Assessing the Hydrologic Implications of Glacier Recession and the Potential for Water Resources Vulnerability at Volcán Chimborazo, Ecuador

Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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2014

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Abstract

Climate change will impact hydrological systems worldwide, and human societies will face increasing water resource vulnerabilities as a result. One key concern is the potential downstream impact of glacier recession in the world’s tropical and temperate mountains. For communities at the foot of Ecuador’s ice-capped volcanoes, glacial meltwater is a potentially important component of irrigation supply, and residents observe the region’s rapidly retreating glaciers with mounting concern. In this dissertation, I present results from a uniquely integrative study examining the relationships among glacier retreat, hydrological change and water resource insecurity at Volcán Chimborazo. Combining remote sensing analyses, direct hydrological measurements, climate data analyses, and detailed household surveys, I report on the recent rate of glacier shrinkage, the role of glacial meltwater in the local hydrological system, the increasing insufficiency of water entering local irrigation systems, and the livelihood adaptations made necessary by increasing water stress.

Results show that while Chimborazo lost 21% ± 9% of its glacier area between 1986 and 2013, each of Chimborazo’s glacierized watersheds is a groundwater-dominated system. Even in the upper Rio Mocha, the only catchment where glacier meltwater is a regular component of surface runoff, glaciers generally directly contribute
only ~5% of total discharge. There are indications of strong linkages between glacier
meltwater and groundwater discharge, however, and this merits further investigation.
Still, water stress is a prominent factor driving widespread local perceptions of reduced
socio-economic well-being in recent decades. While instrumental records document a
local warming trend of 0.11°C per decade since 1986, they do not indicate a shift in local
precipitation patterns. However, local farmers are nearly unanimous in their perception
that precipitation has decreased, and the spatial patterns of glacier change potentially
support this observation. The impacts of these changes have been felt by nearly all people
in the region, though their severity is differentiated across households and is highly
spatially heterogeneous. While non-irrigators have been impacted the most, irrigators at
lower elevation areas, where the climate is drier and soils are less productive, are also
being forced to make considerable adaptations to their livelihood activities. Considering
irrigation’s traditional role as sufficient insurance against the natural hydrological
variability characteristic of this region, this indicates that climate change is already
exceeding local coping capacities and that agrarian livelihoods are highly vulnerable to
future changes.
Many, many people contributed to this dissertation. I offer my sincere appreciation to each of the following individuals:

- Information and data were provided by Luis Maisincho, Marco Villacis and, especially, Bolivar Caceres, of the Instituto Nacional de Meteorología en Hidrología, Ecuador (INAMHI); Dr. Bernard Francou; Dr. Ekkehard Jordan; Nestor Machado, of the Juntas de Riego Las Abras; Vinicio Basante, David Andrade, Carlos Romero and Dr. Leonardo Falconi of the Secretaria Nacional del Agua, Ecuador (SENAGUA); Aurélien Bigo; Ing. Jorge Sanchez of the Proyecto Inversiones de Desarrollo – Chimborazo; Dr. Jeffrey VanLooy; Dr. Andrew Farrow; Dr. Julien Nicolas; and Patricia Mothes and Jorge Bustillos of the Instituto Geofísico, Ecuador.

- Translation and transcription assistance were provided by Maria Angelica Gallardo Baeza; Nellie Mclean-Browne; Ximena Raza; and Jeffrey Vrendenburg.

- Field research assistance and companionship was provided by Sara Brells; Grace Carter; Katherine Collins; Georgia Ennis; Alfonso Fernandez; Lorelyn Hall; Bonnie Holman; Reed Ojala-Barbour; Anjani Polit; and Travis Wheeler.
• Other assistance in Ecuador was provided by Karen Aguilar; Eva Pumina; Leonardo Pumina; Javier Rodriguez; Fernando Sanchez-Flor; Juliana Slocum; and Raul Tenemaza.

• Laboratory analysis, training and support were provided by Dr. Kathleen Welch, Dr. Susan Welch, and Deb Leslie of The Ohio State University School Earth Science Water Isotope and Nutrient Laboratory; and Dr. Ping Nan Lin of the Byrd Polar Research Center.

• Administrative and technical assistance at The Ohio State University were provided by Juliana Hardymon, Suzanne Mikos, Jens Blegvad, Jim DeGrand and Colin Kelsey (Department of Geography) and Michele Cook, Lynn Everett, Lynn Lay, Wesley Haines, and Tom Kassebaum (Byrd Polar Research Center).

• Advice (and camaraderie) were provided by members of the Glacier Environmental Change research group at the Byrd Polar Research Center (led by Dr. Bryan Mark), including Pat Burns; Alicia Campbell; Ryan Crumley; Alfonso Fernandez; Kyung In Huh; Nathan Patrick; Colin Sinclair; Dr. Nathan Stansell; and Oliver Wigmore.

• Funding support was provided by The National Science Foundation (DDRI Grant No. 1103235); Comision Fulbright Ecuador; the Geological Society of America; and the Climate, Water and Carbon Program at The Ohio State University Department of Geography.
• Support and motivation during the writing process were generously given by Dr. Christine Biermann; Dr. Nicolas Crane; Chris Hartmann; Justine Law; and Zoe Pearson.

I give special thanks to the following people who provided many hours of advice and technical assistance: Dr. Michel Baraer; Dr. Jeffrey Bury; Alfonso Fernandez; Dr. Adam French; Dr. Ian Howat; Dr. Desheng Liu; Dr. Jeff McKenzie; and Dr. Frank Paul.

Without Nellie Mclean-Browne, the social aspect of this research doesn’t happen.

I give sincere appreciation to my parents, Robert and Linda La Frenierre, for financial support and much love.

