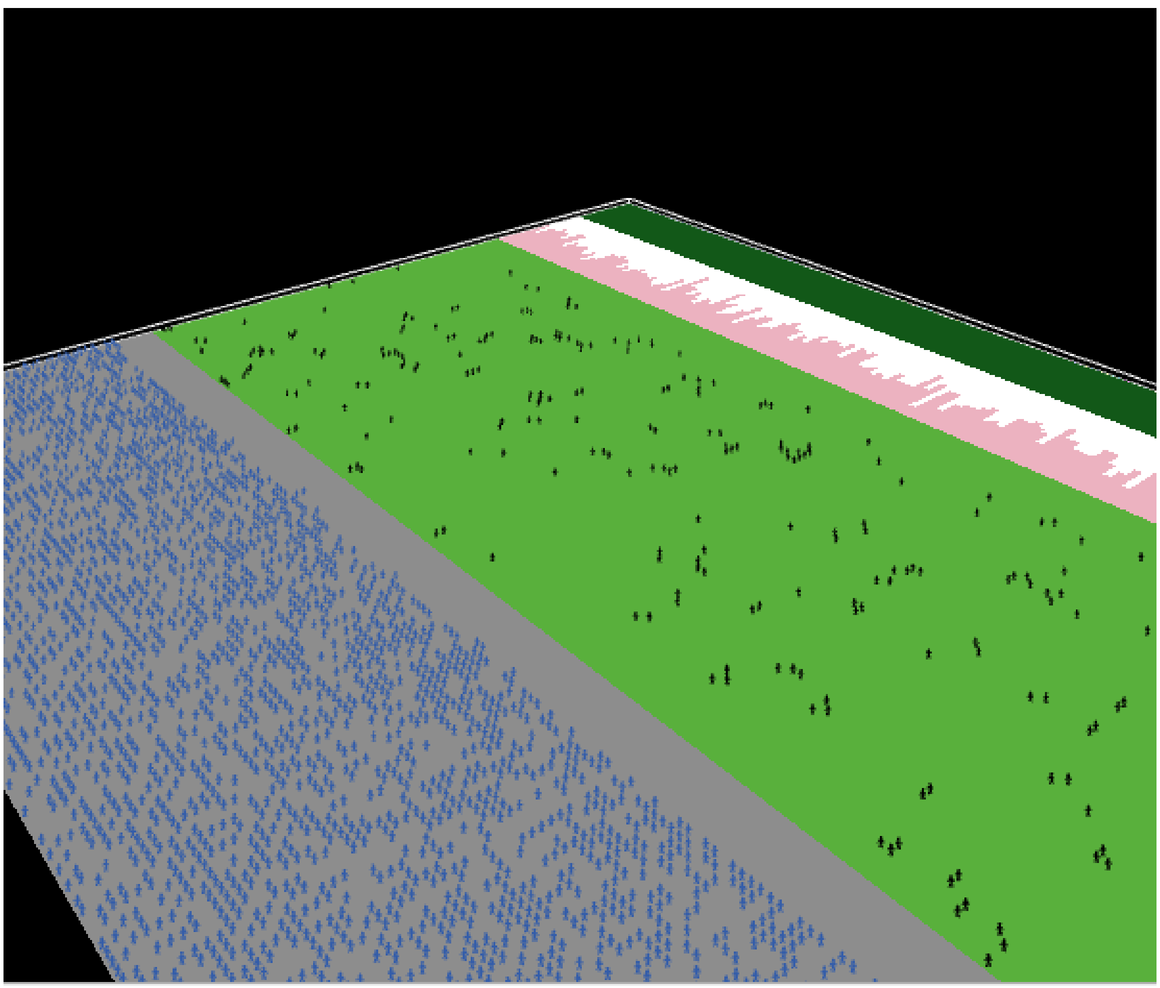


Figure 5.2: Melting of the Huaytapallana

- **Take three**. The model keeps running and the glacier has almost retreated completely. However, the population in the urban area has grown so much that the water balance for the urban area is now negative. The pink patches in the urban area are the patches that are affected by the drought during the *dry season*. The drought is felt progressively from the highest risk zones (leftmost gray zone). If an agent is living in a patch that suffers drought, he may need to move away, depending on his beliefs of future scarcity. There are some urban agents that could not migrate when their resilience was reached. They are already organizing into a network. The peri-urbanization process continues but no rural is feeling relatively deprived yet.

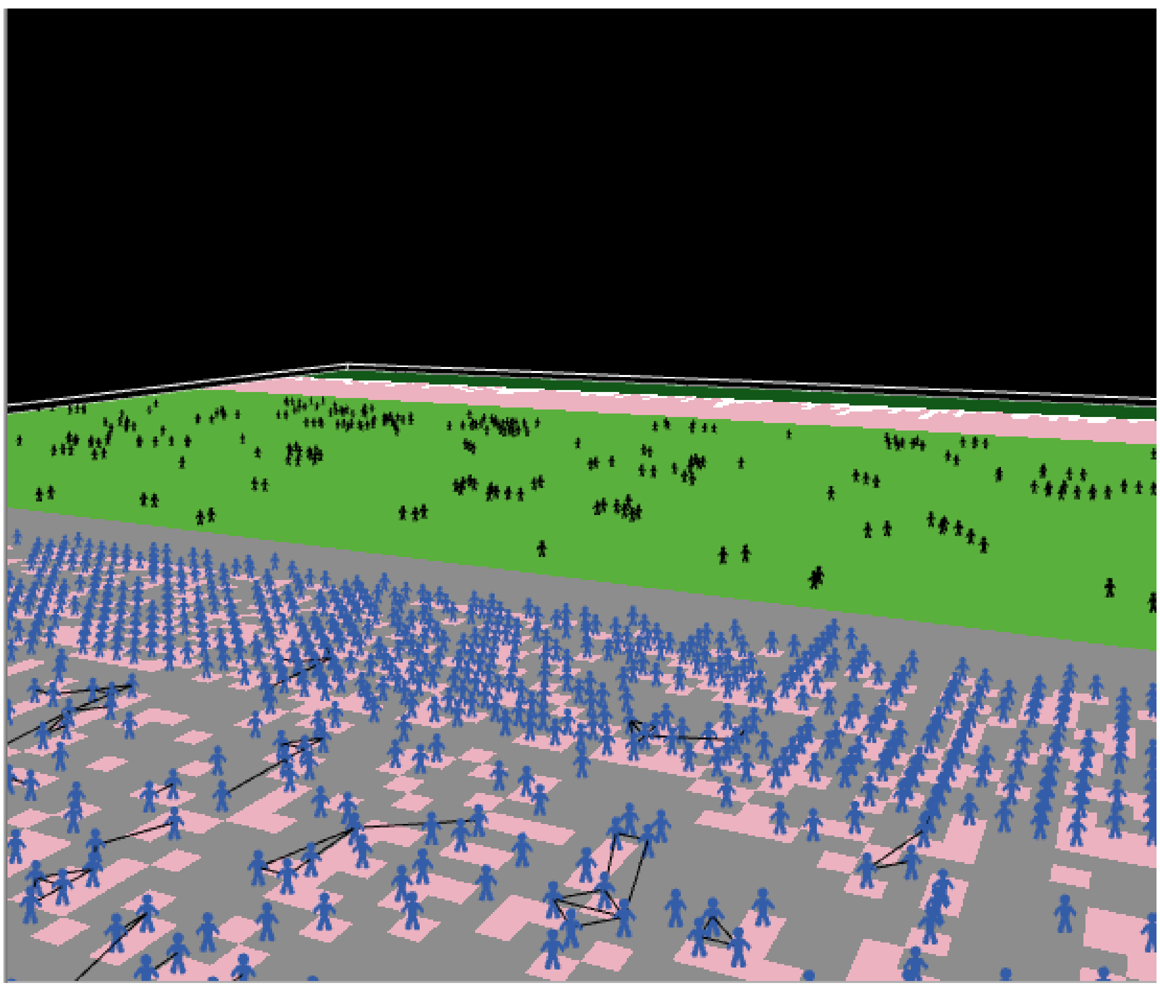


Figure 5.3: Water scarcity and network of urban people frustrated

- **Take four**. The Huaytapallana has melted completely. This has made the situation even worse during the dry season. Urbanites are populating more the peri-urban area, and the increasing presence of non-Huancas has started making rural Huancas feel relatively deprived. The rural agents with a bigger size represent those rural agents. Even though the migration into Lima and the Jungle has been massive, there are still many people feeling frustrated living in Huancayo. Not every frustrated urbanite is connected to one another, but there are many network components and cliques every where in the city. The simulation is about to finish after representing 50 years. The potential for conflict and migration turn into a fact in the model.

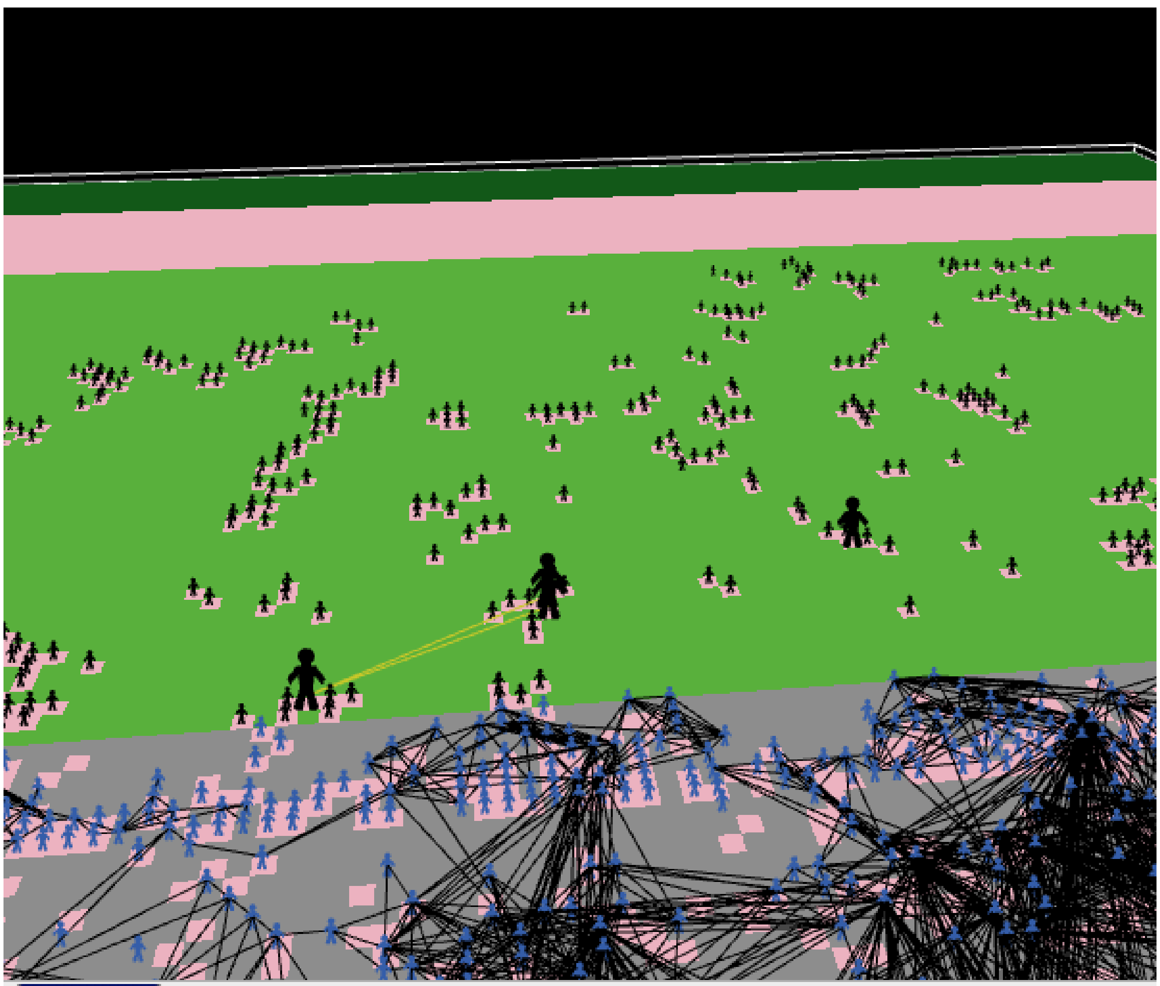


Figure 5.4: Water scarcity, urban people frustrated and relatively deprived rural settlers

5.1 Is extreme migration possible?

Related to migration, Table 5.1 shows the final values obtained. There, one can see that, even though it is possible for rurals to migrate, the balance of water in the urban area the next years would not be an issue, so even though migration is allowed for rurals in the code, no emigration took place. Migration started at season 54 (year 27) and the most extreme migration happened in season 64, 10 seasons later (year 32). If the demographic conditions assumed in algorithm 4 on page 102 held true, the migration to the jungle would be the most alarming.

Table 5.1: Migration-related results

Variable	Value	Variable Name
People that moved to the Jungle	2662	movedtojungle
People that moved to Lima	356	movedtolima
Rural people that moved to urban area	0	movedtohyo
Season when Migration started	54	season-migrate-urban
Max number that emigrated in a year to the Jungle	337	maxjungle
Max number that emigrated in a year to Lima	54	maxlima
Max number that emigrated in a year	391	maxmove
Season when Max number that emigrated in a year was reached	64	maxtimemove
Season when Max number that emigrated in a year to the Jungle was reached	64	maxtimejungle
Season when Max number that emigrated in a year to Lima was reached	64	maxtimelima

Can migration be avoided?

Migration is not an easy option for the population, as the ABM allows the agent to look for water somewhere else within the city. Besides, the agents can even remain in a scarcity crisis because they could not migrate. After a initial data exploration, there are two input variables, one at the individual level and one at the nature level, that have a negative and significant relationship with migration in the model, as the regression results from Table 5.2 show. I produced a visualization to clarify the real impact of those two variables. First, using the scatter plot in Figure 5.5, I can discard the apparent effect of “Water scarcity threshold to move” (movingDecision).

Table 5.2: Regression on migration share (standard error in parenthesis)

	Dependent variable:
	allmove
saveRainSeason	-4.507^{***}
	(0.010)
movingDecision	-0.327^{***}
	(0.004)
Constant	1.034^{***}
	(0.003)
Observations	64,800
R^2	0.753
Adjusted R^2	0.753
Residual Std. Error	0.130 (df = 64797)
F Statistic	$98{,}825.090^{***}$ (df = 2; 64797)
Note:	*p<0.1; **p<0.05; ***p<0.01

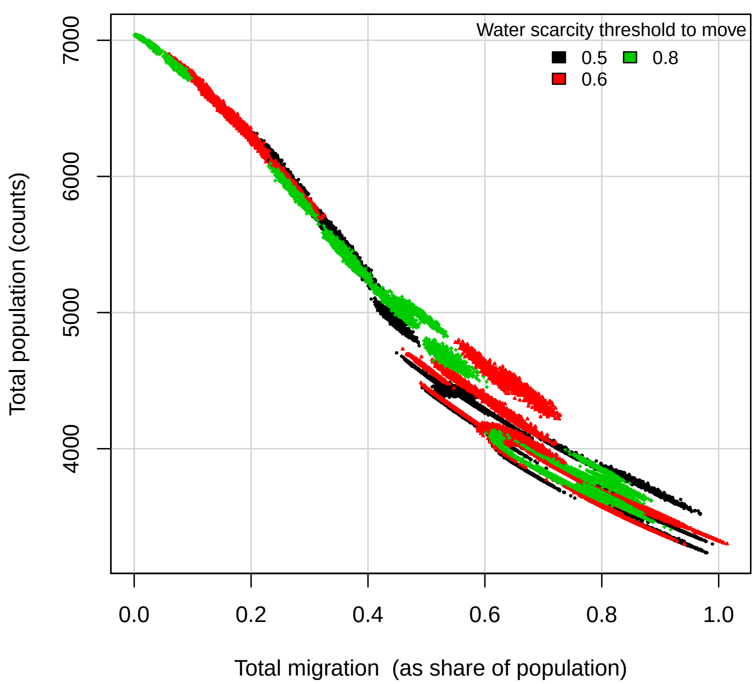


Figure 5.5: Migration share and total population.

As it can be seen, *Water scarcity threshold to move* does not cluster in a particular area, but it is spread along the x values. The linearity present in the plot is the reason why the regression gave good results; however, due to the amount of observations (simulations), the linear regression gives biased and misleading results in this case (see F statistic). From a policy perspective, it is convenient this variable is not a key cause for intervention, as it is related to the way people process information.

On the other hand, the amount of water reserved from rainy season (*saveRainSeason*) has a clearer negative effect on migration. As seen in Figure 5.6, different levels of reserve gives a different cluster of points.

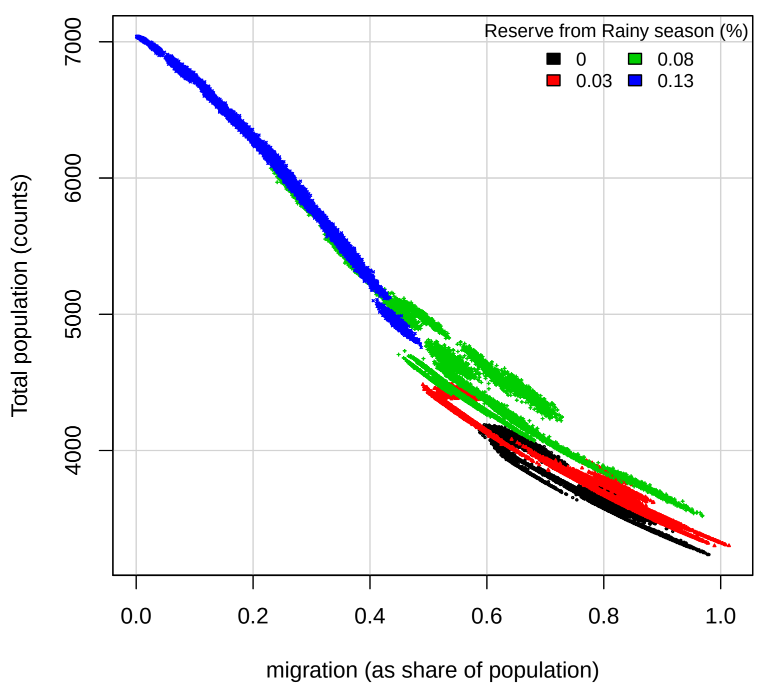


Figure 5.6: Migration share and total population. Color representing the different input values of *Reserve from Rainy season*

Even though these clusters overlap, there is a clear suggestion from Figure 5.6 that if one saved less than 13% there would not be significant impact on migration, that is, any option below that value will keep the migration share at its highest peaks, and as these values (*saveRainSeason*) represent an investment in infrastructure, investing will need to achieve that level of saving, otherwise, the public moneys will give no effective result. Again, from a policy perspective it is a very important result, as it makes clear the type of intervention required, and goal to be achieved.