I cannot express enough my appreciation for my outstanding and kind dissertation committee, who have each given me invaluable advice, incalculable patience, and infinite support. To my advisor, Dr. Bryan Mark, I offer particular gratitude.

My deep appreciation to the many individuals in the Chimborazo region who took the time to speak with me about their lives and their landscape.

Finally, I offer my biggest thank you of all to my wonderful spouse, Paula La Frenierre, who has been there every step – and every word – of the way. Nothing happens without you!
Vita

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Publications


Fields of Study

Major Field: Geography
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Chapter 1: Introduction

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Background and Rationale for Research

There is clear evidence that climate change will have a strong impact on hydrological systems worldwide, and that human societies will face increasing water resource vulnerabilities as a result (Arnell 1999; Bates and others 2008; IPCC 2007;
Milly and others 2008; Vorosmarty and others 2000). A key area of concern is the potential downstream impact of glacier recession in the world’s tropical and temperate mountains (Barry and Seimon 2000; Immerzeel and others 2010; Kaser and others 2010; Viviroli and others 2011). Within their hydrologic systems mountain glaciers provide a critical buffering service, storing excess water during periods of increased precipitation and releasing water downstream when precipitation is minimal and social demand is higher. This buffering service helps maintain the viability of downstream irrigation, hydroelectric generation and domestic water supply. With more than 700 million people living in mountainous areas worldwide (Messerli and others 2004), there is a compelling need to understand the hydrologic significance and social implications of mountain glacier retreat.

The tropical Andes are an exemplar of the potential vulnerability nexus of increasing water demand and decreasing glacial coverage (Bradley and others 2006; Mark and others 2010a; Vergara 2007; Vuille and others 2008). The most heavily-populated and highly-developed sectors of Bolivia, Peru and Ecuador are situated in semi-arid to arid zones, and with glaciers throughout the region steadily retreating (Burns and Nolin 2014; Francou and others 2000; Jordan and others 2005; López-Moreno and others 2014; Ribeiro and others 2013; Vuille and others 2008), there is broad concern for the sustainability of current water supply in these countries (Bradley and others 2006; Mark 2008; Mark and others 2010a; Vergara and others 2008). Because Ecuadorian glacier ice is confined to isolated stratovolcanoes such as Antisana, Cotopaxi and Chimborazo (Hastenrath 1981), there is the appearance that water resource vulnerability
is potentially less acute here than in the more highly glacierized watersheds of Peru and Bolivia. While the scale of Ecuador’s exposure to glacier change vulnerability is indeed smaller, the same concerns exist for those people locally dependent upon the hydrologic systems of these glacierized volcanoes.

The glaciers of Volcán Chimborazo serve as the headwaters of four river systems; while the glacierized portion of each is slight, more than 200,000 people rely on water drawn from these watersheds (INEC 2010). The highland area surrounding the volcano is semi-arid, and reliable irrigation is vital in the maintenance of food and economic security (Boelens and Doornbos 2001; Herrmann 2002; Knapp 1991). All local communities, including the provincial capital of Riobamba, draw their domestic water either from these rivers or directly from springs located on or around the mountain. Two hydroelectric facilities are also situated within Chimborazo’s glacierized watersheds. As glaciers have become noticeably smaller in recent decades, area residents have begun to express considerable anxiety about current and future climatic and hydrologic variability. There is broad regional agreement that weather patterns here are changing, that agricultural production is in decline and that life in general is becoming more difficult. With climate models projecting global atmospheric warming over the next century to be most intense at the high elevations of the tropics (Bradley and others 2006), retreat of Chimborazo’s glaciers is likely to continue, with direct consequences for watershed stakeholders.

To date, there has been little investigation into the hydrologic significance of Chimborazo’s glaciers. No comprehensive efforts to measure the rate and extent of the
mountain’s glacier retreat nor to quantify glacier melt as a component of total watershed discharge have been made. There is minimal existing infrastructure for any discharge monitoring, and climatologic measurements are sparse. The net effect of these conditions is that there is very limited local capacity for modeling Chimborazo’s hydrologic systems, predicting the response of those systems to climate change, and for anticipating the impact of change on current and future water management practices. This limited capacity, combined with their relatively low standard of economic development, suggests that people in the Chimborazo region may be highly vulnerable to evolving hydrological conditions and that they may be poorly positioned to adapt without significant socioeconomic disruption.

Social-ecological vulnerability does not accrue linearly in response to accumulating stress. Instead, stress may accrue with little notice until a critical threshold is reached and the system is forced to adjust (Adger 2006; Luers 2005). A key step in understanding vulnerability, then, is to evaluate both the stressors themselves as well the system’s existing capacity for adapting to those stressors before threshold points are reached. Because water resource vulnerability is a function of tightly interwoven biophysical and social processes (Budds 2008; Vorosmarty and others 2000), integratively inventorying and analyzing these processes – and the stressors acting upon them – is essential if the adaptive capacity of water users is to be enhanced before potentially irreversible vulnerability thresholds are breached.

To reduce their potential vulnerability and enhance their adaptive capacity, it is critical that Chimborazo’s water users be provided with relevant information as quickly
as possible so that they are able to make informed decisions before significant changes in hydrologic conditions take place. This dissertation seeks to address this problem by answering three overarching sets of questions:

1. At what rate have Volcán Chimborazo’s glaciers been shrinking in recent decades, and how much ice remains?

2. What is the hydrological role of Chimborazo’s glaciers and how does glacier shrinkage impact regional water supply?

3. How do residents of the agrarian communities that surround Chimborazo perceive their vulnerability to climate change, how are their livelihoods impacted by shifting hydroclimatic conditions, and what adaptation strategies are realistic given the range of social and environmental stressors they presently face?