Is it possible to delay the migration process?

Migration is an undeniable fact in this situation. The previous analysis has dealt with counts or shares. Now I focus my attention on duration. To answer the question posed, I have recorded particular seasons during the simulation. In this case, I use two particular variables, the one that records when the migration started and the one that informs when the maximum migration was reached (see their distributions in Figure 5.7).

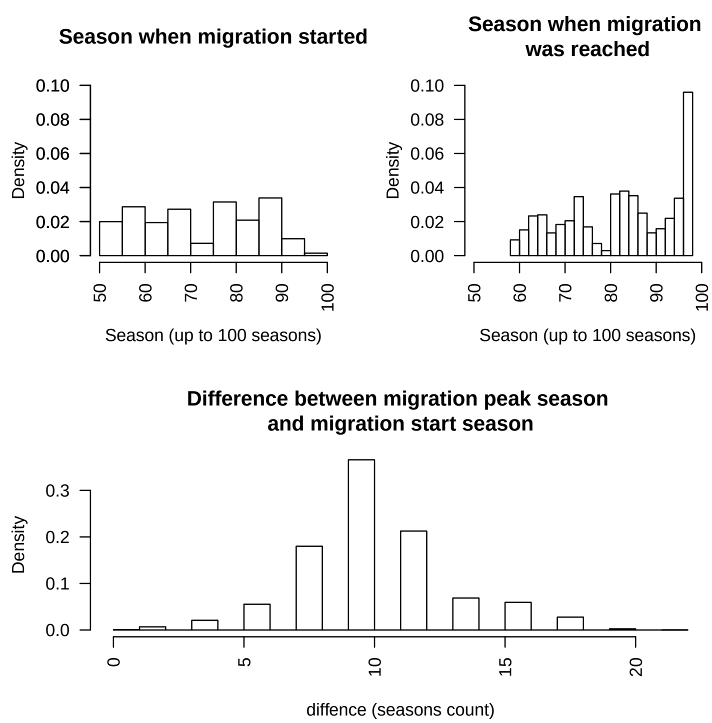


Figure 5.7: Distribution of migration seasons

From the simulations, I know that migration was present in each one of them, so there are no cases that need to be treated as censored. Besides, from the histograms in Figure 5.7, I see there is enough variability to do a further analysis on those variables. Particularly, these variables are adequate for event history analysis (time to event), as they represent duration. To start, I pay attention to the variable *moment-migrate-urban* which represents the season when the first person migrated. For this analysis I have subtracted its value from first time the water balance was negative (*firstnegativebalanceurban*). I will do so to obtain a new value for each simulation that tells the *time* it took for migration to start since the water balance was negative. As I am dealing with duration, I will regress using a **Cox proportional hazard model** [115], a semi-parametric approach to relate the time that passes before some event occurs to one or more covariates (all our input variables being swept) that may be associated with that quantity of time, in this case the *time* between first negative balance until migration started. The results are shown in Table 5.3

Table 5.3: Cox proportional hazard for migration start (standard error in parenthesis)

	Dependent variable:
	timeUntilMigrationStarted
resilience_level	-0.592^{***}
	(0.005)
memory	-0.854^{***}
	(0.006)
movingDecision	-11.333^{***}
	(0.055)
glacier_effect	-2.650^{***}
	(0.236)
saveRainSeason	1.004^{***}
	(0.080)
Observations	64,800
R^2	0.634
Max. Possible R^2	1.000
Log Likelihood	−636,546.300
Wald Test	49,105.840*** (df = 5)
LR Test	65,219.520*** (df = 5)
Score (Logrank) Test	55,471.240*** (df = 5)
Note:	*p<0.1; **p<0.05; ***p<0.01

Even though all the variables are significant, I have to be careful, again. This number of simulations may always detect enough cases that satisfy this regression model, so the significant values become acceptable. In fact, a one-by-one analysis will make evident that only the variable with the highest coefficient may actually represent a clear policy recommendation. To make this clear, I focused on the two coefficients that shows a stronger effect. The effect of the glacier is the less clear, as Figure 5.8 shows.

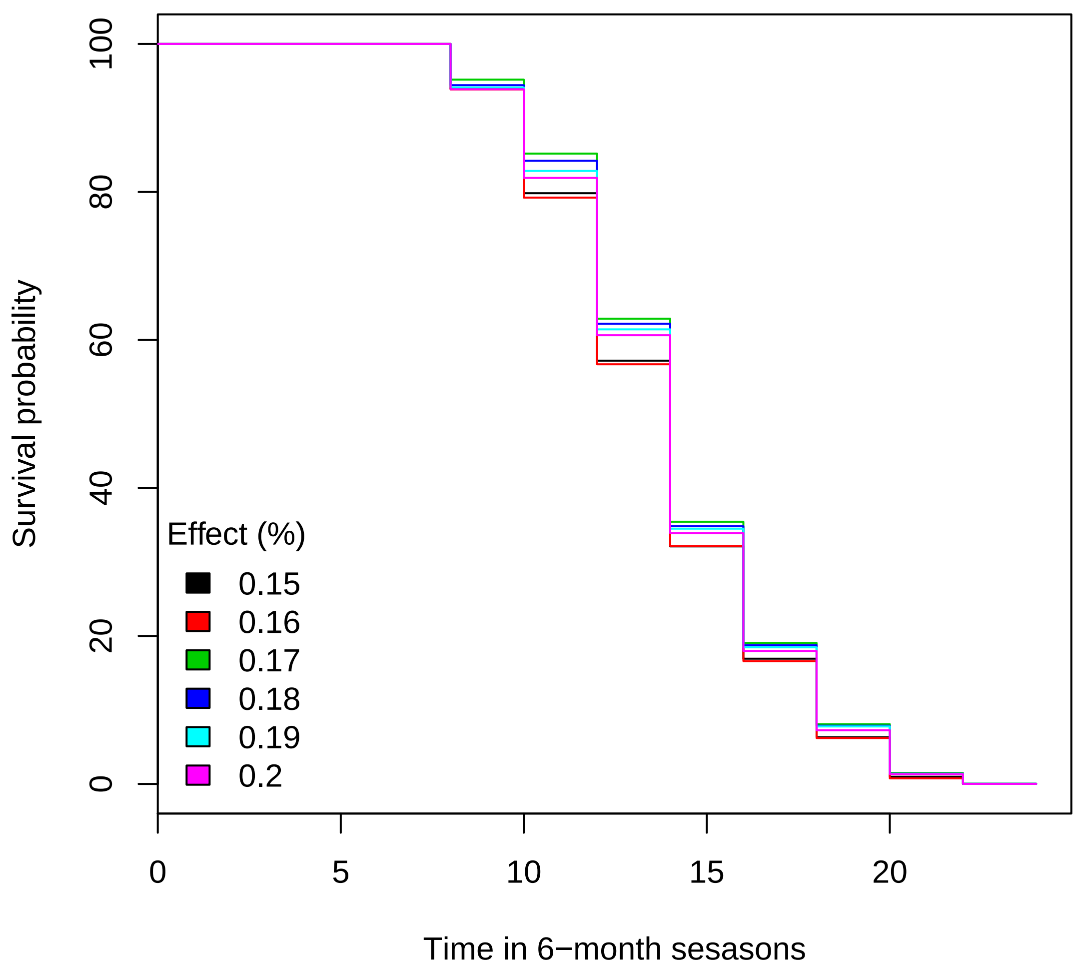


Figure 5.8: Effect of glacier melting on start of migration process

On the other hand the variable *movingDecision* brings clear differences. This situation needs to be carefully interpreted. It is hard, in policy terms to intervene in the *movingDecision* variable, which represents a proxy for the belief of the agent on future water scarcity, which becomes worse if scarcity affects an agent constantly. In this case, Figure 5.9 is telling us that migration would take longer to start if on average the people in Huancayo would become concern about water only when they predict their home have a probability of 0.8 of suffering scarcity in the future. Any effective intervention should consider a set of actions to raise the beliefs threshold of people to that level. If people had lower beliefs, migration will start sooner.

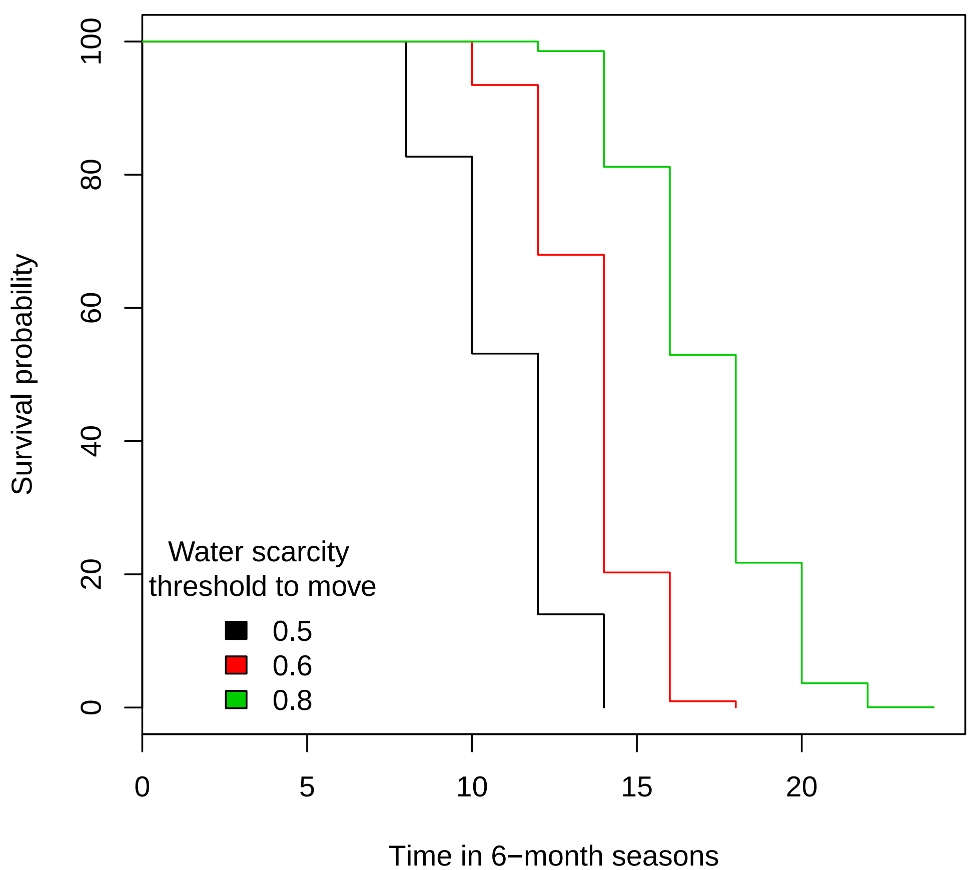


Figure 5.9: Effect of scarcity threshold to move on start of migration process

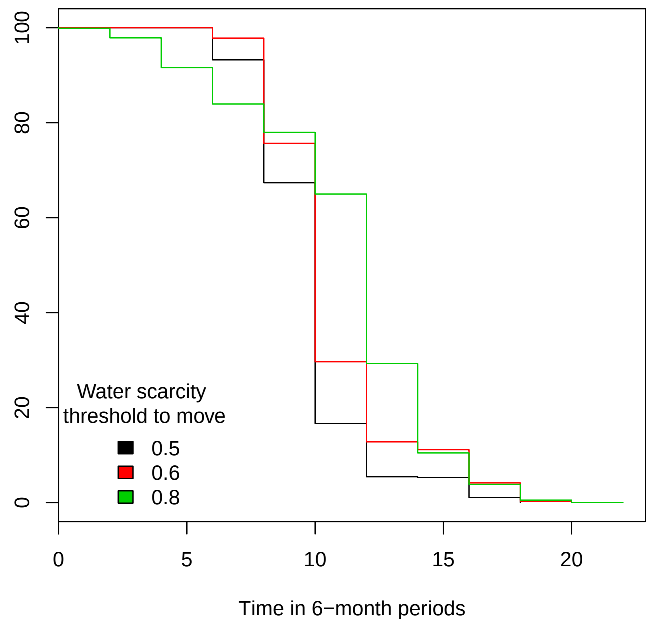
Following a similar approach, I computed the time difference between the peak and start of migration, and apply a Cox model to this variable using as covariates the same input variables. Table 5.4 shows the results.

Table 5.4: Cox proportional hazard for migration peak (standard error in parenthesis)

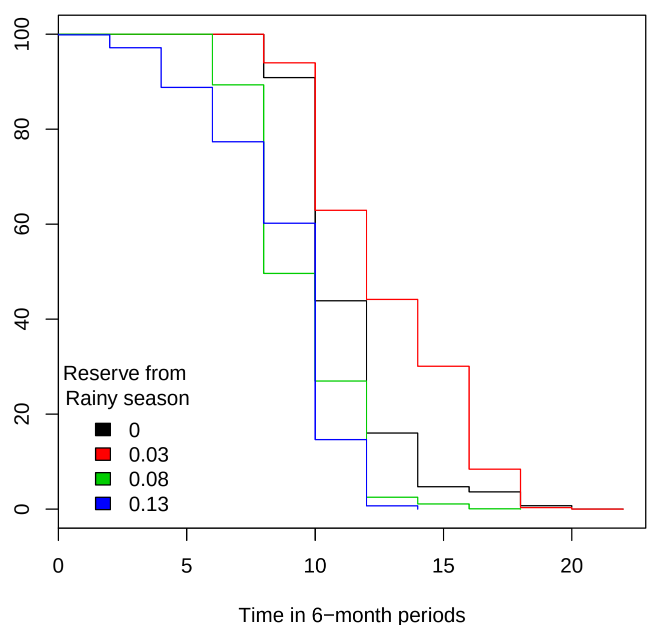
	Dependent variable:
	timeUntilMigrationPeak
resilience_level	−0.073***
	(0.005)
memory	0.075***
	(0.005)
movingDecision	−1.223***
	(0.034)
glacier_effect	−1.482***
	(0.230)
saveRainSeason	6.608***
	(0.087)
Observations	64,800
R^2	0.126
Max. Possible R^2	1.000
Log Likelihood	−666,734.900
Wald Test	9,042.770*** (df = 5)
LR Test	8,762.151*** (df = 5)
Score (Logrank) Test	9,266.991*** (df = 5)
Note:	*p<0.1; **p<0.05; ***p<0.01

Again, I offer a visualization of the top two covariates, and only one offers a clear difference, in this case the percent needed to reserve from the rainy season, while the scarcity threshold offers a less clear pattern[2]. In this case, Figure 5.10b is telling us that a 3% of saving from the rainy season would help delay the peak migration time. Interestingly, the other values may give worse results and are similar among them, as the peak time gets smaller. A decision to control the peak time is important, as it impacts the final population output reviewed in the last subsection. Up to this point, the best alternative is to control the start of migration, as the regression on the peak gives no clear answer.

[2] I discarded this variable in the previous analysis, but now it appears again as an important factor



(a) Effect of water scarcity threshold to move on the appearance of migration peak



(b) Effect of reserve from rainy season on the appearance of migration peak

Figure 5.10: Survival analysis for time until migration peak

Would non-Huancas become the majority in Huancayo?

The Table 5.5 shows the output of the simulation related to the population variables, using the initial values from Table 4.5 on page 98.

Table 5.5: Population-related results

Variable	Value	Variable Name
Final Population	3563.00	population
Final Rural Population	577.00	ruralpopulation
Final Urban Population	2986.00	urbanpopulation
Final Non Huanca Population	2570.00	nonhuancaspop
Final number of angry urban people	2434.00	conflict-mass
Final number of rural families with at least one member feeling relatively deprived	3.00	ruralcountangry
Final Network density of angry urbanites	0.01	density-angrynetworkurban
Season glacier retreated	70.00	timebyeglacier
First season of negative water balance	42.00	firstnegativebalanceurban
Final urban water balance	284251.40	urbanwaterbalance
Final rural water balance	1917858.35	ruralwaterbalance

Assuming a 40% of non-Huancas in every simulation, I ended up realizing that the individual level variables (resilience, memory and moving decision) does not bring about different scenarios, as shown in Figure 5.11.

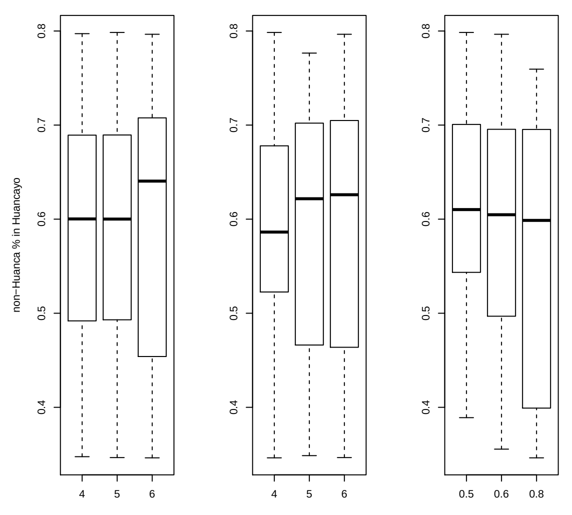


Figure 5.11: Share of non-Huancas and agent variables

The 40% assumed was the average from the 2007 census (35%) and my field work (45%), so the results from the figure above is a relief, as it is more difficult to politically intervene at this level. However, one of the natural system variables may bring some variability. First, as before, the non-Huanca population keeps within a similar share if the glacier effect varies within the assumed range. What is more important, from a policy perspective, is that if water is saved from the rainy season, the share does present significant differences among scenarios. Knowing that if some water is reserved from the rainy season would make a significant impact on non-Huanca share, implies again the need for investment in infrastructure. And Figure 5.12 reinforces that idea. It is an important sign for policy makers as this simple result has many implications I will discuss in the next chapter.

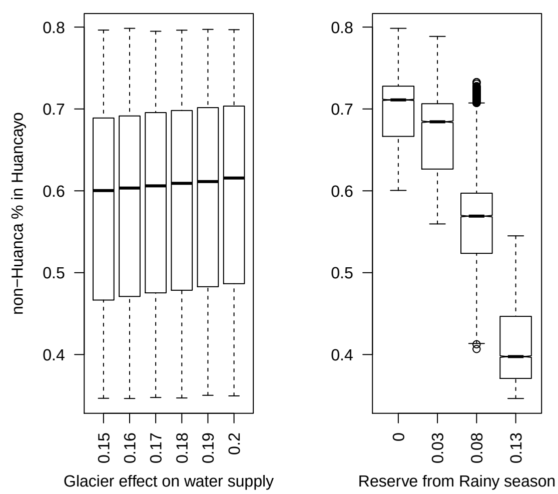


Figure 5.12: Share of non-Huancas and nature variables.

5.2 Is social conflict possible?

The Table 5.6 shows that the simulation reached a peak of 2497 frustrated agents in season 96. This peak represents the 80% of the urban population in that season. This peak is also greater than the rural population altogether. It is also worth noticing the first relatively deprived agent appeared 16 seasons earlier, in season 80. It is clear after this information that social conflict can become a reality.

Table 5.6: Conflict-related results

Variable	Value	Variable Name
Max number of angry people reached	2497.00	maxmass
Density of Angry Network when max number of angry people reached	0.01	maxdensitymass
Average clustering coefficient of Angry Network when max number of angry people reached	0.41	maxmeancc
Number of network components when Max number of angry people reached	491.00	maxcomp
Season when Max number of angry people reached	96.00	maxmassangrytime
Rural population when max number of angry people reached	569.00	maxmasspoprural
Urban population when max number of angry people reached	3116.00	maxmasspopurban
Season when first rural started feeling relatively deprived	80.00	season-conflict-rural

Table 5.6 also shows that after running the simulation for 100 periods (50 years), the network statistics have to be carefully and jointly interpreted. The low density can be affected by the high number of components. As a matter of fact, the clustering coefficient does inform there is a relevant level of connectivity, but at a local level. The panorama is complex so further analysis follows.

Can the conflict in the peri-urban area be avoided?

In the 64 800 runs carried out in this work, 45% of them had the presence of at least one member of a rural family feeling relatively deprived. In general, this variable stayed very low in he runs with $median = 0$ and $mean = 1.3$. As seen in Figure 5.13, none of the input variables makes a significant difference on conflict. That does not mean that policy makers should not worry about this outcome. As that plot also shows, every combination presents outliers in the upper zone of the boxplot. Outliers could be discarded if one can prove they are in fact atypical and irrelevant. The outliers in this case does not seem to be irrelevant, as they are present in the higher values of every boxplot. They do not seem atypical, since there are many of them in every case. As it looks in this case, they may represent that high values are still probable.

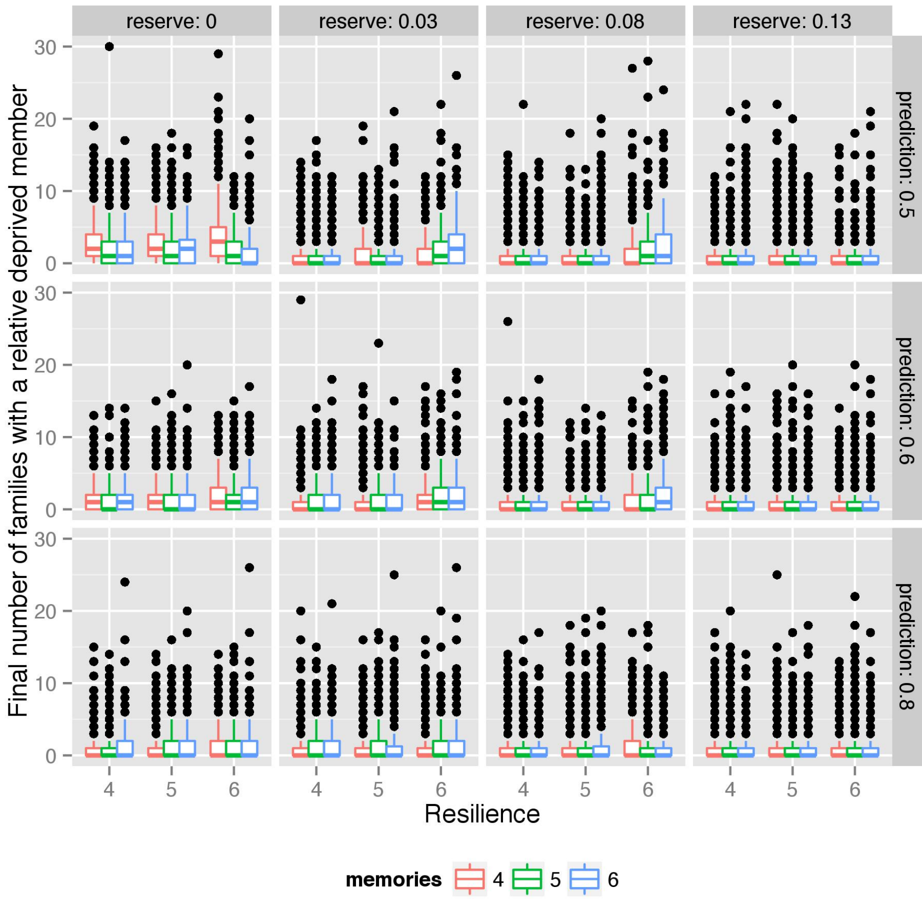


Figure 5.13: Distribution of families with a relatively deprived member.

The Figure 5.14 shows a behavior policy makers should be very aware of. To prove the outliers from Figure boxesdeprived are not neither improbable, atypical nor irrelevant events, I need to prove that discarding of these outliers is a wrong decision. Discarding outliers is a rule-of-thumb related to Normal *Gaussian* thinking, as the events in the tail (above three standard deviations from the mean) of a bell-shaped distribution are highly improbable. But the behavior of this variable is following a *heavy-tailed* distribution, closer to a *log-normal*, which makes those outliers more probable than expected in a normal distribution. Policy must not be blind to this and include this fact in the discussion. Allowing the city to urbanize the farm land without a serious plan is a potential invitation for massive violent outbreak considering the cultural differences of the area.

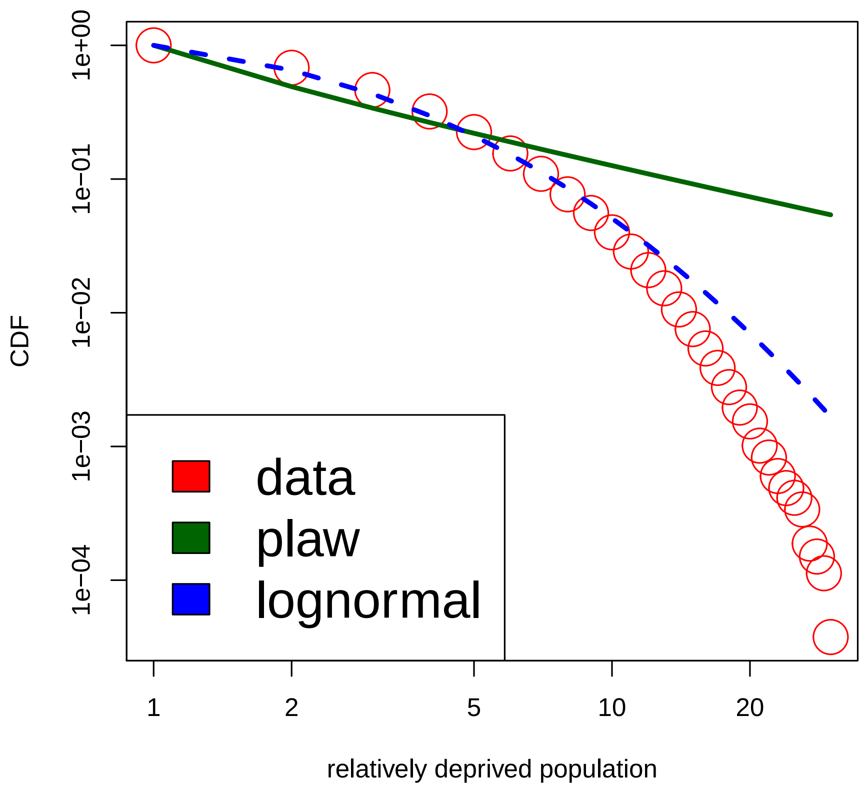


Figure 5.14: Relatively deprived population. This variable follows a heavy-tailed distribution closer to a log-normal were the probability of higher outliers should not be discarded

In considering cultural differences, it is important to keep in mind a possible social network effect. That is, this variable is counting only the relatively deprived person, but each rural person could involve its relatives in a fight. That has not been measured in the simulation directly, but is highlighted while running and, as I just said, I could count every relatively deprived rural person as the amount of household eager to go into conflict.

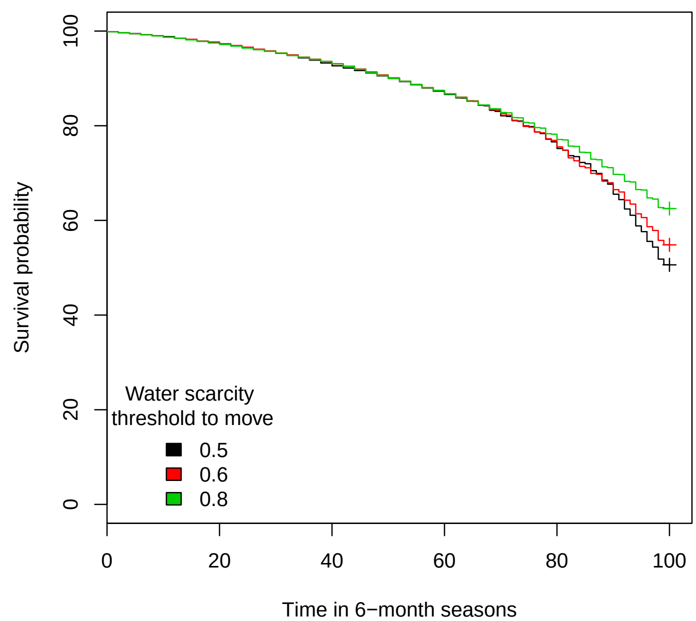
Can potential conflict in the rural area be delayed?

From the previous sections, it is always important to know this answer. I measured this duration with the variable *moment-conflict-rural.* As there are situation with no conflict, this variable has not changed its initial value (-1) in many cases, so these cases have to be censored in the regression. The result of the Cox model is shown in Table 5.7.

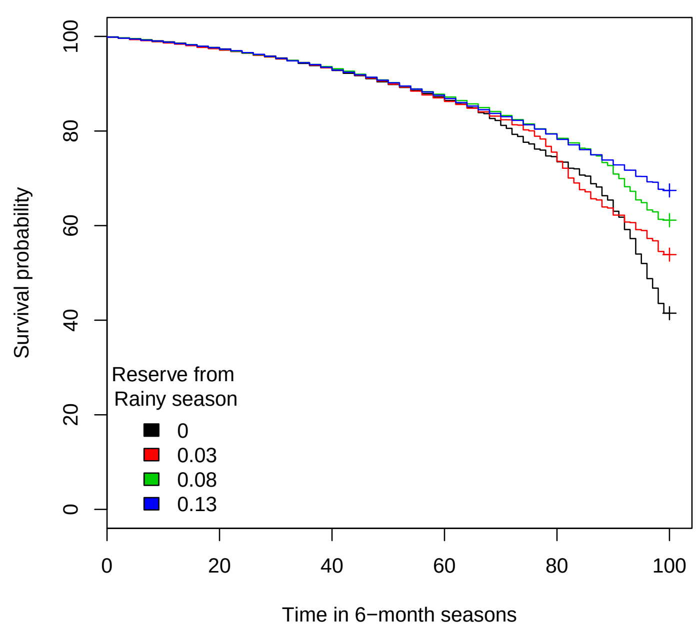
Table 5.7: Cox proportional hazard for deprivation start (standard error in parenthesis)

	Dependent variable:
	timeUntilDeprivation
resilience_level	0.123***
	(0.007)
memory	0.015**
	(0.007)
movingDecision	−1.100***
	(0.049)
glacier_effect	0.567
	(0.347)
saveRainSeason	−5.284***
	(0.125)
Observations	64,800
R^2	0.039
Max. Possible R^2	1.000
Log Likelihood	−307,427.700
Wald Test	2,530.510*** (df = 5)
LR Test	2,610.457*** (df = 5)
Score (Logrank) Test	2,561.145*** (df = 5)
Note:	*p<0.1; **p<0.05; ***p<0.01

The top 2 covariates from Table 5.7 suggest the policy measures, the same as in previous findings. Notice the effectiveness makes a difference in the upper values (see Figure 5.15).



(a) Effect of water scarcity threshold to move on the start of relative deprivation



(b) Effect of reserve from rainy season on the start of relative deprivation

Figure 5.15: Survival analysis on the start of relative deprivation

What can decrease the number of urban people frustrated?

In Figure 5.16, I summarize the effect of each variable on the number of angry people, a process that includes some randomness (see Algorithm 1 on page 90 for details). This randomness produces the variability highlighted in the boxplots, where one can see that the lowest values are outliers in the distribution, with a couple of exceptions. The most important from these plots, however, is that the lowest values are not outliers when *moving decision* is at 0.8 or when the saving from rainy season is around 13%. It also worth noticing that in both cases, the higher values are distributed below the other ones. Again, these two variables seem to indicate the most effective policy intervention. These interventions have to be carefully interpreted, as our base year is 2011. The longer it takes to implement these measures may weaken the effectiveness of the intervention.

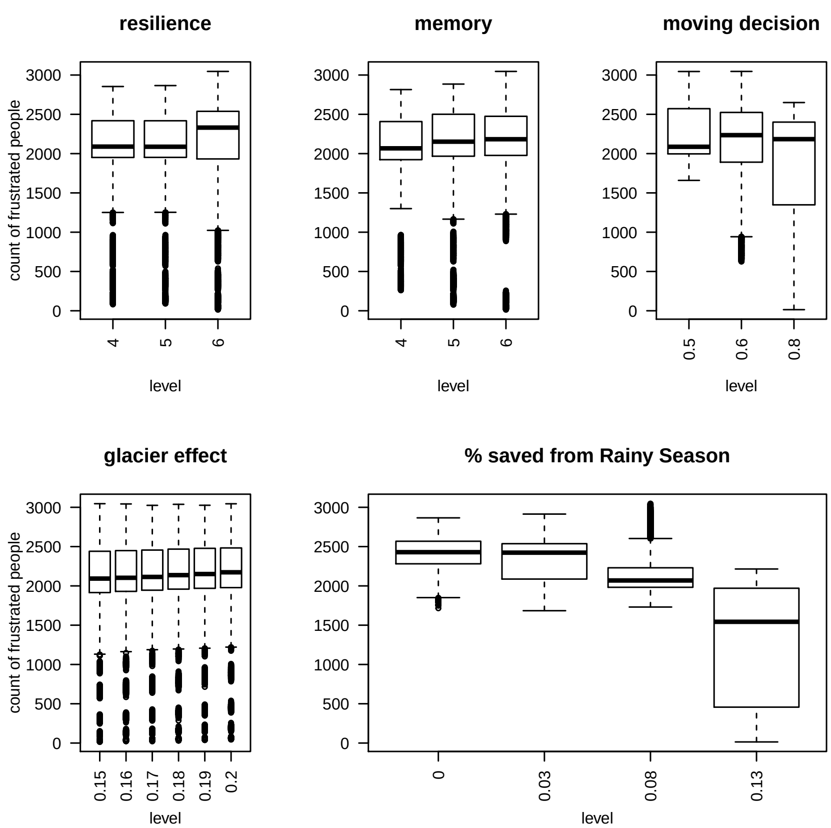


Figure 5.16: Distribution of maximum angry population

How to delay conflict in urban area?

The model captures the season when the maximum amount of angry people is present in the urban area. Combining multiple input variables, Figure 5.17 gives an clear idea of how to delay this critical season. The most consistent strategy requires that the saving be kept at 13% (right column), which will have higher variability if the prediction threshold is 0.5. The worst case is when the reserve stays at 0% and prediction threshold reaches 0.8. It also important to notice the we can achieve this delay without reserving water from the rainy season, if prediction keeps at 0.5 resilience and memory are less than or equal to 5.

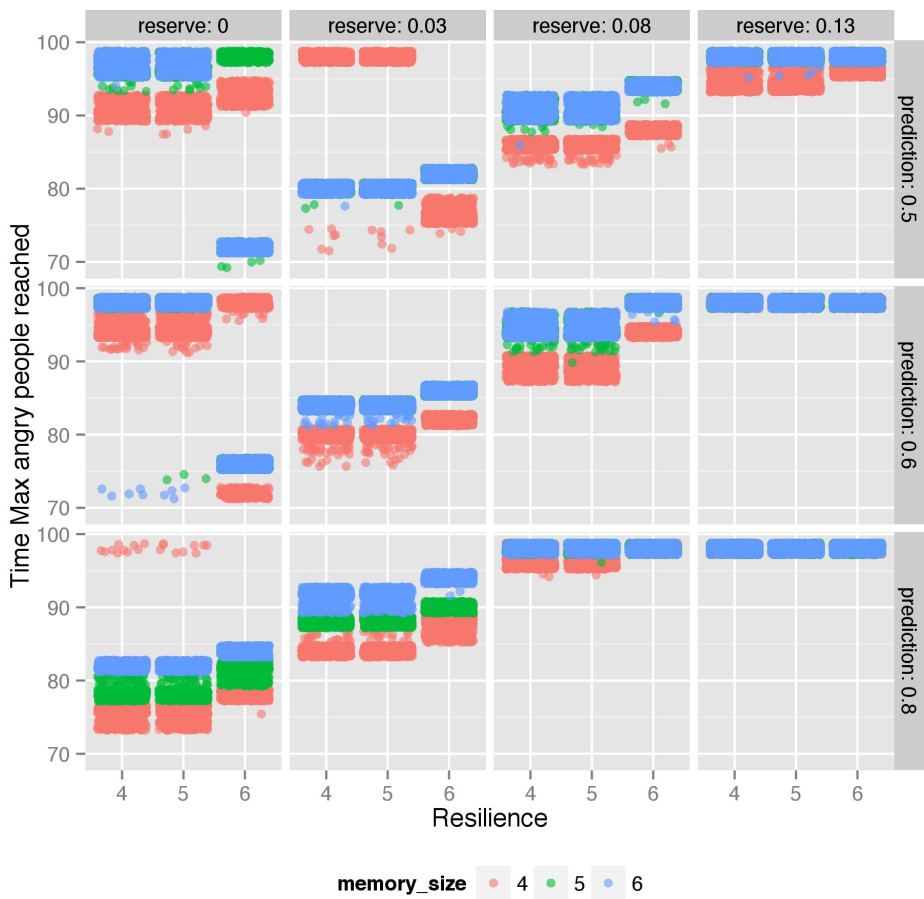


Figure 5.17: Distribution of season when maximum angry population was reached.

What would increase the potential for conflict?

It is not enough to have frustrated people to speak of conflict. Some level of organization among them is needed. This is detected and measured according to Algorithm 7 on page 106. **The average clustering coefficient** (ACC) reports the global tendency of an agent network to form a clique (everybody connected to everybody). If that were the case, this value will be *one* (the highest ACC has been 0.508). In the Figure 5.18, to keep a low ACC, one must achieve a water reserve of 13% and the agent must have a prediction threshold of 0.8. A lower prediction threshold will increase variability towards higher values (bottom corner to the left).