The scope of this dissertation has demanded a perspective that integrates physical and social process research. Building upon the innovative work of Drs. Bryan Mark, Jeffrey Bury, Jeff McKenzie and others of evaluating the vulnerability of water users to glacier change in the Peruvian Andes (Bury and others 2013; Bury and others 2011; Mark 2008; Mark and others 2010b), I have employed a methodological approach that combines hydrologic, climatologic and glaciologic data analysis, analysis of remotely-sensed imagery, and qualitative research techniques such as focus groups and household surveys. Overlying the need to empower Chimborazo’s water users with specific information about their hydrologic system is a wider mandate for transformative science that advances our knowledge of how disparate social and biophysical factors are tangibly
manifested in climate change vulnerability. As such, my objective has not been to develop in-depth expertise in any one of these methodological areas, but rather to model the value of integrating knowledge and capacity across all areas to better understand the local-scale impacts of climate change in a mountain setting.

Structure of this Dissertation

I have written this dissertation a series of four discrete manuscripts, each of which is intended for publication in the peer-reviewed, scientific literature. As such, each of the four primary chapters (Chapters 2 – 5) features its own introduction, research site description, methodological overview, results, discussion, conclusion, and references. Chapter 2, *A review of methods for estimating the contribution of glacial meltwater to total watershed discharge*, offers a comprehensive evaluation of the various techniques thus far employed to estimate the contribution of glacial meltwater to total watershed discharge. This manuscript has now been published in Progress in Physical Geography (La Frenierre and Mark 2014). Chapter 3, *Detecting patterns of climate change at Volcán Chimborazo, Ecuador by integrating instrumental data, public perceptions and glacier change analysis*, describes the recent, local-scale patterns of climate change at Volcán Chimborazo while documenting the extent of glacier surface area change between 1986 and 2013. Chapter 4, *Patterns of mountain livelihood vulnerability and adaptation in a changing world: A case study from Chimborazo Province, Ecuador*, examines vulnerability and adaptation to the compounding challenges of climate change and globalizing in several agrarian communities. My objective here is to better understand the spatial patterns of these processes in the Chimborazo region, and to predict which types
of households may be most at risk of livelihood disruption due to the continued evolution of environmental and socioeconomic conditions. Chapter 5, *Assessing the significance of glacier change on local water supply at Volcán Chimborazo, Ecuador: A case study from the Las Abras irrigation system*, explores the role of glacier meltwater runoff in Chimborazo’s hydrological system and, specifically, the implications of hydrological change for households dependent upon water from the Las Abras irrigation system for their livelihoods. The final chapter, Conclusions and Future Research Directions, briefly summarizes the key findings of this integrative project and identifies possible directions for future research.

References


Chapter 2: A review of methods for estimating the contribution of glacial meltwater to total watershed discharge

Introduction

Glaciers store water over a range of temporal scales (Jansson et al., 2003) while providing baseflow for downstream water users during periods of otherwise low precipitation (Willis, 2005; Viviroli et al., 2007; Kaser et al., 2010). With an estimated 119 million people worldwide living in watersheds where glacial meltwater comprises at least 50% of total discharge at least one month per year (Schaner et al., 2012), the water resources implications of persistent glacier retreat are worrisome (Barnett et al., 2005). Glaciers in most of the world’s mountain areas are retreating (Barry, 2006; Zemp et al., 2009) and there have already been noticeable changes in hydrological behavior in many watersheds (Casassa et al., 2009). Ice loss is projected to continue and even accelerate under most plausible climate change scenarios (IPCC, 2007b) and water stress is expected to intensify as a result (Bradley et al., 2006; Immerzeel et al., 2010; Huss, 2011). Because meltwater runoff is essentially a non-renewable resource under extended periods of negative glacier mass balance (Immerzeel and Bierkens, 2012), an accurate assessment of the contribution of glacial meltwater runoff to total watershed discharge is an integral part of climate change risk assessment and sustainable water management in glacierized watersheds (Viviroli et al., 2011; Miller et al., 2012; Schaner et al., 2012).
Quantifying the contribution of glacial meltwater in a watershed is a challenging task. The physical processes involved in glacier ablation and watershed hydrology are complex, and measuring the various stores and fluxes incurs large uncertainties (Braun and Aellen, 1990; Miller et al., 2012; Zemp et al., 2013). Detailed hydrological, glaciological and climatological data are often limited to a small number of easily-accessible, well-studied watersheds and downscaling of global data for use at the watershed scale remains problematic, especially in complex mountain environments (Buytaert et al., 2010; Koboltschnig and Schoner, 2011). Furthermore, attempts to directly compare the volume of water produced by a glacier with the volume of water at some point downstream are confounded by highly dynamic climatic (e.g. evaporation), geologic (e.g. groundwater exchange) and human (e.g. irrigation diversions) factors modulating downstream flow (Kaser et al., 2010). Indeed, the very definition of ‘glacier meltwater’ is viewed inconsistently (Hopkinson and Young, 1998), with some researchers including not only ice melt itself, but also seasonal snowmelt or all runoff, including precipitation quick-flow, (e.g. Nepal et al., 2013) generated from glacierized portions of a watershed.