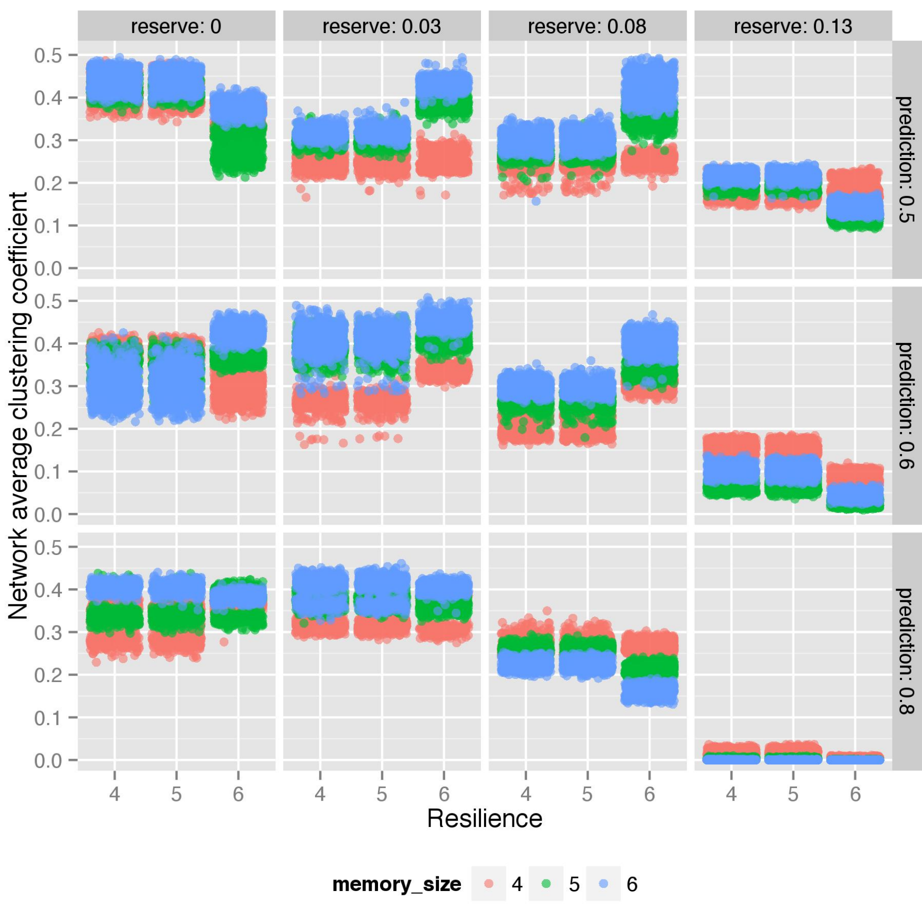


Figure 5.18: ACC when maximum number of angry urban people reached

The number of connected component (NCC) also reports on the connectivity of the network. It tells us how many isolated sub graphs are present at any given season. So it is a measure negatively related to ACC. Policy makers must interpret NCC carefully. High values will mean many groups to deal with or many small and irrelevant groups. If a high NCC were desired, one would chose the lower bottom corner in Figure 5.19.

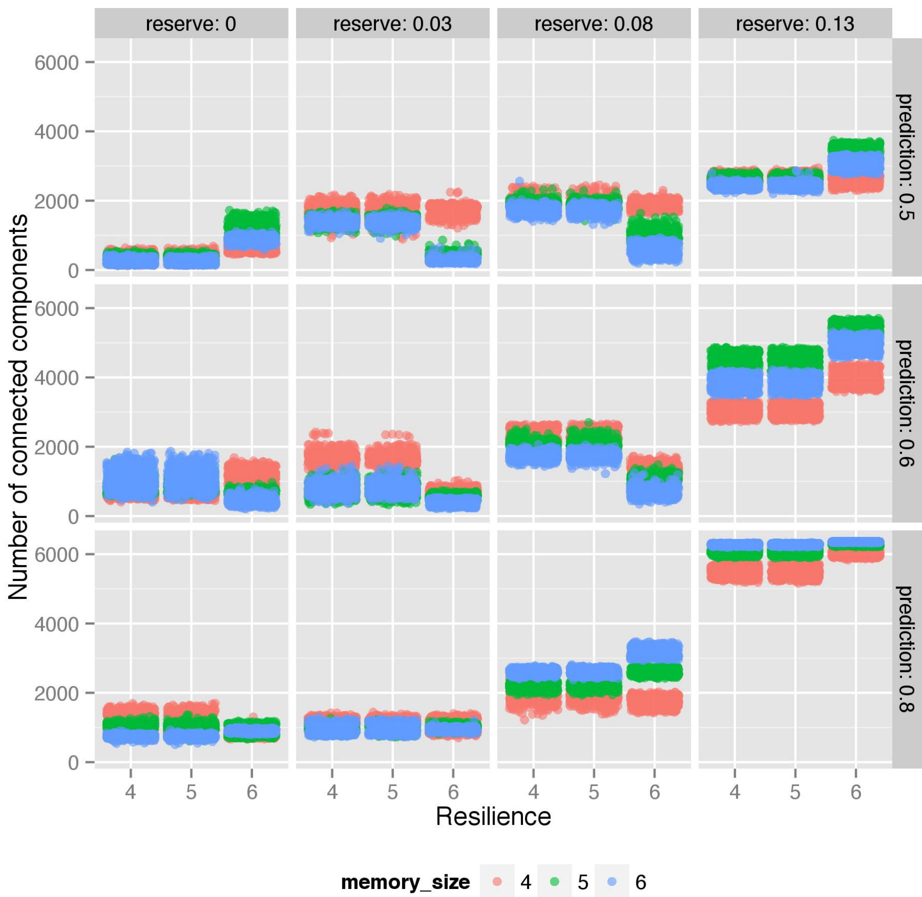


Figure 5.19: NCC when maximum angry people reached

The density of a network (DN) informs how well connected it is. A value of 1 will inform that every node is connected to every node, and a value of 0 will say the network is just isolates with no structure.

The density of the network has been very low when the maximum number of angry urban people was reached. As Figure 5.20 reveals, non of the variables are very influential for this metric.

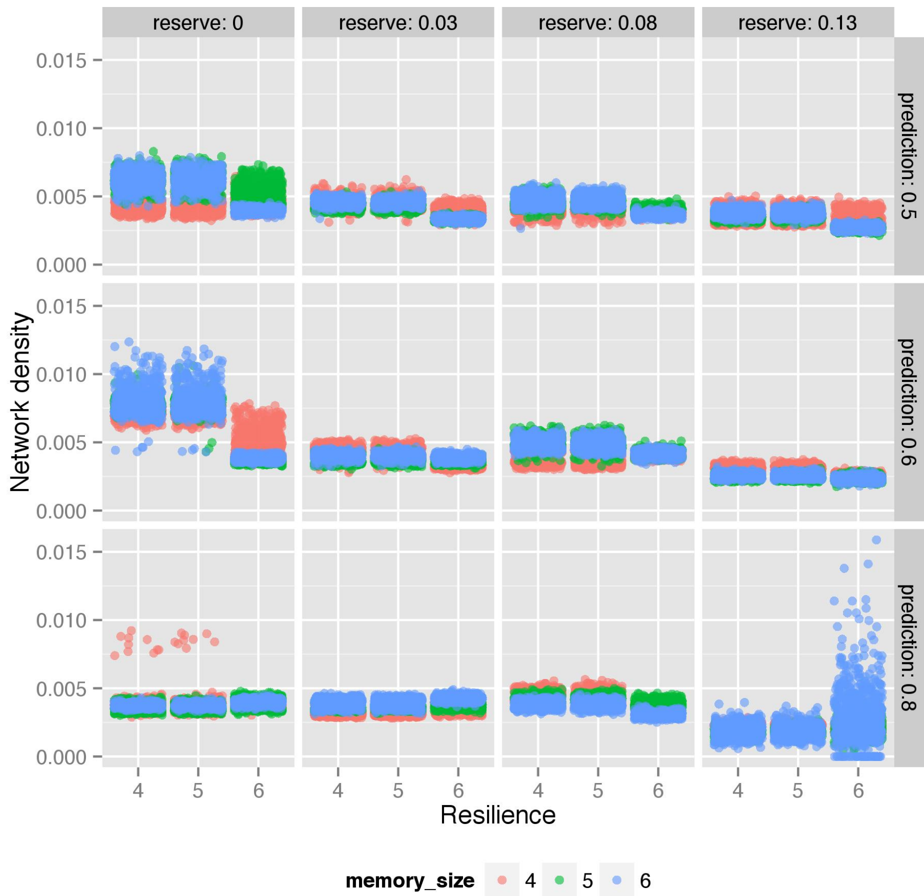


Figure 5.20: DN when maximum angry people reached

These results could give the reader a wrong impression if no other measure of connectivity had been obtained. Fortunately, I am aware that the low density does not mean a low potential for conflict, but that there are many components, some of them very tightly connected that could make and escalate conflict. Figure 5.21 is a sample network at a season of maximum angry people, showing how unmanageable this situation can become.

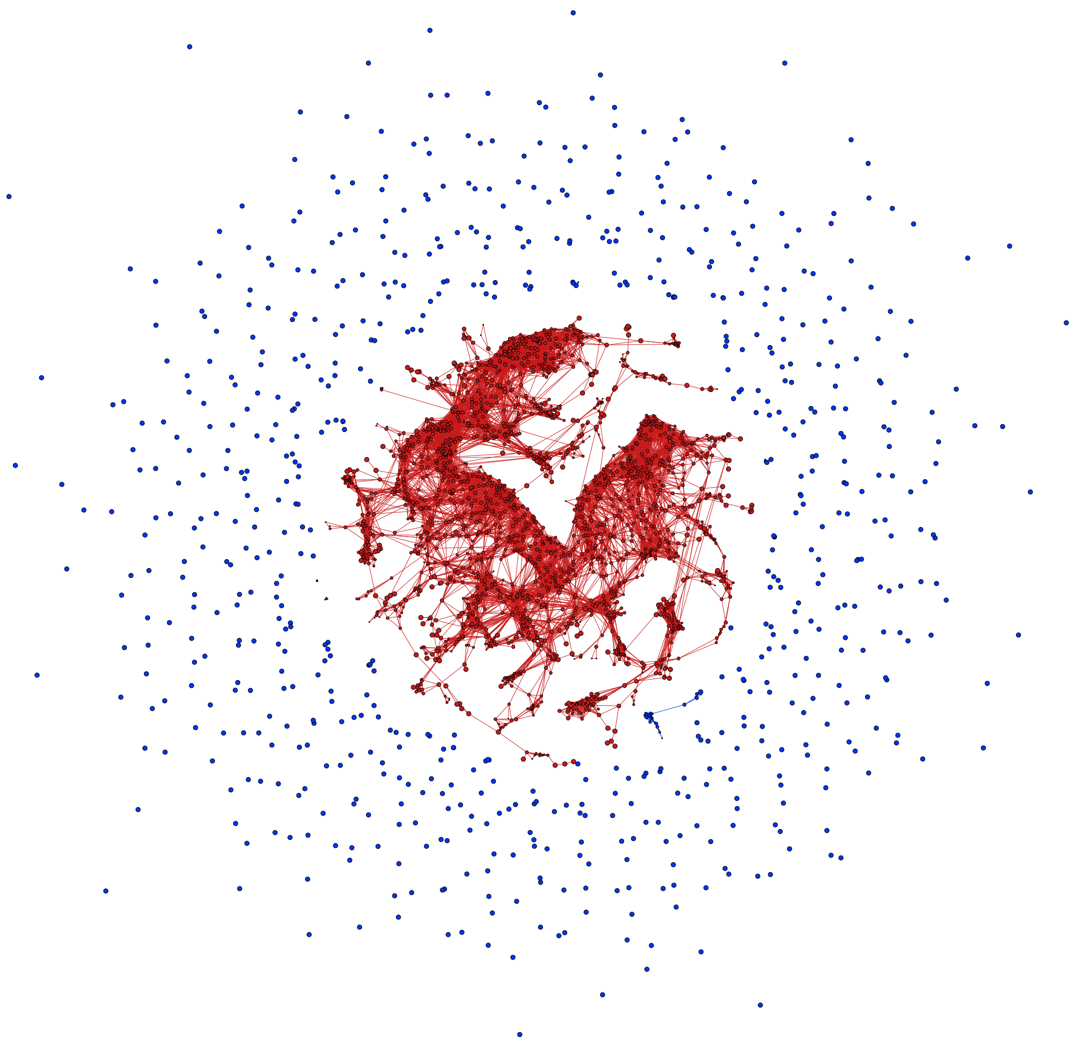


Figure 5.21: Network of frustrated people. This is a network during the season when the maximum number of angry people was reached. It shows isolates and connected networks. This network has an average clustering coefficient= 0.3635 with 705 connected components and a density = 0.007.

Chapter 6: Discussion

Social issues in polities are solved by the political institutions. As there are no easy ways to answer to everybody's demands regarding particular issues, policies are political instruments that explicitly state the organization of the polity, what is allowed, and what is forbidden. A basic diagram prepared by Cioffi using Unified Modeling Language [34] can help summarize the entities and relationships involved (see Figure 6.1).

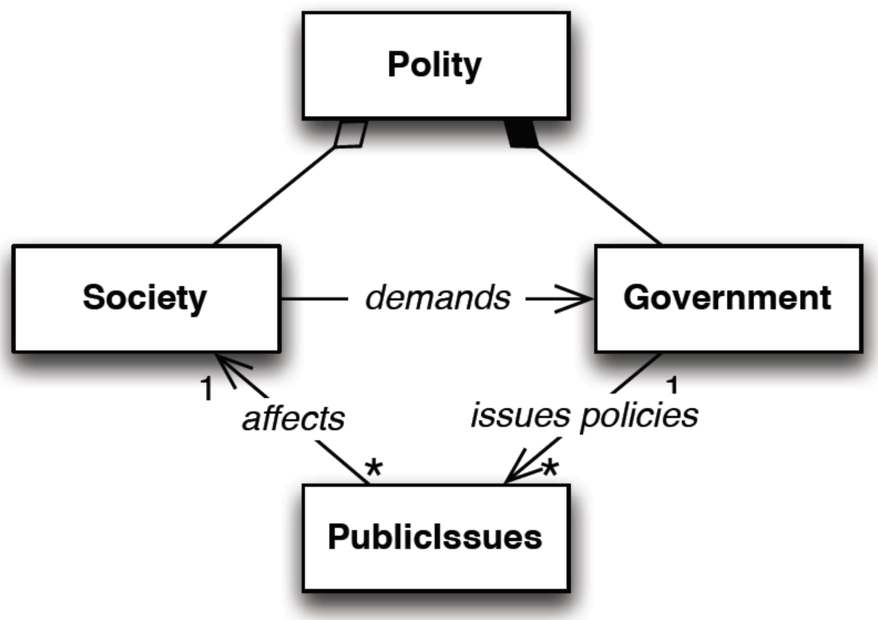


Figure 6.1: Standard model of a polity in political science
Source: [34]

In this work, I present a future situation that requires action in the present in order to prevent the potential for drastic migration and conflict in Huancayo. The agent-based model prepared can now serve for comparisson purposes to other similar models. In my case, this work has particular value as it has been the result of my close collaboration to the *Mason-Smithsonian Joint Project on Climate and Society*, from where I improved my know-how in modeling and interdisciplinary work. However, beyond the computational offered to policy makers in this work, there are some final considerations worth mentioning next.

6.1 Challenges to anticipatory policy-making

The natural barrier to anticipation in a reactive mindset, which is very common in policy making [116]. For sure, one can not blame decision makers for being reactive as generally the political institutions are a set of rules that have been conceived based on what is known. There may be many examples of catastrophes that could have been avoided if the right anticipatory measure had been taken previously, but it is also true that the legal systems generally lack means to make decision makers liable for their lack of planing. Only electoral means are a way to express the general discontent for their lack of proactiveness. However, electing a new or better political leader does not undo the damage and suffering of the affected people.

A reactive system of policies is not completely bad, and could even be considered an efficient way of spending public moneys. However, when combined with other factors, the whole situation can become catastrophic. A first negative factor can be extremely centralized systems or weakly decentralized. A centralized system will react only after every institution beneath has considered that there is a need for anticipation, and a weakly centralized system gives the local institutions the illusion of decision making, when in reality there is a regulation that will force the local authority to deal with the central one. The Shullcas river and the Huaytapallana glacier are clearly affected by this situation. As learned in this work, this watershed "belongs" to two districts, but the water company affects three. Any local action in the area will require a mutual agreement that has not been achievable since the discussion on the Huaytapallana glacier melting started ten years ago [117]. The responsibility of the districts related to the river and the glacier is limited, but they are indeed the direct responsible for the granting of housing and business licenses, which are related to peri-urbanization, and an indirect factor that may contribute to conflict. Besides, these districts (including all the urban and rural areas studied here) belong to the Huancayo Province where the urban and transportation policy is approved and executed. The Province is part of the Junin Region, where the social and development policies are planned, executed and funded. Up to this point, it might seem that the problem can be solved within the regional political boundaries, but all of these instances still need to agree on what to do based on some constraints that the central government imposes.

The central government resides in Lima. There, the Ministries for every sector of the executive government impose a series of constraints, beyond basic coordination, to any action taken in the state. The Ministry of Economy has to approve any movement of money that any state organization wants to spend (which some times is a routine process, but other times requires months of preparation and bargaining as the amount to be spend increases). The Ministry of Energy and Mining has to decide when to give permission to mining or energy activities, which due their nature are located in the Andes of Peru (it is worth noticing that no local authority has any power related to this kind of licenses)[1]. Other Ministries such as Education, Health or Labor have competences at every level of government despite the local governments have their own Offices to deal with those subjects, which are currently limited to promotional activities. Finally, the Ministry of Agriculture (MAG) and the Ministry of Environment (MENV) deserve especial attention. The MENV is a new institution (less than a decade old), particularly in charge of climate change, water and land management issues. The MAG, from where most of the environmental functions where transferred to the MENV, is supposed to deal with the productivity or economical dimension of the land in Peru. However, as soon as some functions left the MAG, some new similar functions were born in MAG again, particularly climate change, water and land management. So now there are climate change initiatives in both sides. Not surprisingly, there are also commissions that exist in the Prime Minister Office related to the climate

[1]It is very surprising to see how this Ministry is part of the climate change committee, and realize that since 2006 its has given permission to 43 mining companies to explore near Huaytapallana (`http://www.larepublica.pe/22-03-2011/nevado-de-huaytapallana-en-peligro`. The exploration continues, even though the Regional government has declared Huaytapallana a *protected zone* since 2011).

change issue.