Despite such challenges, multiple approaches for quantifying the proportional contribution of glacial meltwater have been presented. These can be classified into one of five different categories that: 1) compare measured discharge at the glacier snout with measured downstream discharge (direct discharge measurement); 2) estimate the water produced by changes in glacier mass (glaciological approaches); 3) estimate glacier meltwater discharge by solving for other components of the hydrological balance
(hydrological balance equations); 4) utilize hydrochemical tracers to solve the hydrological balance; and 5) employ hydrological models. Many studies utilize multiple approaches in order to independently validate their results (e.g. Mark and Seltzer, 2003; Nolin et al., 2010; Gascoin et al., 2011). The earliest such studies date from the 1950s, with much work (in German) focused upon conditions in the European Alps, as reviewed by Lambrecht and Mayer (2009) and Koboltschnig and Schoner (2011). With recognition of climate change and its implication for water resources, there has been a rapid expansion in the scientific literature within the past decade, and scenario-based estimates of future glacial meltwater contribution are also increasingly common. While most major mountain areas have been studied, a particular emphasis on present and future conditions in the Himalaya-Hindu Kush region reflects recent controversy over the impact of glacier retreat on the densely settled river basins originating there (e.g. Barnett et al., 2005; IPCC, 2007b; Immerzeel et al., 2010; Immerzeel and Bierkens, 2012; Miller et al., 2012). The European Alps also continue to be a nexus of research, and enough glaciohydrological modeling studies have now been completed in Austria that a meta-analysis of the relationship between glacierized area and glacial meltwater contribution to discharge was recently presented (Koboltschnig and Schoner, 2011). Table 2.1 summarizes the literature discussed within this review and Figure 2.1 illustrates its geographic distribution.

In this paper, we review the different methodological approaches that have been employed to estimate the contribution of glacial meltwater to total watershed discharge. After a brief summary of the role of glaciers in watershed hydrology, we evaluate each
Table 2.1: Literature discussed in this review, grouped by primary methodological approach.

<table>
<thead>
<tr>
<th>Number</th>
<th>Author(s)</th>
<th>Region</th>
<th>Secondary Method(a)</th>
<th>Basin Scale(b)</th>
<th>Glacier Cover(c)</th>
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<td>Micro</td>
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</table>

(a) Secondary Method describes studies where multiple methodological approaches have been taken; (f) indicates an additional scenario-based modeling of future glacier meltwater contribution component; (f*) indicates that scenario-based modeling of future glacier meltwater contribution was the sole study objective.

(b) Basin Scale describes the overall average size of watersheds in the study area (Micro: < 100 km²; Meso: 100 – 10,000 km²; Macro: > 10,000 km²); the notation (*) indicates that the study includes basins at different scales.

(c) Glacier Cover describes the overall average proportion of the total watershed area that is covered by glacier ice (Low: < 10%; Moderate: 10-30%; High: > 30%); the notation (+) indicates that the study includes basins with different glacier coverages.

Continued
Table 2.1 (Continued)

<table>
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<tr>
<th>Number</th>
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approach with regard to their respective data requirements, assumptions, and associated uncertainties. Next, we discuss some of the factors that researchers must consider in deciding upon a particular methodological approach, then conclude with a discussion of
future research needs. To delimit this review, we consider only research attempting an explicit quantification of current or future glacial meltwater contribution, although there is much additional literature describing the potential hydrological consequences of glacier change more broadly (Barnett et al., 2005; Casassa et al., 2009; Kaser et al., 2010; Miller
et al., 2012). We do not impose a singular definition of glacier meltwater beyond what is
presented by published papers to represent the total liquid contribution of melted glacier
ice that enters the watershed from the glacier snout. We further limit our review to papers
published in English-language journals, acknowledging that similar research has been
published in German (see Koboltschnig and Schoner, 2011), Russian (see Sorg et al.,
2012) and Mandarin (see Liu et al., 2009). We also exclude non-peer reviewed technical
reports and other gray literature.

The role of glaciers in watershed hydrology

The presence of glaciers has a number of important consequences for the
hydrological behavior of a watershed (Fountain and Tangborn, 1985; Rothlisberger and
Lang, 1987; Chen and Ohmura, 1990b; Jansson et al., 2003; Willis, 2005; Kaser et al.,
2010). Here, we summarize the most salient points and refer readers to the
aforementioned literature for a more detailed discussion.

Glaciers store a proportion of total precipitation and modulate downstream river
discharge over daily to multi-century time-scales (Jansson et al., 2003; Fleming and
Clarke, 2005; Hock et al., 2005). The seasonal and interannual modulation of discharge is
of particular importance for water supply. On a seasonal basis, glaciers ensure a
dependable water supply throughout the dry season while on an interannual basis, this
‘glacier compensation effect’ (Lang, 1986; Rothlisberger and Lang, 1987) mitigates the
impact of extended meteorological runoff deficits. The glacier compensation effect is
maximized when watershed glacier coverage is moderate (~30-40%; Moore, 1992;
Fleming and Clarke, 2005), since more highly glacierized watersheds tend to be small
and with a relatively limited elevation range (Willis, 2005). Climatic regime is also a dominant factor modulating the intensity of the glacier compensation effect and thus the potential hydrological significance of glacial meltwater, especially at the macro-watershed scale (Kaser et al., 2010). The value of the glacier compensation effect to water users is well-illustrated by conditions in the European Alps during the exceptionally hot, dry summer of 2003. During August, the proportional contribution of glacial meltwater was as much as twelve times greater than normal (Koboltschnig et al., 2008), permitting normal to enhanced hydroelectric production in glacierized watersheds whereas power production was significantly reduced elsewhere on the continent (Koboltschnig and Schoner, 2011). Tropical glaciers behave somewhat differently from those in temperate regions in that ablation occurs year-round rather than seasonally and annual maxima in accumulation and ablation may be coincident (Wagnon et al., 1999; Kaser and Osmaston, 2002). Nonetheless, they provide the same seasonal and interannual compensating effects, especially in areas with pronounced dry seasons (Mark et al., 2005). The seasonal effect is diminished in monsoonal climates like those of the eastern Himalaya since the ablation season is coincident with the period of heaviest rainfall (Immerzeel and Bierkens, 2012; Miller et al., 2012). Conversely, glacier meltwater becomes more hydrologically significant when the summer monsoon is relatively weak.