Another negative accompaniment to reactive policy-making is symbolic and superficial proactiveness. Particularly when dealing with this climate change issue, programs and organizations are created, technical documents are produced, presentations and dinners are offered, but at the end there are no real measures. The production of information and regulation on climate change is abundant in Peru, as detailed below:

- The Geophysical Institute of Peru (IGP), part of the MENV, has 73 publications in its website[2].

- The National Service of Meteorology and Hydrology (SENAMHI), part of the MENV, has at least 60 publications in its website[3].

- The Office of Environment Assessment (OEFA), part of the MENV, has at least 16 publications in its website[4].

- The Climate Change Portal of the Office of Climate Change, Deserts and Hydrological Resources (DGCCDRH), part of MENV, has around 80 publications in its website [5].

- The Agrorural project[6], part of the MAG, has around 200 publications.

Using simple word cloud for the documents from IGP (see Figure 6.2)[7], one can see that the Mantaro basin is of real interest to these institutions.

However, I believe that symbolic and superficial proactiveness is present. For instance, the *Second Communication on Climate Change to the United Nations* [118], an official report produced jointly by all of the institutions related to this issue to report the adaptive strategies being carried out. Sadly, the strategies occupy just five pages in the 204-page report,

[2] http://www.igp.gob.pe
[3] http://www.senamhi.gob.pe
[4] http://www.oefa.gob.pe/publicaciones
[5] http://cambioclimatico.minam.gob.pe/category/publicaciones/
[6] http://www.agrorural.gob.pe/
[7] I use the application from wordle: http://www.wordle.net/

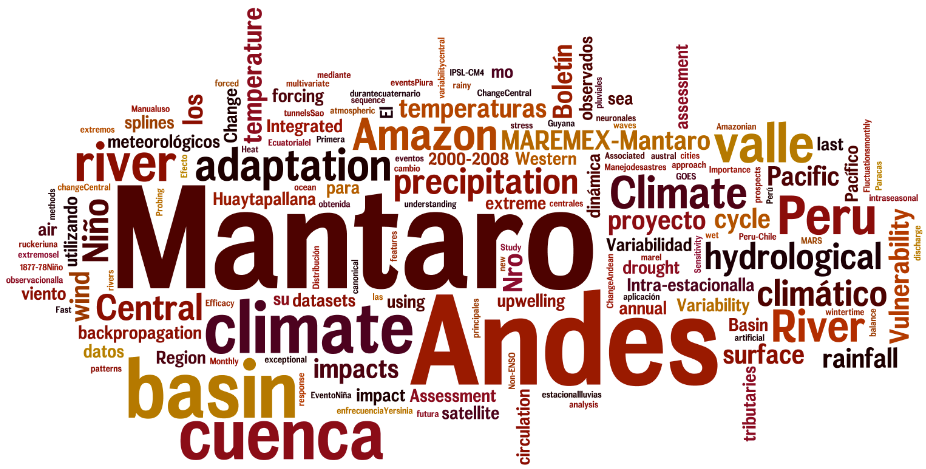


Figure 6.2: Word count of publications on climate change by IGP

Similarly to that report, the IGP [119] published a whole document about adaptation to climate change in the region of our concern, where only 5 pages out of 106 are dedicated to propose adaptive measures (pp. 86-90). Other salient cases are reports that are produce by different institutions about the same problem but sharing most of the contents [46, 47].

The level of economic development is also a key factor in understanding the ability to cope with water shortages, as more developed countries have more technological and financial resources to deal with drastic environment issues, while poorer regions, countries, or localities have meager funds and often suffer through political instability that constrains implementation of effective and long-lasting policies. However, economic development has not stopped advance economies like the USA to be reactive in many cases in many different issues like the Challenger accident, the 9/11 terrorist attack, Katrina hurricane, and so on (for more cases see [120]). Peru is not a developed country, but as an emerging economy, the central government is constantly looking for foreign international investment, which has come to Peru with oil and mining companies, bringing along conflict between local communities and central governments, as I presented in Figure 3.20 on page 72.

Poor leadership affects enormously a reactive system of policies. A poor leader plays safe, and tends to leave difficult situations to *experts*, framing complex issues as *technical*. As explained by Heifetz and Linsky [121], once leaders frame a complex problem as technical instead of complex-adaptive, the political system just does "routine management" instead of "change management". This explains that the reports on the watershed appeared around 2010, and all of them were very technical. Since then, no more knowledge on this area has been produced from the government.

6.2 Beyond the model

What should be improved in the model?

Every model needs assumptions and facts. Those facts can be qualitative or quantitative. This agent based model has dealt very well with facts and assumptions. However, the most urgent areas of improvement are:

- Have a better sub-model of what an agent could do when it predicts water scarcity is serious. In my model, the agent looks for another sources of water, and when the agent finds a better place to live, it abandons its home and moves to another place within Huancayo. Agents keep doing that until their desire to stay in the system is surpassed. However, I need in the future to find a way to get information on neighborhoods and their economic capacity, to implement an algorithm considering that information. That data does not exist yet. An significant investment would be needed to produce that data.

- This model assumes the main destinations for the emigrants from Huancayo are Lima and the Jungle, but Lima in fact represents "big cities in the coast" and the Jungle represent "good places to go if you are a risk taker and your are not planing to bring your family". Although the interviewees mentioned these two places, it would be important to expand the model and see how the new arrivals are received and what new issues arise in those destinations. The answers also mentioned "foreign countries", but that destination was not included (but "Lima" could represent it).

- It would be important to consider more strategies for the agents according to their economic capacity. The economic capacity is unknown at agent level, so further work on this should be done. It is also important to conduct a more detailed analysis on water regulation by the government to get the agents to reduce consumption. Since Peru is a country where no political authority wants to alter the price of water (water is very cheap in Peru), a different regulation mechanism should be thought following a participatory approach.

- A different programming platform could be important to consider. At this point, I have reached the capacity of NetLogo but if this model becomes more computing-intensive, there is clear need to migrate the model into Mason, Repast or Gamma. In fact, the code is ready to use real maps, and see the simulation in a more realistic setting, but those other ABM platforms are needed to make the conversion useful.

What measures should be taken?

Before this model, policy makers and stakeholders involved in the future of Huancayo had no way to make basic sense of the different information available on the Shullcas river, the Huaytapallana glacier, the land use change, the immigration into the city and the positive population growth. This model represents the first basic interdisciplinary approximation to the problem, and it is hardly likely there will be there another one to integrate the knowledge available any time soon. Now they have a movie of the next 50 years of water balance in Huancayo assuming the current hydrological and demographic conditions hold. The first impression from every international researcher knowledgeable of the situation, is that the model looks a little conservative, as they suspect the scenario could be worse than presented as the glacier retreats. The consensus is that more data or investment will not move the model output into a more optimistic scenario.

However, this model, despite the real data that has been used to feed it, is still more a political tool than a engineering one. Its purpose is to show potential futures and not clear forecasts of counts and seasons, but a clear picture of what might happen and what to do to avoid it or gain time. My ultimate goal is to raise enough awareness to trigger real political action. With that in mind, there are some recommendation on the next steps policy makers should follow:

- *Make sure people in rural area have enough rights and mechanisms to keep their lands in good condition.* The tendency of immigration may not diminish in the short run and rural people have no intention to leave Huancayo. To avoid relative deprivation, policy makers from the central government need to assist rural populations in adapting their farming practices. Regional planers need to determine buffers that separate urban from rural area as well as assure minimal literacy conditions. And local governments need to stop giving building permits in the buffer area. The local University may also contribute to raising competitiveness of the local production.

- *Create mechanisms to ensure political participation of rural people.* Rural people are politically under represented. They only have local committees that regulate their internal activities in the community, but they have no real presence in the regional decision making. Local and regional governments should make sure that rural people have voice in every meeting held monthly where their participation will avoid potential future problems. Policy makers have to keep in mind that the model is consistently recommending to increase the water reserve from the rainy season, which will need investment and the use of arable and/or herding land. In either case, rural communities will feel they are affected to favor exclusively the urban.

- *Improve participatory water governance.* The distribution of water between rural and urban area is currently a process that causes constant debate. From the interviews, rural people believe that the city is taking more than water than they should from the Shullcas river during the dry season and that the rural needs are relegated due to the pressure of the urban majority. Water management has many actors involved, including two Ministries from the central government (Agriculture and Environment), but the technical criteria adopted so far is biased toward the needs of the urban area.

- *Create and save the institutional memory.* This model has been done in the USA, but very distant from the modeling conditions in Peru. Developed countries have long understand the importance of collecting, organizing and sharing data for the research community to engage research problems and offer different solutions, or more importantly, to keep a memory of the events a community has experienced and help their local analysts do their job. Peru is the opposite. There is not a system to organize the information at any level in the country for this kind of research. The general rule at central government is that the data belongs to the officer that prepares it, and if that person is moved to another position, the data disappears. Of course, it remains on some hard disk or server protected by the IT department. But the IT department is never authorized to share that data again, or if it were, they will not prepare a query to get the data needed. At the local level, things are more dramatic. Mayors in every District and province, and Presidents of the Regions are politically elected by their respective communities, and once in office, they have complete power to change the whole staff, and in fact it is what they do. As there are no policies enforcing the custody of the information collected and organized by the previous administration, every 4 years, most of the institutional memory is erased. For sure they save the local taxes information, but the rest is not considered important, until there is a time when some data is needed. If funds are available, they will hire a consultant to get the data needed. This work has experienced this problem closely, but I successfully managed to connect the right dots and get the information needed. however it is updated up to 2011 and no further updates are available.

- *Do not hide the crisis, but show a plan.* The dramatic situation has to be shared with the population, but in a message that shows the local governments have a plan that needs urban people to alter their inefficient use of water, or to learn routines that avoid unnecessary use of water. If the water demand decreases in the long run, make sure this process gets as slow as possible. For that purpose, different campaigns should be promoted at elementary and high school level to be more efficient using water in the future generations of *Huancainos*; organize contests at college level to promote local inventions; and organize neighborhood contests to demonstrate how to achieve efficient practices in the use of water.

- *Seek collaboration from civil society, especially research institutions.* The highlands of Peru have been always scenarios for non governmental organizations (NGOs) to operate. Ideally, NGOs detect social problems and work with the community to empower their actors, but this time the challenge is different. It deals with the resilience and adaptive capacity of people facing high uncertainty of the future environmental conditions and the reactions their neighbors themselves will have in those critical moments. In this situation, the production of more knowledge is needed as well as interdisciplinary debate. The government has serious limitations on hiring people permanently, but the local public university (Universidad Nacional del Centro) is the forgotten partner that could make all the difference. The local university has enough resources to fund important programs that can keep updating the knowledge base on the social and natural situation for more informed policy- making and modeling, and which should create mechanisms for a two-way knowledge transfer, that is, sharing scientific knowledge and collecting traditional knowledge. It is also a must finding mechanisms to institutionalize the research interests that different institutions (the ones where the people that collaborated with me belong) interested in this area have, via the local university.

- *Be careful of easy solutions.* This work has suggested many times the saving of water. This is a decision that needs to be very well planned. To start, a huge reservoir for the area seems to be a good solution, but decision makers have to be aware of the Huaytapallana failure. This failure can cause any time a huge earthquake, and a huge reservoir represents a great potential for disaster. The saving of water will need a lot of work from the political class and the people themselves. From the top down, the infrastructure to save or become more efficient should be built; and the urban and rural settlers have the responsibility to be more efficient using water. Another important way to secure water will be a better management of the ground water, which currently is used without detailed knowledge of its quantity nor quality, and without any recharging policy.

I created a conservative model not only because no one likes bad news, but especially because I consider that hope in difficult conditions can trigger creativity and accountability. This is a time for political leadership and to demonstrate that the future is yet to built, and if it is so, the current and next generation of Huancainos will build it well. I hope that the model serves to show a future that will never happen.

Chapter 7: Summary

This work has shown that migration and social conflict are possible in Huancayo. To study that eventuality, an agent based model was built and tested, achieving not only the confirmation of this hypothesis, but also rich information for decision making.

To accomplish both achievements, this work has collected the available information on water balance and population growth trends and has extended these trends 50 years into the future. The water balance has been computed for the year 2011, which was possible due to the data produced by different official institutions that were involved during those years in the PRAA project (see section 3.3 on page 61). As this was the first time the water balance has been computed for this area, I made use of additional information to build reliable trends for both the water balance and the population growth.

For water supply and demand, the data collected by Carlos and Grijalva [36] was used. Their data computed yearly water balance since 1995. With that information, I computed the slope of the trend for water supply (see 3.7 on page 64). In their work, Carlos and Grijalva also computed the parameters of water demand per capita, which was used in the model to gradually increase water demand as population keeps growing (see section 3.3 on page 61).

The yearly population growth of the area has been computed using the official census data (see Table 3.1 on page 57). The specific value chosen for population growth used in the model has been the lowest value shown in that table to be conservative.

An important issue in this work was understanding the local glacier's melting and its effect in the water supply. For that, I used the data from Lopez at al. [37]. The data from that work clearly shows a decreasing trend in the area of Huaytapallana glacier (see Figure 3.9 on page 48). With this value, the glacier area represented in my model disappears after the period projected in that work [37]. The model from Lopez et al. [37] does not address the impact in water supply, but fortunately, Prof. Bryan Mark supplied it [78] from his recent measurements in the area during the first months of 2015.

The simulation produced the following results:

1. The Huaytapallana glacier melted, affecting the water supply during the dry season. The variability of its contribution was between 15% and 20% of the total water supply, but none of these values had significant impact in the migration and social conflict output obtained.

2. With the population continuing to following the official rate, the population demand met and surpassed the water supply, causing the appearance of serious periods of scarcity.

3. The reactions of people (simulated as agents in the model) when facing water scarcity was modeled following some official information (demographic data), interviews and participant-observation studies, as well as theoretical frameworks. Based on simulations with that information, there were particular moments when migration reached extreme values and conflict became a possibility.

4. The destinations of the migrants were Lima and the jungle, and people were assigned to migrate to those places based on their competences, the most competent were assumed to go to Lima, and the rest to the jungle.

5. According to the model, people that were ready for migrating, but did not in the simulation, remained in place and became frustrated.

6. Frustrated agents were given the option to connect with other frustrated agents. This emergent network was monitored during the simulation, and revealed that the composition of this network represented a serious threat to the actual peace in the area.

7. The relative deprivation that could be felt in the rural area was also considered as a proxy for the emergence of conflict. This situation was present whenever a rural

agent in poor condition found a richer urban neighbor who was also a recent incoming immigrant (non-Huanca).

8. Finally, the most important variable that could reduce the potential for conflict and migration was found to be the amount of water that could be saved during the rainy season. The model showed that to avoid issues, a minimum of 13% should be saved.

This work was also presented to the Regional authorities in Huancayo on July 17, 2015; in the presence of the political decision makers, the community, the faculty from the local universities, the specialists on these issues in the region, and some news reporters. The model was praised for its simplicity, usefulness and for having integrated several different knowledge sources into a platform that facilitates the participation of stakeholders regardless of their expertise. The final decision, after the presentation, was that this model would be the basis for the strategic planing on this issue and the President of the Region asked the Director of Environmental Management of the Junin Region to start the coordination with me to find mechanism of mutual cooperation.

Appendix A: Appendixes

A.1 ODD Tables for State Variables and Scales

Table A.1: Variables for all agents

Variable	Definition	Reference
college?	Boolean. Agent has college degree?	[45]
married?	Boolean. Is agent married?	[45]
working?	Boolean. Is agent employed?	[45]
setDemography?	Boolean. Has agent set its demographical information?	depends on *college?, married?, working?*
activeMemory?	Boolean. Can agent start recording in memory?	depends on *drySeason?*
nonHuanca?	Boolean. Is agent non-Huanca?	[45]

Table A.2: Variables for rural agents

Variable	Definition	Reference
relativeDeprived?	Boolean. Neighbors turned this true/false	[92]
myInSatisfaction	Integer. Seasons without water	depends on whether home has water or not
origin	Categorical. Saves the origin "breed" of rural agent when it turns urban when moving to city	depends on *myInsatisfaction*

Table A.3: Variables for urban agents

Variable	Definition	Reference
alpha	Integer. Alpha parameter for beta distribution to compute estimated scarcity following Bayesian approach	[103]
beta	Integer. Beta parameter parameter for beta distribution to compute estimated scarcity following Bayesian approach	[103]
history	List. Registers if water was available (1) or not (0) at home	author
estimated-scarcity	Real [0,1].The estimated water scarcity at home	[103]
resilience	Integer. The maximum times the agent moves before considering migration.	Fieldwork
angry?	Boolean. Indicates that an agent has exhausted its resilience but could not migrate.	depends on *migrate?*
migrate?	Boolean. Indicates if the agent has migrated (1) or not (0)	depends on *resilience-level* and **uniform random process**
moving-counter	Integer. An internal counter that informs how many times the agent is moving trying to find a better place.	depends on simulation *clock*

Table A.4: Variables for patches

Variable	Definition	Reference
region	Categorical. Informs the region where the patch is located, it can be rural, urban, glacier, Lima or jungle	depends on initialization parameters and [45]
water?	Boolean. Informs if the patch has water scarcity.	depends on *urbanWaterBalance, ruralWaterBalance*
newRural?	Boolean. It is a variable in rural area, to show visually how the glacier disappears	depends on *retreat?*
retreat?	Boolean. It informs when a patch in glacier region is dried now.	depends on *MELTING-SPEED*
scarcityLevel	Categorical. It creates zones of scarcity, that is water will start being scarce from the worst zone.	[36, 40, 42]
originalColor	Categorical. It saves the color of the patch to recolor it when there is water again during rainy season	author
permit?	Boolean. Patch able for urban housing	[40, 42]
CounterOfWater-Issues	Counter per patch	author