Glaciers modulate discharge at different temporal and spatial scales, so that the proportional contribution of glacial meltwater is highly variable in both place and time. Koboltschnig et al. (2008) quantify the contribution of glacial meltwater to discharge in the upper Salzach watershed (Austria) and find that while the contribution for 1999-2000
hydrological year was only ~1%, the contribution for August of 2000 was ~4% and, on
August 26, 2000, the contribution was 12%. In the climatically-extreme year of 2003, the
August contribution was 58%. Glaciers generally contribute a much greater proportion of
total discharge than would be expected given the proportion of the watershed that is
glacierized, at least on a seasonal basis. Mark et al. (2005) find that glaciers contribute as
much as 40% of dry season discharge in the Rio Santa watershed (Peru) despite covering
only 8% of the watershed area while Jost et al. (2012) estimate glacier-derived waters to
be 25-35% of August/September inflow to the Mica Reservoir (British Columbia,
Canada) despite the watershed having only 5% glacier coverage.

Unsurprisingly, glacial meltwater provides a higher proportion of total discharge
as one approaches the glacierized headwaters of a watershed, while input from other
water sources such as precipitation and groundwater discharge increase as the watershed
area grows larger (Immerzeel et al., 2010). In some areas, the hydrological significance
of meltwater may be negligible at the macro-watershed scale despite the presence of large
glaciers in the headwaters area (Rees and Collins, 2006; Immerzeel, 2008). Again, this is
largely a function of climatic regime. Glaciers in highly arid regions such as the western
Himalaya, Central Asia and the central Andes are a very important component of
discharge even at the macro-watershed scale (Kaser et al., 2010). In the densely-
populated Indus River basin, for example, glacier meltwater contributes an estimated
26% of total annual discharge despite watershed glacier cover being only 2.2%
(Immerzeel et al., 2010). The same can hold true even in more temperate climatic
regimes during the driest, warmest months. Nearly 4% of the Danube River discharge
entering the Black Sea in September is of glacial origin despite 0.06% glacier area coverage (Huss, 2011).

Considering the prognosis for enhanced atmospheric warming in the centuries ahead (IPCC, 2007a) understanding the potential evolution of glacial meltwater contribution in response to extended glacier retreat is an increasingly prominent area of research. Under conditions of net mass loss, discharge from glacierized watersheds will initially increase due to the glacier compensation effect. However, if net mass loss persists, glaciers will at some point pass a critical threshold whereby shrinking ice mass can no longer sustain elevated discharge (Braun et al., 2000). Casassa et al. (2009) analyze discharge data from glacierized watersheds worldwide to determine their state relative to the critical threshold and found that rivers in Central Asia (Tien Shan Mountains and Central Tibet), the Peruvian Andes, the northern Canadian cordillera and highly-glacierized watersheds in the European Alps were generally exhibiting increased runoff while those in the southern Canadian cordillera, the central Chilean Andes and more modestly-glacierized European watersheds had already experienced diminished discharge. Baraer et al. (2012) incorporate both discharge volume and variability characteristics in identifying four phases of discharge response to extended glacier retreat. During the first phase, annual discharge increases and interannual discharge variability decreases in response to the enhanced input of meltwater. Phase two begins when interannual variability reaches a minimum and begins to increase; while annual discharge continues to increase, the rate of increase begins to slow. The transition to phase three represents the passing of the critical threshold after which discharge begins to
steadily decrease while interannual variability continues to increase. The final stage occurs only when glacier retreat ceases (or deglaciation is complete) and both annual discharge and interannual discharge variability reach a new equilibrium state.

**Methodological approaches**

We describe five categories of methodological approaches that have been developed for quantifying the contribution of glacial meltwater to watershed discharge. Table 2.2 summarizes each method, its essential data requirements, controlling assumptions and key sources of uncertainty.

**Direct discharge measurement**

A comparison of streamflow measurements taken immediately downstream of the glacier tongue with those taken simultaneously at points farther downstream (accounting for water transit time) offers the simplest, least data-intensive approach for quantifying that glacier contribution to total watershed discharge (Nolin et al., 2010; Thayyen and Gergan, 2010; Gascoin et al., 2011). The presence of existing stream gauge infrastructure and/or the relatively simple and inexpensive installation of small, continuously-recording discharge loggers, makes the direct measurement approach a potentially attractive option. However, the logistical requirements of installing and maintaining measuring devices effectively restrict this approach to watersheds where all glaciers have easily-accessible tongues. Furthermore, there are multiple factors which combine to produce relatively high levels of uncertainty, thus the application of this approach has been limited to validation of estimates obtained via one of the more complex methods described below.
Table 2.2. Summary of methodological approaches for estimating the contribution of glacier meltwater to watershed discharge.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Appropriate Spatial Scale(s)</th>
<th>Appropriate Temporal Scale(s)</th>
<th>Primary Advantages</th>
<th>Primary Sources of Uncertainty</th>
<th>Measurement Type</th>
<th>Dependence on Existing Data</th>
<th>Differentiates Glacier Melt from Wastage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct discharge measurement</td>
<td>Micro</td>
<td>Hourly; other scales possible with repeated measurements or installation of reliable gauges</td>
<td>Simple technique; no existing data needed</td>
<td>Inability to differentiate seasonal snowmelt and precipitation runoff originating above the glacier tongue; difficulty in routing all glacier meltwater past a measuring gauge; measurement error</td>
<td>Discrete</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Glaciological</td>
<td>Micro to meso (macro if geodetic mass balance approaches used)</td>
<td>Annual to decadal (can be scaled to shorter time scales with climate data)</td>
<td>Potentially the most precise; leverages existing mass balance data</td>
<td>Extrapolation of point mass balance or energy balance measurements across all glacier surfaces (direct and energy balance approaches); DEM error (geodetic approach); accuracy of area/volume scaling equations (geodetic approach); unquantified loss of glacier melt to other hydrological pathways; measurement error</td>
<td>Averaged</td>
<td>High</td>
<td>Yes (if direct mass balance measurements are used)</td>
</tr>
<tr>
<td>Hydrological balance equations</td>
<td>Micro to meso (high uncertainty at macro)</td>
<td>Monthly to decadal (longer time scales may be more accurate)</td>
<td>Measurement of some non-glacial terms is relatively simple; existing data may be available</td>
<td>Interpolation of hydrological balance terms from limited point measurements; measurement error (esp. with precipitation); difficulty accounting for evaporation, sublimation and groundwater exchange</td>
<td>Averaged</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td>Hydrochemical tracers</td>
<td>Micro to meso</td>
<td>Daily; other scales possible with repeated measurements</td>
<td>No existing data needed; water sampling easy/inexpensive (though laboratory analysis is required); captures temporal and spatial variations in contribution</td>
<td>Lack of heterogeneity of end-member chemical signatures within watershed; end-member chemistry that is not conservative; inability to differentiate some end-members in certain chemical environments</td>
<td>Discrete</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Hydrological modeling</td>
<td>Any (depends on input data)</td>
<td>Hourly to decadal</td>
<td>Potentially applicable at a range of temporal/spatial scales; provides hypothesis testing capabilities; can pinpoint areas where additional processes knowledge is needed</td>
<td>Measurement error of input data; interpolation/rescaling of measured input data; equifinality; model simplification of complex processes</td>
<td>Depends on model time step</td>
<td>High</td>
<td>Yes (depending on model design)</td>
</tr>
</tbody>
</table>
The direct measurement approach requires two fundamental assumptions: 1) that all of the water draining from the glacier tongue is of glacial origin; and 2) that all of the glacial meltwater within the watershed is measured at the first stream gauge. The first assumption is challenged by the fact that water flowing from glaciers is nearly always some combination of melting ice, melting seasonal snow cover on the glacier surface (i.e. wastage and melt; see Hopkinson and Young, 1998), and direct precipitation runoff, so proportional estimates of glacier contribution made using this approach will typically be unable to isolate true glacial meltwater from other components. Additionally, since some proportion of the surface area upstream from the glacier tongue will be ice-free (e.g. bare moraine slopes; exposed rock faces), the water measured at the tongue will also include surface runoff from these non-glacier areas. For example, Thayyen et al. (2005) estimate that 10-26% of the water measured at the tongue of a glacier in the Indian Himalaya was monsoonal precipitation runoff. Thayyen and Gergan (2010) recommend installing a rain gauge at some point above the glacier tongue during the melt season to help quantify this contribution. The second assumption ignores the potential for infiltration at the glacier bed whereby meltwater reappears at the surface some distance downstream from the glacier tongue (Favier et al., 2008) as well as the possibility that other, non-visible ice bodies such as debris-covered and rock glaciers may also contribute to watershed discharge (Gascoin et al., 2011). Nolin et al. (2010) find significant discrepancies in their estimate of glacial meltwater contribution to one of the sub-watersheds in the Oregon Cascades (31% via direct discharge measurement versus 88% +/- 5% via hydrochemical
tracer) and speculate that a primary cause was their inability to measure all of the discharge issuing from all of the glacier ice in that watershed.

There is often considerable uncertainty associated with the volumetric measurement of flowing water due to the technical limitations of measuring equipment, the need to interpolate/extrapolate point discharge measurements to create stage-discharge rating curves, and the frequent presence of unsteady flow conditions (Di Baldassarre and Montanari, 2009; Soupir et al., 2009). Furthermore, the highly-dynamic channel conditions of the pro-glacial environment – where frequent shifts in course, sudden surges and high sediment loads are common – may result in an even greater level of measurement error than would occur in non-glacial streams (Nolin et al., 2010). Researchers may be forced to compensate for these conditions by establishing their first gauges at more stable locations hundreds of meters below the glacier tongue (e.g. Thayyen and Gergan, 2010), though doing so increases the uncertainty that all of the water being measured is of glacial origin.

Glaciological approach

If the volume of ice melting from glaciers in a watershed can be determined, the volumetric water equivalent can be compared to downstream measured streamflow to determine the proportional contribution of glacial meltwater to total discharge. Some of the earliest attempts at quantifying the glacial meltwater proportion of watershed yield applied this glaciological approach by leveraging existing glacier mass balance, climate, and discharge data (Collier, 1957; Henoch, 1971), and it continues to be employed in
watersheds where glacier monitoring programs are well established (e.g. Lambrecht and Mayer, 2009; Huss, 2011; Pelto, 2011).

Three different methods for estimating the volume of melted ice are used. The most common utilizes direct mass balance measurements obtained from ablation stake networks (Pelto, 1992; Lambrecht and Mayer, 2009; Pelto, 2011). Depending upon the inclusion/exclusion of water-equivalent accumulation data, this approach can be used to quantify the contribution from either glacier ‘melt’ (water generated from melting ice in the ablation area exclusive of glacier mass balance state), or ‘wastage’ alone (water generated by net ice loss only when the glacier is in a negative mass balance state; Hopkinson and Young, 1998). A fundamental assumption is that the mass balance calculation derived from a sample of surface measurements is truly representative of accumulation and ablation rates over the entire glacier (Collier, 1957; Marshall et al., 2011). In reality, glaciers can experience wide variation in point-measured mass balance behavior due to variable topography and patterns of snow distribution (Konz and Seibert, 2010), providing a potential source of notable uncertainty. A dense stake network can ameliorate this uncertainty to some degree (Pelto, 2011), though stake networks are often limited to accessible parts of the glacier surface, giving a potentially skewed estimate of mass balance. Furthermore, because ablation stake networks are typically limited to a small number of glaciers within a region, it is usually necessary to extrapolate these data to represent the volumetric contribution of glacial meltwater at the watershed scale (e.g. Hopkinson and Young, 1998; Huss, 2011; Marshall et al., 2011). Such extrapolation introduces further uncertainty given the highly heterogeneous nature of ablation within
individual glaciers as well as among glaciers featuring different headwall elevations, aspects, slope gradients and basin morphologies (Benn and Lehmkuhl, 2000). Mass balance estimates based on ablation stake data will also be subject to both systematic and random measurement errors (Zemp et al., 2013), which also propagate into uncertainty about the actual volume of glacier meltwater released into the watershed.