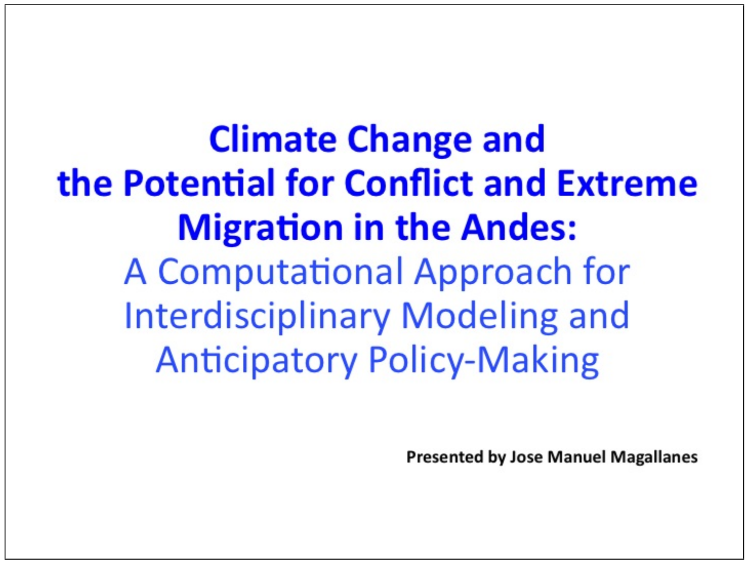
Table A.5: Natural system variables

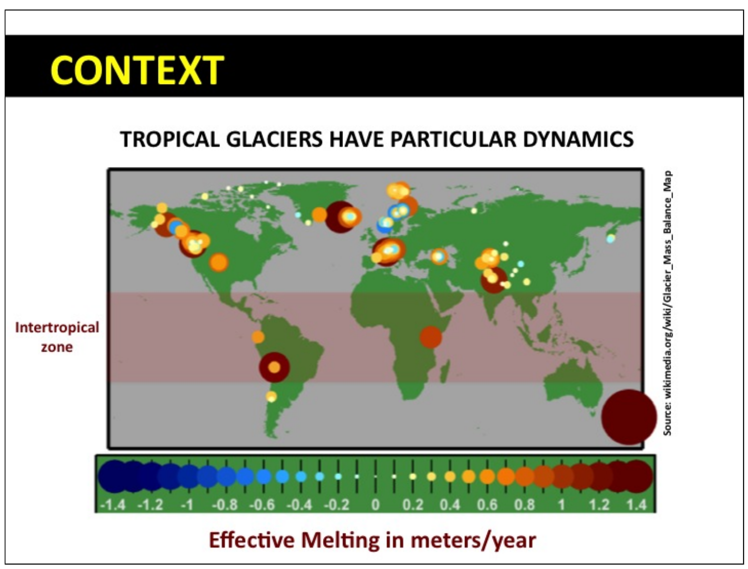
Variable	Definition	Reference
drySeason?	Boolean. To know if schedule is in dry season or not. One tick one season. Two ticks one year.	author
FirstNegative BalanceUrban	Integer. It stores the moment water balance was negative	Depends on water demand
yearly-Water OferedUrban	Real (cubic meters). Water supplied for urban area (without inefficiencies)	[46] and [36]
yearly-Water OferedRural	Real (cubic meters). Water supplied for rural area (without inefficiencies)	[46] and [36]
yearly-Water DemandUrban	Real (cubic meters). Water demand in urban area (without inefficiencies)	[46]
yearly-Water DemandRural-notFarming	Real (cubic meters). Water demand in rural area (for domestic use)	[46]
yearly-Water DemandRural-farming	Real (cubic meters). Water demand in rural area (for farming use)	[46]
seasonalWater DemandPerRural	Real (cubic meters). Recomputed yearly demand for rurals (Non farming needs)	Depends on *ruralpopulation, yearly-waterdemand rural-notfarming*
seasonalWater DemandPerUrban	Real (cubic meters). Recomputed yearly demand for urbanites (Non farming needs)	Depends on *urbanpopulation, yearly-waterdemandurban*
seasonalWater OfferPerRural-in Patch	Real (cubic meters). Recomputed yearly supply for rurals (Non farming needs)	Depends on *dryseason? Ruralpopulation, yearly-wateroffereddrural*
seasonalWater OfferPerUrban-inPatch	Real (cubic meters). Recomputed yearly supply for urbanites (Non farming needs)	Depends on *dryseason? Urbanpopulation, yearly-wateroffereddurban*
noGlacier?	Boolean that informs glacier disappeared	author
glacierArea	Real. Current glacier area.	[37]
glacierArea ABM	Integer. Number of patches in the simulation that represents the glacier area.	[37] and *glacierArea*
patchesMelting Abm	Integer. Number of patches that melt while glacier retreats.	depends on *glacierArea ABM* and *MELTING-SPEED*
MELTING-SPEED	Real. Coefficient from the model by lopez et al.	[37]
urbanWater Balance	Real (cubic meters). Urban water balance needed to decide if some urban patches should dry	Real (cubic meters). Depends on water supply and water demand
ruralWater Balance	Real (cubic meters). Rural water balance needed to decide if some urban patches should dry	Depends on water supply and water demand
resilience-level	Integer. Resilience level for all agents	fieldwork
glacier-effect	Real [0,1]. Effect in water supply when glacier retreats completely	[78]
drySeasonShare	Real [0,1].Percent of the total water supply available during dry season	[46]
Water-Loss	Real [0,1]. Coefficient used to diminish water in the system yearly	[36]

Table A.6: Social system variables

Variable	Definition	Reference
conflict-mass	Integer. Urbanites that are angry (not necessarily connected)	Depends on *angry?*
maxmass	Integer. Max amount of total angry people	Depends on *angry?* and *conflict-mass*
density-AngryNetworkUrban	Real [0,1]. Density of angry network	[108]
maxdensity-moment	Integer. Moment when max density was reached	[108]
maxdensity	Real [0,1]. Max value of density reached	[108]
maxdensityMass-moment	Integer. Max value of density reached when maxmass was reached	[108]
maxdensityMass	Integer. Value of density reached when maxmass was reached	[108]
moment-migrate-Urban	Integer. Detect moment migration started	Depends on **clock** and *movedToLima* or *movedToJungle*
moment-conflict-Rural	Integer. Detect moment first rural felt frustrated or relative deprived	[94]
maxMeanCC	Real [0,1]. Max average clustering coefficient	[108]
timemaxMeanCC	Moment when max average clustering coefficient	[108]
urbanPopulation	Integer. Population of urbanites	[45]
ruralPopulation	Integer. Rural population	[45]
Population	Integer. Total population	[45]
movedToLima	Integer. Population that moved to Lima	Depends on *migrate?*, *college?*, *working?* and *married?*
movedToJungle	Integer. Population that moved to jungle	Depends on *migrate?*, *college?*, *working?* and *married?*
movedToHyo	Integer. Population that moved to Huancayo (rurals)	Depends on *migrate?*, *college?*, *working?* and *married?*
RuralShare-PopulationGrowth	Real [0,1].Rate of rural population growth	[45]
movingDecision	Real [0,1]. Threshold that limits moving looking for water in the urban area	Fieldwork
prop-Immigrants	Real [0,1]. Percent of non Huancas in the urban area	[45] and fieldwork
populationGrowth	Real. Growth rate of the population	[45]
ALPHA-INITIAL	Integer. Initial alpha for Bayesian updating	[103]
BETA-INITIAL	Integer. Initial beta for Bayesian updating	[103]

A.2 Slides used during dissertation defense





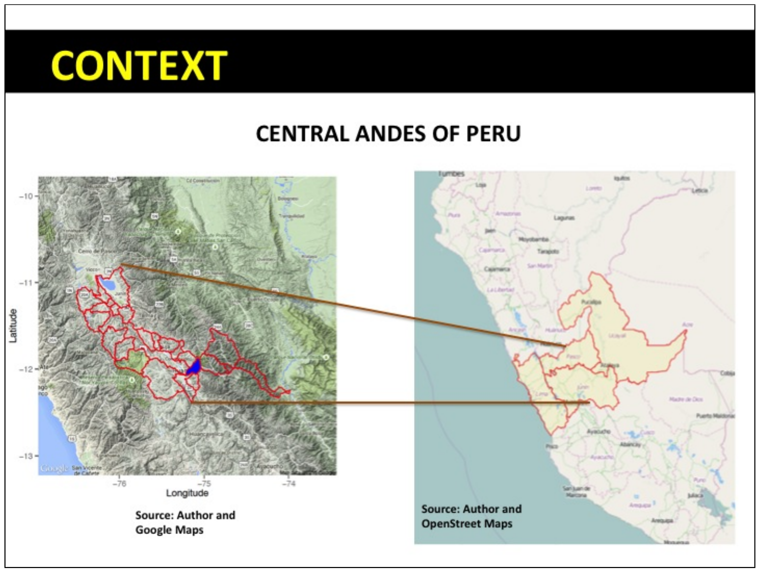
CONTEXT

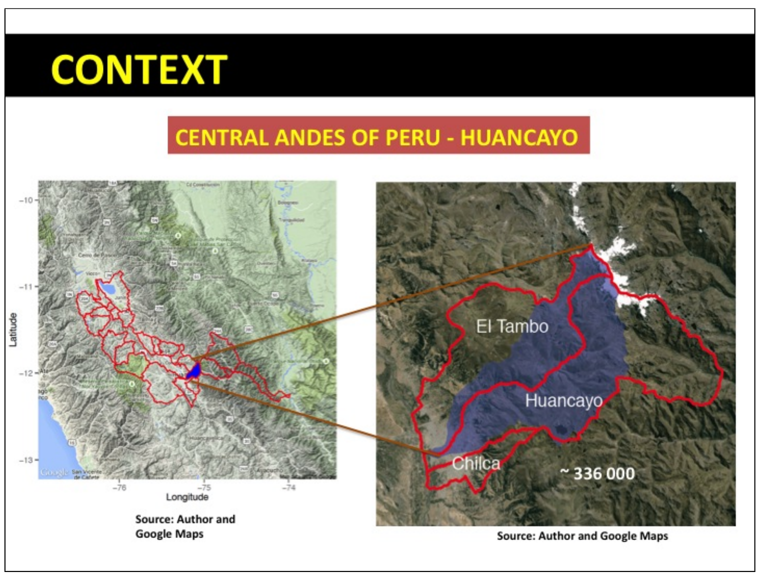
ANDEAN TROPICAL GLACIERS

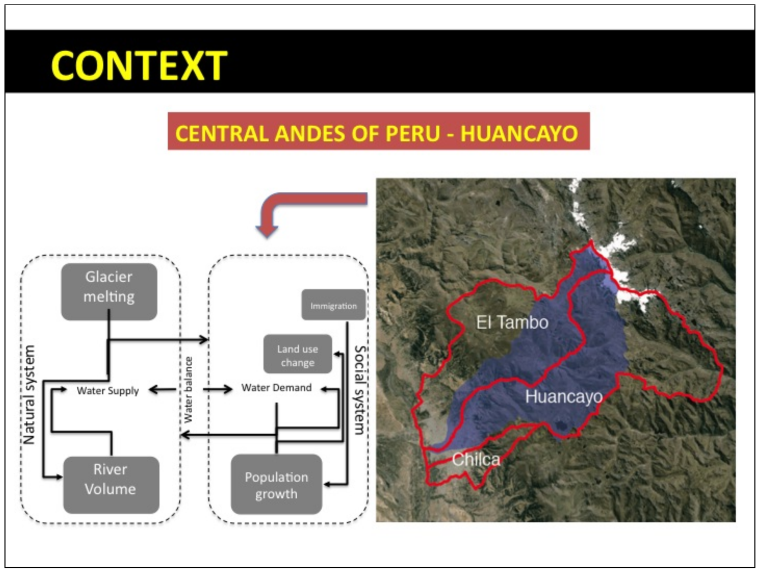
- The Andean glaciers are located in the warmest part of the world. The temperatures are warm year round, resulting in a lack of a colder winter season in which snow and ice can recover.
- The glaciers are in mountains, on average, shorter than the ones in the middle latitudes.
- They are the most likely glaciers to show rapid response to changing climate patterns. The forecasts state Kilimanjaro glaciers and remaining Oceania glaciers will disappear by 2020.
- The African and Oceania glaciers represent only the 0.36% of these tropical glaciers, and the Andes of South America represent 99.64% of tropical glaciers.
- Around 70% of Andean glaciers are in Peru.

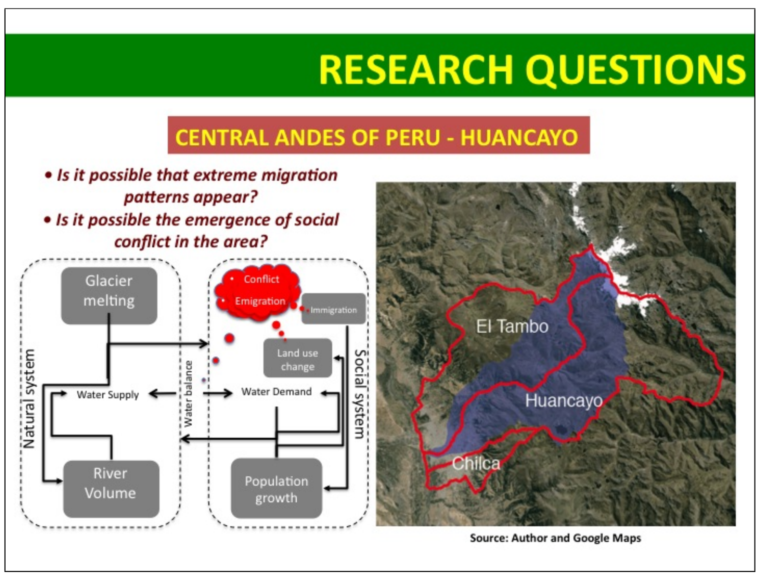
CONTEXT

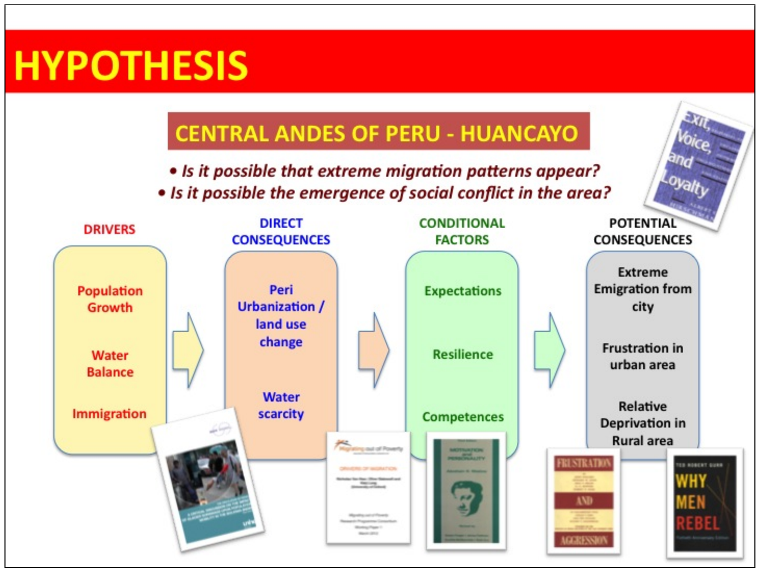
CENTRAL ANDES OF PERU

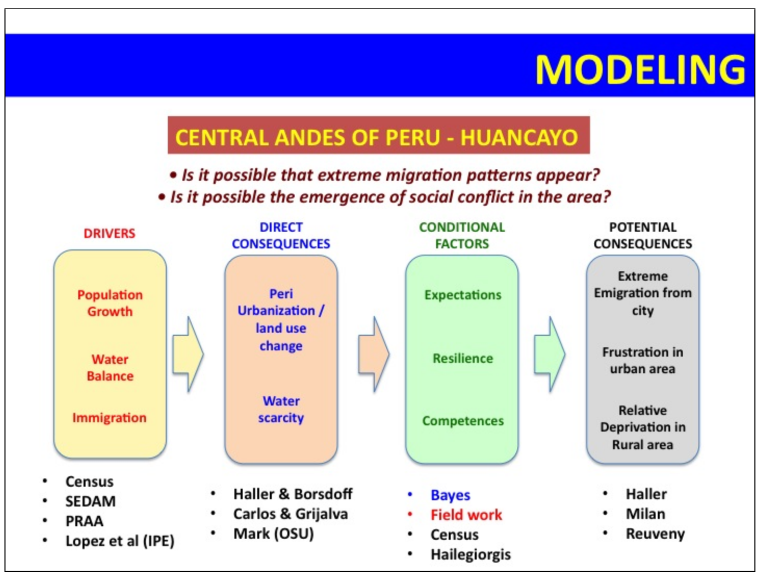

CONTEXT
CENTRAL ANDES OF PERU
Latitude
Longitude
Source: Author and
Google Maps
Source: Author and
OpenStreet Maps


CONTEXT
CENTRAL ANDES OF PERU - HUANCAYO
Latitude
Longitude
El Tambo
Huancayo
Chilca
~ 336 000
Source: Author and
Google Maps
Source: Author and Google Maps


CONTEXT
CENTRAL ANDES OF PERU - HUANCAYO
Glacier melting
River Volume
Water Supply
Natural system
Water balance
Water Demand
Immigration
Land use change
Population growth
Social system
El Tambo
Huancayo
Chilca


RESEARCH QUESTIONS
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
Glacier melting
River Volume
Water Supply
Natural system
Water balance
Conflict
Emigration
Water Demand
Immigration
Land use change
Population growth
Social system
El Tambo
Huancayo
Chilca
Source: Author and Google Maps


HYPOTHESIS
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
Exit, Voice, and Loyalty
DRIVERS
Population Growth
Water Balance
Immigration
DIRECT CONSEQUENCES
Peri Urbanization / land use change
Water scarcity
CONDITIONAL FACTORS
Expectations
Resilience
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
FRUSTRATION AND AGGRESSION
WHY MEN REBEL


MODELING
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
DRIVERS
Population Growth
Water Balance
Immigration
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Competences
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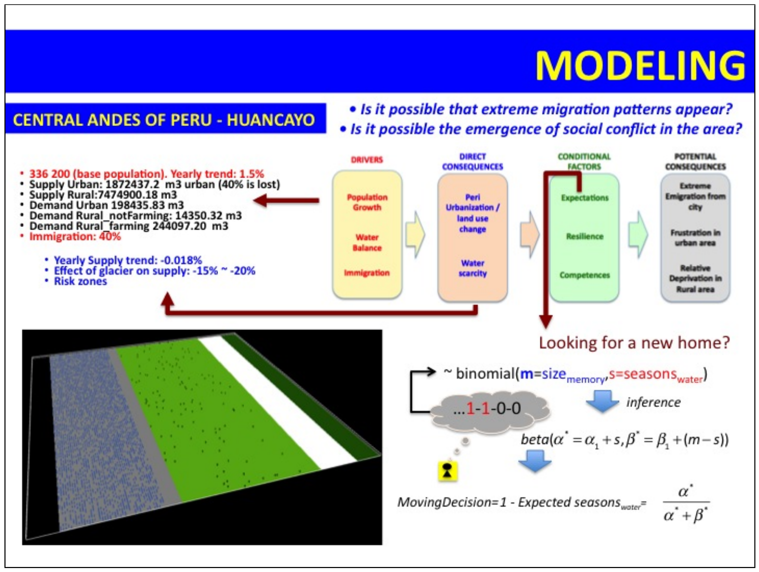
Frustration in urban area
Relative Deprivation in Rural area
• Census
• SEDAM
• PRAA
• Lopez et al (IPE)
• Haller & Borsdoff
• Carlos & Grijalva
• Mark (OSU)
• Bayes
• Field work
• Census
• Hailegiorgis
• Haller
• Milan
• Reuveny