Comparison of multi-temporal remote-sensing products such as digital elevation models (DEM) (Huss, 2011; Jost et al., 2012) or volumetric estimates based on 2D data sources such as imagery or maps (Farinotti et al., 2009; Marshall et al., 2011) offers a second method for estimating changing ice volume, particularly where direct mass balance measurements are unavailable. Assuming complete data coverage, these techniques have the advantage of providing measured volumetric change estimates for all glaciers in the watershed. A limitation of this geodetic approach is that it cannot account for meltwater that is generated when the glacier is in an overall positive mass balance state. High-resolution DEMs can be generated from techniques such as conversion of existing contour maps (Racoviteanu et al., 2007), photogrammetry (Lambrecht and Kuhn, 2007), and airborne or terrestrial laser scanning (lidar) (Hopkinson and Demuth, 2006). The free availability of satellite-derived DEMs from the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Paul and Haeberli, 2008) make these coarser DEMs (90 m and 30 m, respectively) a popular option, though coarser resolution limits use to glaciers with relatively larger surface areas. All DEMs will have some quantity of error (Frey and Paul, 2012) that directly influences the uncertainty associated with the resulting estimate of
glacial meltwater volume. The relatively poor vertical accuracy of ASTER DEMs (Fujisada et al., 2005), especially over ice and water, makes this product particularly problematic in this regard (Racoviteanu et al., 2007).

Where multi-temporal DEMs of sufficient quality are unavailable, an alternative method for quantifying ice volume change is to estimate initial and final glacier volumes based on 2D representations of glacier area obtained from aerial or satellite imagery or recent large-scale maps. Empirical equations based on the physical relationship between glacier surface area and volume have been developed (Chen and Ohmura, 1990a; Bahr et al., 1997). Variables within the equation adjust for specific conditions such as tropical glaciers or glaciers located on volcanoes. Empirical scaling relationships will introduce a great deal of uncertainty into estimates of ice volume loss on individual glaciers through time (up to 50% error, Marshall et al., 2011), though it is argued that the error is reduced as a greater number of glaciers are considered based on the assumption that the measurement mean will approach the true mean in a normally-distributed data set (Comeau et al., 2009; Marshall et al., 2011). Glacier volume has also been approximated using ice thickness-glacier surface slope equations (Farinotti et al., 2009; Huss, 2011; Immerzeel et al., 2012). Nevertheless, Farinotti et al. (2009) find that differences between estimated ice depth using this method and measured ice depth ranged from 20-30% for four Swiss glaciers. Given the cascading uncertainties that result from multiple estimates representing before/after conditions, hydrological conclusions drawn from such a reckoning must be treated with caution (Marshall et al., 2011).
A third approach to estimating the volume of melted ice involves the use of energy balance models (Jiskoot and Mueller, 2012) or temperature-index models (Aizen et al., 1996; Zhang et al., 2008; Liu et al., 2009; Zhang et al., 2011a). Energy balance models compute the amount of meltwater generated by a glacier based on the state of controlling variables such as air temperature, humidity, radiative fluxes, wind velocities and surface albedo (Arnold et al., 1996; Oerlemans and Klok, 2002; Hock and Holmgren, 2005). Such models are useful because output is controlled by the physical conditions that result in ice melt, though they remain limited in their ability to capture all of the complex processes that drive ablation as well as their ability to sufficiently represent the variable conditions that exist across the glacier surface (Jiskoot and Mueller, 2012) or throughout the watershed. Temperature-index (a.k.a. degree-day) models are based on the empirical relationship between atmospheric temperature and glacier ablation (Ohmura, 2001; Hock, 2003). They have the additional advantage of providing information about historic glacier meltwater contributions to discharge, since temperature and discharge are generally the most readily available and highest quality data over decades past (Liu et al., 2009). Furthermore, because temperature is generally more persistent across large areas than are other energy balance parameters, the uncertainty associated with extrapolation to the watershed scale may actually be reduced using this technique. In several instances, temperature-index models have been used as stand-alone tools for estimating the current (e.g. Zhang et al., 2008; Zhang et al., 2011a) and future (e.g. Aizen et al., 2007; Zhang et al., 2012) contribution of glacier meltwater.
Certain assumptions, uncertainties and limitations are inherent in the glaciological approach regardless of the specific technique used to estimate the volume of water generated by glacier melt. By excluding other components of the hydrological cycle, this approach assumes that all lost glacier mass is converted to water volume that enters and remains in the stream channel as far as the first discharge measurement point. Researchers typically justify this by assuming that sublimation and evaporation in high mountain watersheds are minimal relative to the amount of meltwater generated by a glacier (Pelto, 2011; Jiskoot and Mueller, 2012) and that steep slopes and extensive areas of exposed bedrock limit infiltration while producing rapid runoff (Lambrecht and Mayer, 2009). In arid climates, however, sublimation can be a significant factor in glacier mass balance (e.g. Gascoin et al., 2011), and the turbulent conditions of many alpine streams – a function of their frequently steep gradients and obstructed channels – may enhance evaporation (Hopkinson and Young, 1998). The glaciological approach also assumes that both the measured loss of ice mass and measured discharge are reasonably accurate, though both components are subject to considerable uncertainties as described above (Bamber and Rivera, 2007; Di Baldassarre and Montanari, 2009; Zemp et al., 2013).