MODELING
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
• 336 200 (base population). Yearly trend: 1.5%
• Supply Urban: 1872437.2 m3 urban (40% is lost)
• Supply Rural:7474900.18 m3
• Demand Urban 198435.83 m3
• Demand Rural_notFarming: 14350.32 m3
• Demand Rural_farming 244097.20 m3
• Immigration: 40%
• Yearly Supply trend: -0.018%
• Effect of glacier on supply: -15% ~ -20%
• Risk zones
DRIVERS
Population Growth
Water Balance
Immigration
DIRECT CONSEQUENCES
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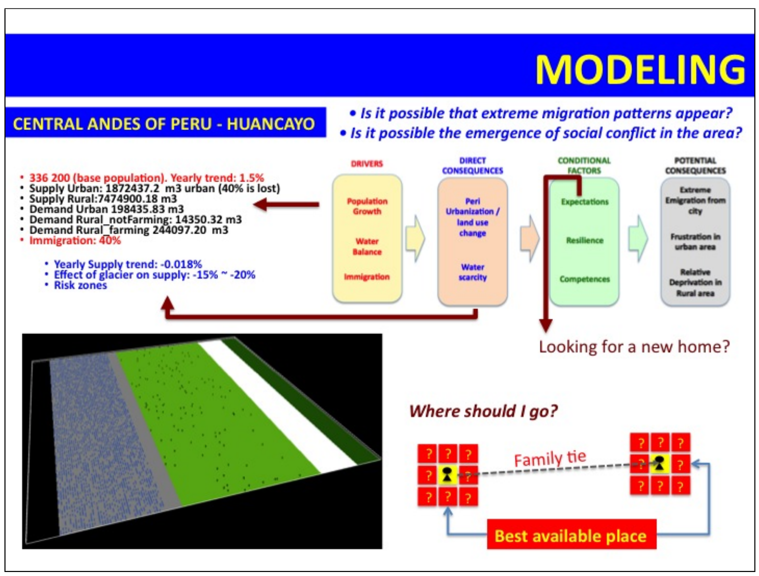
Water scarcity
CONDITIONAL FACTORS
Expectations
Resilience
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
Looking for a new home?
~ binomial(m=size$_{memory}$, s=seasons$_{water}$)
...1-1-0-0
inference
$beta(\alpha^* = \alpha_1 + s, \beta^* = \beta_1 + (m-s))$
MovingDecision=1 - Expected seasons$_{water}$= $\frac{\alpha^*}{\alpha^* + \beta^*}$


MODELING
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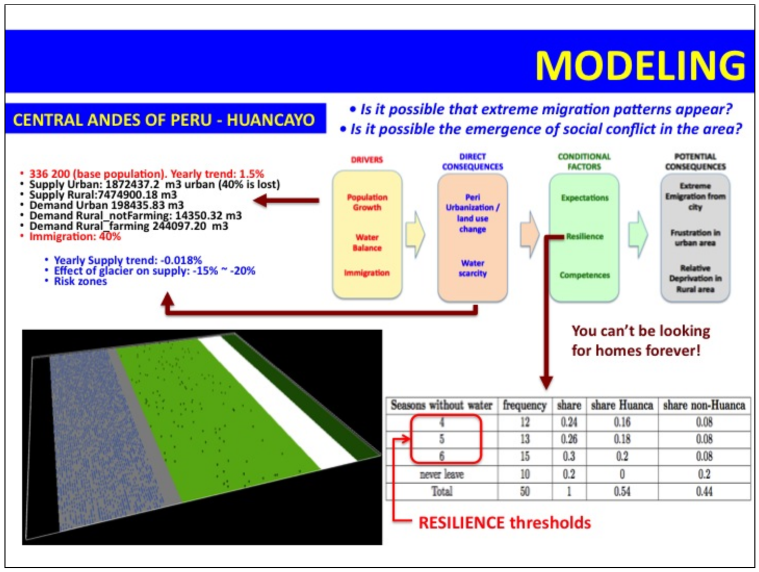
Water scarcity
CONDITIONAL FACTORS
Expectations
Resilience
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
Looking for a new home?
Where should I go?
Family tie
Best available place


MODELING
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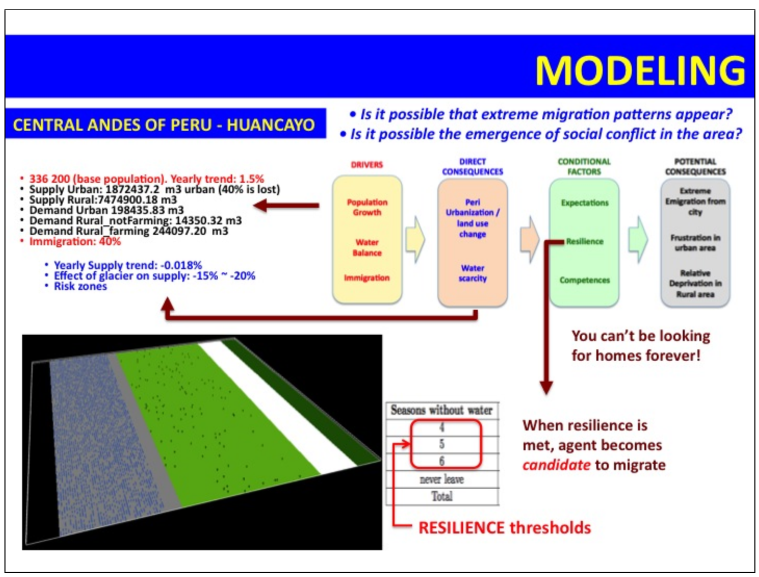
Water scarcity
CONDITIONAL FACTORS
Expectations
Resilience
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
You can't be looking for homes forever!
Seasons without water | frequency | share | share Huanca | share non-Huanca
4 | 12 | 0.24 | 0.16 | 0.08
5 | 13 | 0.26 | 0.18 | 0.08
6 | 15 | 0.3 | 0.2 | 0.08
never leave | 10 | 0.2 | 0 | 0.2
Total | 50 | 1 | 0.54 | 0.44
RESILIENCE thresholds


MODELING
CENTRAL ANDES OF PERU - HUANCAYO
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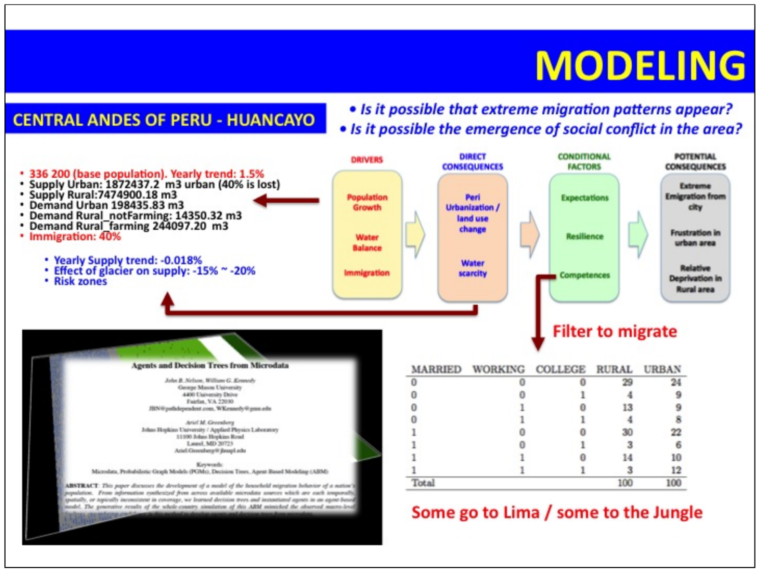
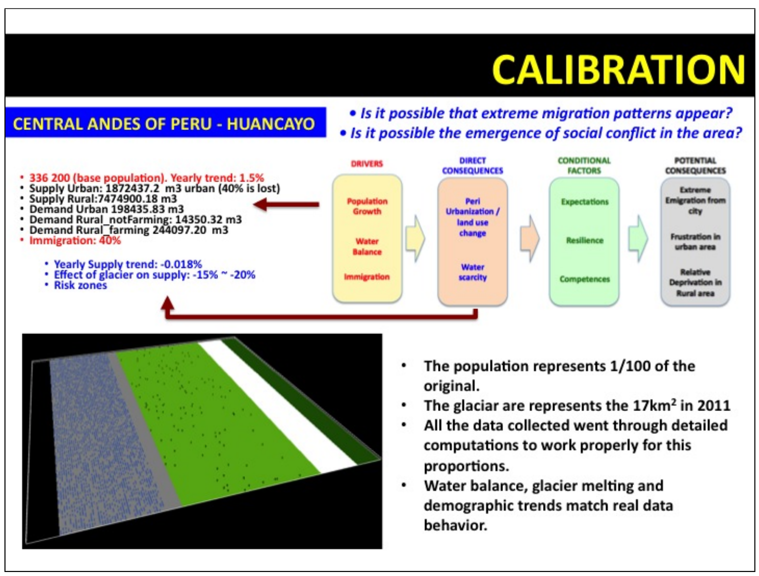
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
You can't be looking for homes forever!
Seasons without water
4
5
6
never leave
Total
When resilience is met, agent becomes candidate to migrate
RESILIENCE thresholds



MARRIED	WORKING	COLLEGE	RURAL	URBAN
0	0	0	29	24
0	0	1	4	9
0	1	0	13	9
0	1	1	4	8
1	0	0	30	22
1	0	1	3	6
1	1	0	14	10
1	1	1	3	12
Total			100	100



VERIFICATION

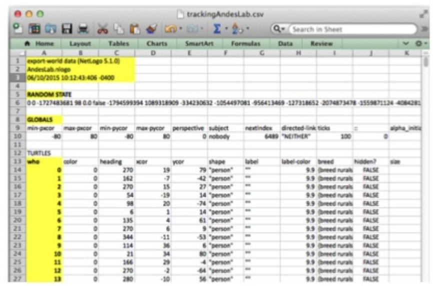
CENTRAL ANDES OF PERU - HUANCAYO

• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?

I carried out:

- Recording/tracking agent behavior
- Profiling,
- Minimal model testing, and
- Parameter sweeps and variability testing

NetLogo offers a function to save the world and the agent activity in a separate file.



I managed to detect and correct particular agent misbehavior due to coding issues, paying attention to the behavior of the attributes as seasons passed by.

VERIFICATION

CENTRAL ANDES OF PERU - HUANCAYO

• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?

I carried out:

- Recording/tracking agent behavior
- **Profiling,**
- Minimal model testing, and
- Parameter sweeps and variability testing

NetLogo offers an extension for profiling

It allowed me to verify the most and least time consuming procedures in the code. The results were as expected.

Name	Calls	InclusiveT(ms)	ExclusiveT(ms)	Exclusive/calls
CONFLICT-IN-URBAN-REGION	100	21676.10	21676.10	216.76
GO	99	54692.66	14577.05	147.24
URBANS-COMPUTE-SATISFACTION-AND-SCARCITY	50	5065.86	5065.86	101.32
URBANS-MOVE-BUT-NOT-MIGRATE	100	4086.79	4086.79	40.87
DRY-PATCHES	53	1694.46	1694.46	31.97
MIGRATION-OF-URBANS	100	851.35	1171.03	11.71
UPDATE-SEASONAL-WATER-PATCH	100	4112.20	1165.61	11.66
DRY-URBAN-PATCHES-BY-RISK-LEVEL	100	2409.43	805.46	8.05
CONFLICT-IN-RURAL-REGION	100	470.58	470.58	4.71
DRY-RURAL-PATCHES-BY-RISK-LEVEL	100	537.16	446.67	4.47
POPULATION-GROWTH	100	1437.46	433.80	4.34
UPDATE-GLACIER	100	401.97	401.97	4.02
WANNA-LIMIT-URBAN-GROWTH?	100	247.01	247.01	2.47
UPDATE-POPULATION-COUNT	50	121.13	121.13	2.42
AGENTS-DECIDE-TO-MIGRATE	100	5597.78	181.54	1.81
MIGRATION-OF-RURALS	100	158.42	158.42	1.58
FIND-NEW-SPOT-Rural	446	360.50	360.50	0.81
AGENTS-COMPUTE-SATISFACTION	100	5134.04	68.18	0.68
FIND-NEW-SPOT-Urban	2690	522.03	522.03	0.19
AGENTS-DECIDE-TO-CONFLICT	100	22148.07	1.39	0.01

VERIFICATION

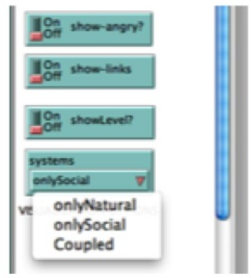
CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***

I carried out:

- Recording/tracking agent behavior
- Profiling,
- **Minimal model testing**, and
- Parameter sweeps and variability testing

Currently, the model can run only the river and glacier dynamics without the social dynamics, and viceversa. It was very useful during calibration process.



VERIFICATION

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***

I carried out:

- Recording/tracking agent behavior
- Profiling,
- Minimal model testing, and
- **Parameter sweeps and variability testing**

Lowest and extreme values gave no issues. Lowest value runs reminded me to control for division by zero

World: Base model run 100 times

CV	Statistic	Mean	St. Dev.	Min	Max
0.0096	population	3,625.35	34.78	3,551	3,732
0.0009	ruralpopulation	577.25	0.54	576	578
0.0114	urbanpopulation	3,048.10	34.79	2,974	3,156
0.0130	nonhuancaspop	2,602.35	33.72	2,532	2,673
0.0163	conflict-mass	2,443.31	39.86	2,348	2,531
1.3493	ruralcountangry	1.46	1.97	0	10
0.1000	density-angrynetworkurban	0.01	0.001	0.01	0.01
0.0000	timebyeglacier	70.00	0.00	70	70
0.0000	firstnegativebalanceurban	42.00	0.00	42	42
0.0039	urbanwaterbalance	282,146.90	1,102.38	279,828.10	284,742.90
0.0003	ruralwaterbalance	1,917,614.00	527.56	1,916,879.00	1,918,837.00

VERIFICATION

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***

I carried out:

- Recording/tracking agent behavior
- Profiling,
- Minimal model testing, and
- **Parameter sweeps and variability testing**

Conflict: Base model run 100 times

CV	Statistic	Mean	St. Dev.	Min	Max
0.01	maxmass	2,529.220	36.229	2,452	2,619
0.07	maxdensitymass	0.007	0.0005	0.006	0.008
0.05	maxmeancc	0.376	0.020	0.340	0.420
0.12	maxcomp	635.530	75.569	443	778
0.01	maxmassangrytime	94.440	0.833	94	96
0.01	maxmasspoprural	562.950	3.173	560	569
0.03	maxmasspopurban	3,331.960	91.046	3,114	3,475
0.77	moment-conflict-rural	56.340	43.222	−1	99

VERIFICATION

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***

I carried out:

- Recording/tracking agent behavior
- Profiling,
- Minimal model testing, and
- **Parameter sweeps and variability testing**

Migration: Base model run 100 times

CV	Statistic	Mean	St. Dev.	Min	Max
0.01	movedtojungle	2,599.05	35.51	2,509	2,670
0.05	movedtolima	353.11	18.76	310	414
	movedtohyo	0.00	0.00	0	0
0.02	moment-migrate-urban	53.44	0.90	52	54
0.05	maxjungle	371.80	18.61	339	425
0.11	maxlima	51.44	5.69	40	68
0.05	maxmove	420.12	20.11	376	472
0.00	maxtimemove	64.04	0.28	64	66
0.01	maxtimejungle	64.08	0.39	64	66
0.09	maxtimelima	65.28	5.74	62	94

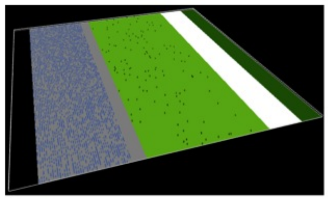
VALIDATION

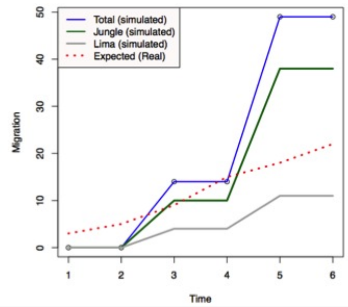
CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***

Micro-macro correspondence:

- **Migration**
- Peri-urbanization





VALIDATION

CENTRAL ANDES OF PERU - HUANCAYO

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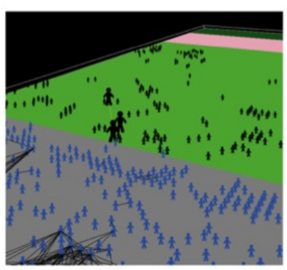
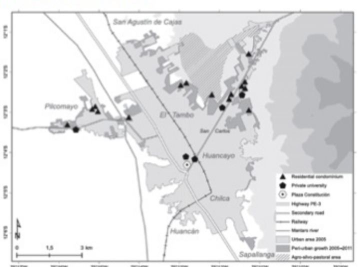
- ***Is it possible the emergence of social conflict in the area?***

Micro-macro correspondence:

- Migration
- **Peri-urbanization**





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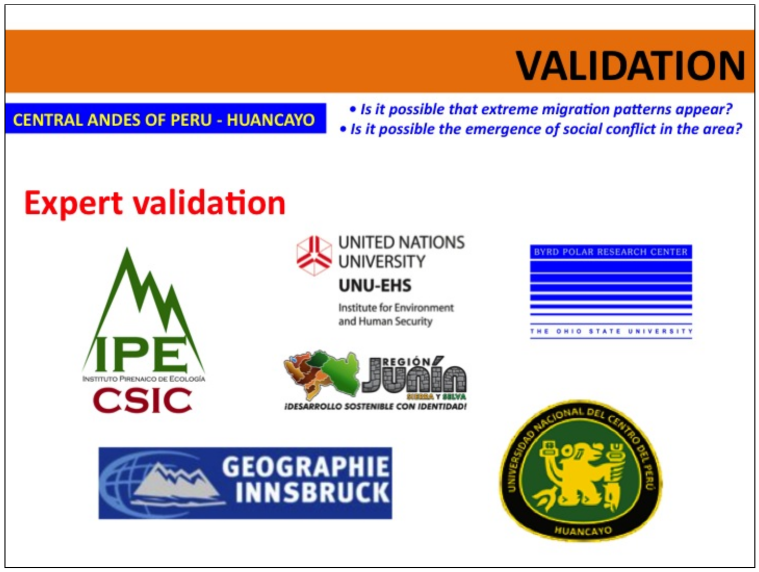
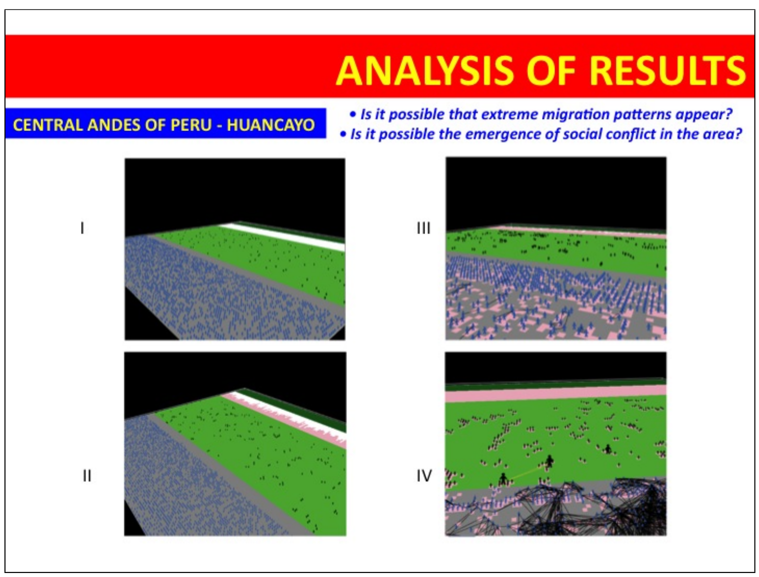

VALIDATION
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
Expert validation
IPE
INSTITUTO PIRENAICO DE ECOLOGÍA
CSIC
UNITED NATIONS UNIVERSITY
UNU-EHS
Institute for Environment and Human Security
BYRD POLAR RESEARCH CENTER
THE OHIO STATE UNIVERSITY
REGIÓN JUNÍN
SIERRA Y SELVA
¡DESARROLLO SOSTENIBLE CON IDENTIDAD!
GEOGRAPHIE INNSBRUCK
UNIVERSIDAD NACIONAL DEL CENTRO DEL PERÚ
HUANCAYO


ANALYSIS OF RESULTS
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
I
III
II
IV

ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***

Extreme emigration occurred in the model

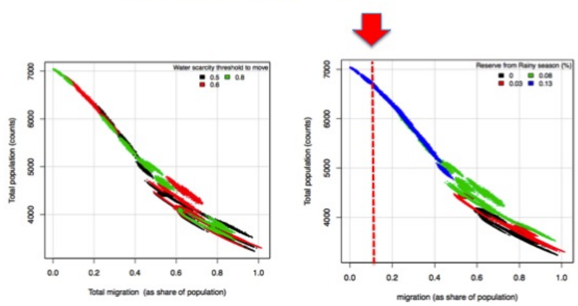
Variable	Value	Variable Name
People that moved to the Jungle	2662	movedtojungle
People that moved to Lima	356	movedtolima
Rural people that moved to urban area	0	movedtohyo
Season when Migration started	$\boxed{54}$	season-migrate-urban
Max number that emigrated in a year to the Jungle	337	maxjungle
Max number that emigrated in a year to Lima	54	maxlima
Max number that emigrated in a year	$\boxed{391}$	maxmove
Season when Max number that emigrated in a year was reached	$\boxed{64}$	maxtimemove
Season when Max number that emigrated in a year to the Jungle was reached	64	maxtimejungle
Season when Max number that emigrated in a year to Lima was reached	64	maxtimelima

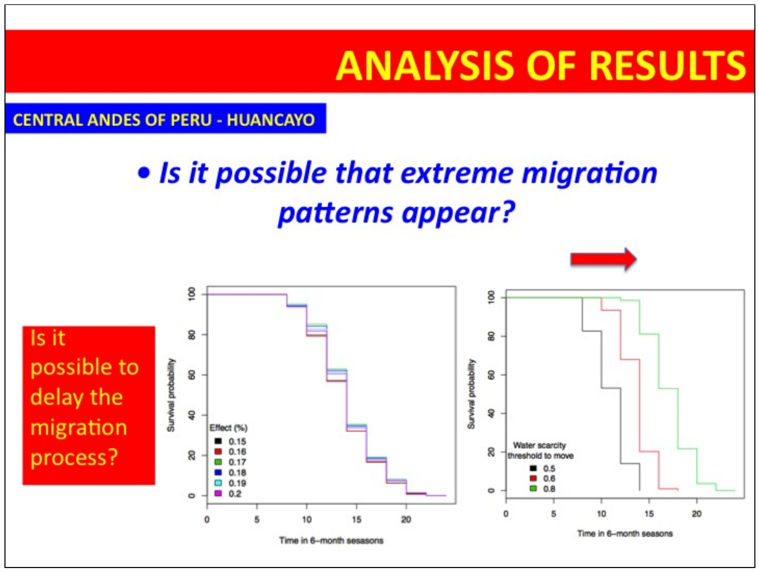
ANALYSIS OF RESULTS

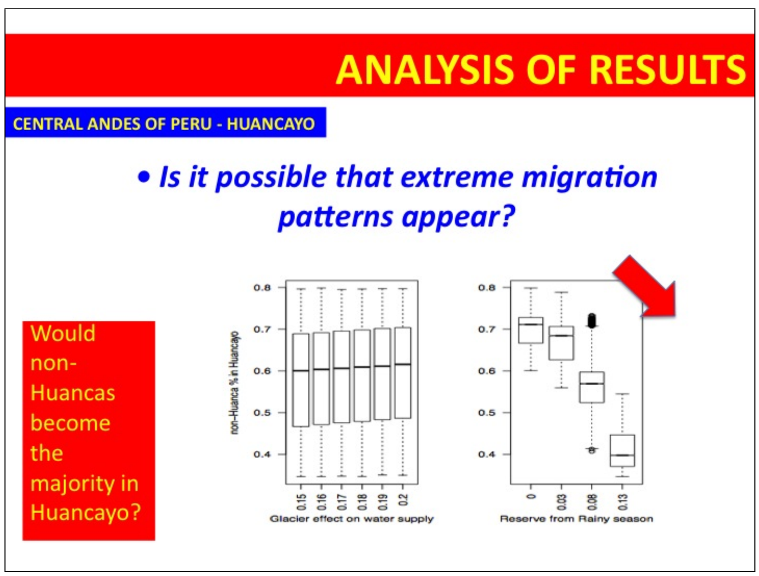
CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***

Can migration be avoided?




ANALYSIS OF RESULTS
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
Is it possible to delay the migration process?
Survival probability
Effect (%)
0.15
0.16
0.17
0.18
0.19
0.2
Time in 6–month sesasons
Water scarcity threshold to move
0.5
0.6
0.8
Time in 6–month seasons


ANALYSIS OF RESULTS
CENTRAL ANDES OF PERU - HUANCAYO
• Is it possible that extreme migration patterns appear?
Would non-Huancas become the majority in Huancayo?
non–Huanca % in Huancayo
Glacier effect on water supply
Reserve from Rainy season

ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- *Is it possible the emergence of social conflict in the area?*

Social conflict is possible in the model

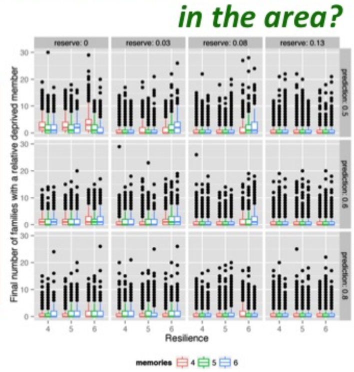
Variable	Value	Variable Name
Max number of angry people reached	2497.00	maxmass
Density of Angry Network when max number of angry people reached	0.01	maxdensitymass
Average clustering coefficient of Angry Network when max number of angry people reached	0.41	maxmeancc
Number of network components when Max number of angry people reached	491.00	maxcomp
Season when Max number of angry people reached	96.00	maxmassangrytime
Rural population when max number of angry people reached	569.00	maxmasspoprural
Urban population when max number of angry people reached	3116.00	maxmasspopurban
Season when first rural started feeling relatively deprived	80.00	season-conflict-rural

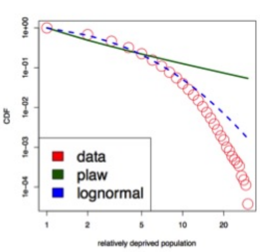
ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- *Is it possible the emergence of social conflict in the area?*

Can the conflict in the peri-urban area be avoided?



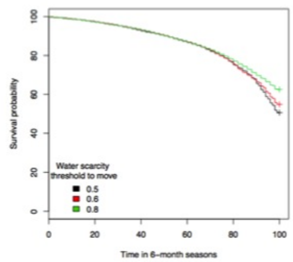


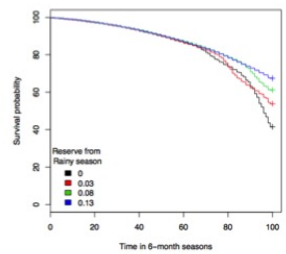
ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible the emergence of social conflict in the area?***

Can potential conflict in the rural area be delayed?



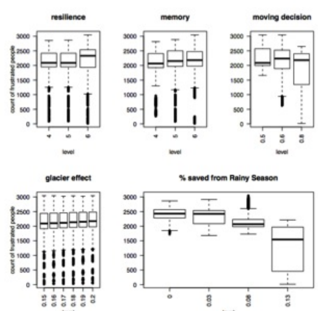


ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible the emergence of social conflict in the area?***

What can decrease the number of urban people frustrated ?

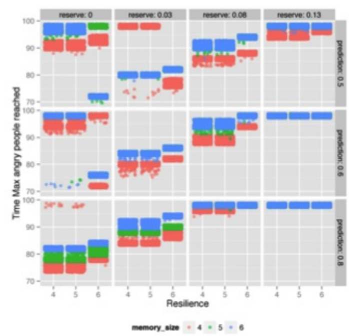


ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- *Is it possible the emergence of social conflict in the area?*

How to delay conflict in urban area?

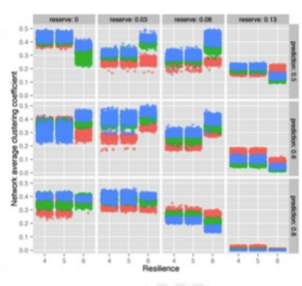


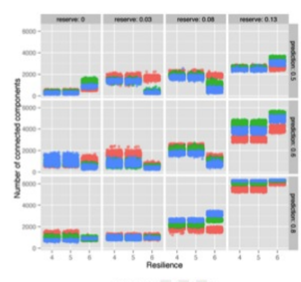
ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

- *Is it possible the emergence of social conflict in the area?*

What would increase the potential for conflict?





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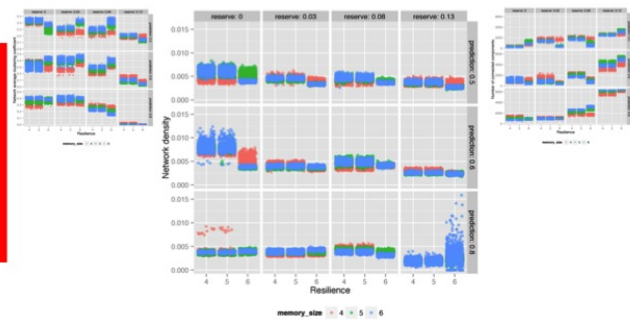

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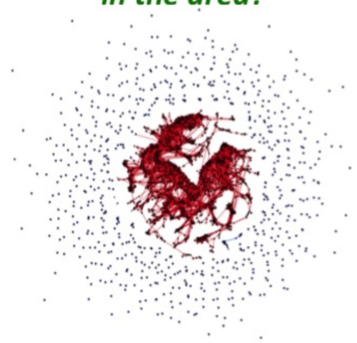


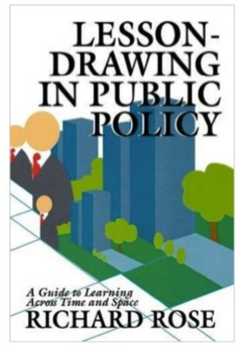
- average clustering coefficient= 0.3635
- 705 connected components
- density = 0.007

ANALYSIS OF RESULTS

CENTRAL ANDES OF PERU - HUANCAYO

• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?

Although policymakers cannot draw lessons from events that have yet to occur, they can try to anticipate events. In doing so, they may treat the future as an extension of the present in order to bound speculation by existing knowledge. Theorists can claim future success for their prescriptions on the grounds that predictions follow logically from premises, whether or not their premises are plausible. Politicians can exploit uncertainty about the future by willfully asserting faith in their proposals, which have yet to be proven wrong" (pp.91)



DISCUSSION

CENTRAL ANDES OF PERU - HUANCAYO

• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?

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- Challenges to the model
  - reactive mindset
  - Strong Centralization and weak decentralization
  - symbolic and superficial proactiveness
  - economic development
  - Poor leadership
- Beyond the model
  - Extended: What happens in destinations of migrants
  - Needed: Economic capacity and water access
  - Improvement: A different programming platform could be important to consider.
  - Needed: Information on neighborhoods and their economic capacity

DISCUSSION

CENTRAL ANDES OF PERU - HUANCAYO

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***

- Measures to be taken
  - Make sure people in rural area have enough rights and mechanisms to keep their lands in good condition.
  - Create mechanisms to ensure political participation of rural people.
  - Improve participatory water governance
  - Create and save the institutional memory
  - Do not hide the crisis, but show a plan
  - Seek collaboration from civil society, especially research institutions.
  - Be careful of easy solutions.

- Challenges to the model
  - reactive mindset
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  - Poor leadership

- Beyond the model
  - Extended: What happens in destinations of migrants
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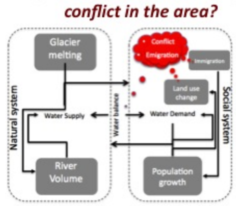
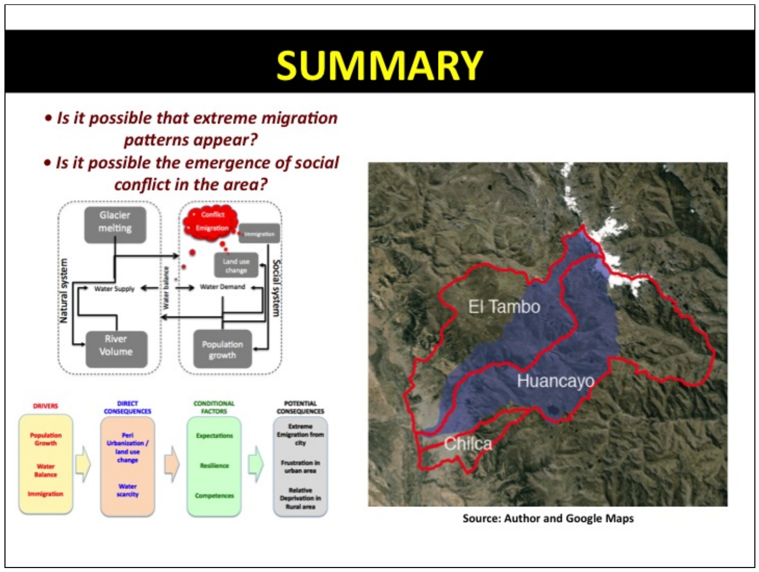
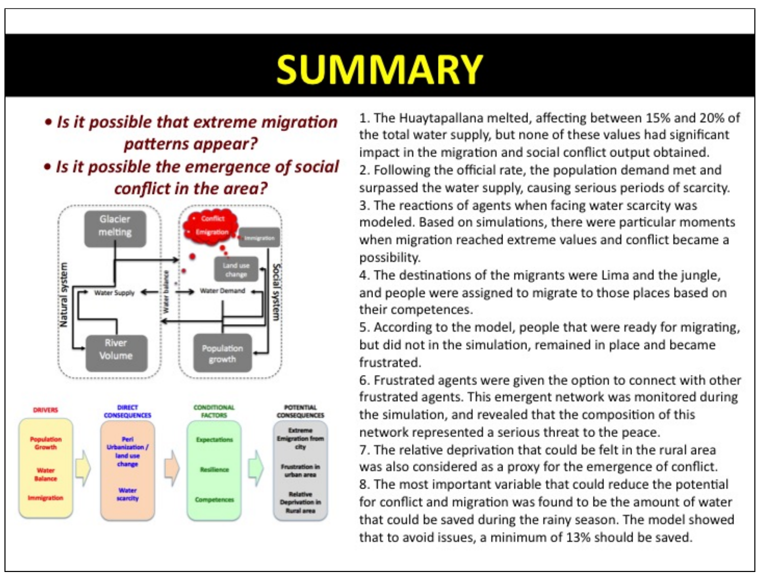
SUMMARY

- ***Is it possible that extreme migration patterns appear?***
- ***Is it possible the emergence of social conflict in the area?***



Source: Author and OpenStreet Maps


SUMMARY
• Is it possible that extreme migration patterns appear?
• Is it possible the emergence of social conflict in the area?
Glacier melting
Conflict
Emigration
Immigration
Land use change
Natural system
Water Supply
Water balance
Water Demand
Social system
River Volume
Population growth
DRIVERS
Population Growth
Water Balance
Immigration
DIRECT CONSEQUENCES
Peri Urbanization / land use change
Water scarcity
CONDITIONAL FACTORS
Expectations
Resilience
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
El Tambo
Huancayo
Chilca
Source: Author and Google Maps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Water scarcity
CONDITIONAL FACTORS
Expectations
Resilience
Competences
POTENTIAL CONSEQUENCES
Extreme Emigration from city
Frustration in urban area
Relative Deprivation in Rural area
1. The Huaytapallana melted, affecting between 15% and 20% of the total water supply, but none of these values had significant impact in the migration and social conflict output obtained.
2. Following the official rate, the population demand met and surpassed the water supply, causing serious periods of scarcity.
3. The reactions of agents when facing water scarcity was modeled. Based on simulations, there were particular moments when migration reached extreme values and conflict became a possibility.
4. The destinations of the migrants were Lima and the jungle, and people were assigned to migrate to those places based on their competences.
5. According to the model, people that were ready for migrating, but did not in the simulation, remained in place and became frustrated.
6. Frustrated agents were given the option to connect with other frustrated agents. This emergent network was monitored during the simulation, and revealed that the composition of this network represented a serious threat to the peace.
7. The relative deprivation that could be felt in the rural area was also considered as a proxy for the emergence of conflict.
8. The most important variable that could reduce the potential for conflict and migration was found to be the amount of water that could be saved during the rainy season. The model showed that to avoid issues, a minimum of 13% should be saved.

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Curriculum Vitae

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