Depending upon the method chosen for calculating glacier mass change, the application of the glaciological approach limits some of the conclusions that can be drawn about the contribution of glacial meltwater to total watershed discharge, particularly over varying time scales. If direct mass balance measurements are only obtained on an annual basis, the intra-annual variation of glacier meltwater and its role in
buffering seasonal periods of otherwise low flow will be difficult to quantify unless it can be assumed that ablation occurs only during a specific set of months (Pelto, 2011) or some sort of temperature-index ablation scaling relationship can be used (Lambrecht and Mayer, 2009). Multiple mass balance measurements made during the course of the hydrological year will help obviate this weakness, however such data are typically limited to relatively easily-accessed sites where long-term glaciological monitoring programs have been established (e.g. Pelto, 2008; Huss, 2011; Pelto, 2011). The geodetic approach is even more limited in this regard since the epoch between different ice volume estimates may extend across decades except in a few exceptionally well-studied areas such as the European Alps (e.g. Huss, 2011). This is one area where energy balance models offer a distinct advantage, given that they can quantify glacier meltwater over very short periods of time (hourly or daily) rather than providing only a lumped contribution estimate.

_Hydrological balance approach_

The hydrological balance approach is a relatively simple technique premised on mass conservation in the hydrological cycle. Various components of the water cycle are quantified such that one remaining unknown, typically glacier melt, can be estimated from measured discharge. The basic hydrological balance equation may be stated as:

\[ Q = P + \Delta G - G_W - E \]

where \( Q \) is total discharge from the glacierized watershed, \( P \) is precipitation, \( \Delta G \) is change in glacier storage, \( G_W \) is groundwater flux and \( E \) is net evapotranspiration (Mark and Seltzer, 2003). Balance equations may be further simplified if the assumption that
evapotranspiration and/or groundwater flux are minimal in high mountain watersheds can be justified (Aizen et al., 1996; Mark et al., 2005). Conversely, the balance equation can be rendered significantly more complex if processes such as sublimation and differential evaporation (as a function of land cover type) are considered (Baraer et al., 2012). The hydrological balance may be calculated for a specific season in which glacier meltwater is expected to be at a maximum, over the entire hydrological year, or even for an aggregated collection of years. Decadal balance calculations are viewed as advantageous based on the assumption that interannual variability in precipitation, groundwater fluxes, and soil moisture status will tend towards zero over an extended period of time (Singh et al., 1997; Baraer et al., 2012).

Accurate watershed-scale quantification of each term in the water cycle is limited by measurement error and the uncertainty of basin-wide extrapolation of point observations. Stream discharge and precipitation are challenging variables to measure accurately (Wood et al., 2000; Legates and Willmott, 2006). Precipitation is also the most difficult component to interpolate since local factors such as elevation, aspect, vegetative cover and wind patterns result in very high spatial heterogeneity (Mark and Seltzer, 2003; Mark et al., 2005). This uncertainty is compounded by the fact that pertinent data may only be available from meteorological stations located at lower elevation sites, where hydro-climatic conditions are likely to be considerably different than those farther upstream. The precipitation measurement challenge can make it difficult to differentiate glacier meltwater from seasonal snowmelt (Mark et al., 2005), and some studies report only an aggregated glacier melt/seasonal snowmelt term (e.g.
Singh et al., 1997; Singh and Jain, 2002), prohibiting direct comparison with studies that are able to isolate the two.

Evaporation and sublimation are also challenging to quantify in mountain watersheds, where few direct observations are maintained. Some studies exclude them completely (e.g. Baraer et al., 2012) while others use minimal empirical information to estimate them. Given a lack of local data, Mark and Seltzer (2003) apply an evaporation factor to their precipitation measurements based on data obtained at a site hundreds of kilometers away while Singh et al. (1997) and Singh and Jain (2002) are forced to extrapolate evaporation obtained from a single evaporation pan across seasonal snow-free areas in watersheds of 22,200 km$^2$ and 22,305 km$^2$, respectively. In the latter two cases, evaporation from snow-free areas is estimated, but sublimation from snow and ice-covered areas is not. In arid mountain watersheds with strong winds and high solar radiation, sublimation can be a substantial component of the water cycle. In the arid Chilean Andes, Gascoin et al. (2011) estimate that sublimation reduced annual discharge by as much as 10%.

Hydrochemical tracer approaches

Waters of different provenance tend to have unique hydrochemical signatures as a result of the specific hydrological, geological and biological processes to which they have been exposed (Drever, 1997). Thus, it is possible to quantify the proportion of hydrochemical ‘end-members’ to streamflow by analyzing the water chemistry (Christophersen and Hooper, 1992). Conservative chemical constituents in natural waters such as stable isotopes and major solutes can serve as tracers that can be used to
reconstruct the hydrological routing of an end member (Hooper and Shoemaker, 1986). Hydrochemical tracer approaches to quantifying the contribution of glacial meltwater to watershed discharge thus isolate the hydrochemical signature of the meltwater and employ volumetric mixing models to estimate its proportional contribution to streamflow (Mark et al., 2005). The simplest mixing models differentiate two end members (glacial and non-glacial) in a ‘concentration space’ such as a Piper diagram (Mark et al., 2005), though more complex mixing models that distinguish a greater number of end members (e.g. glacier melt, surface runoff and groundwater discharge) are possible using Bayesian and other statistical analysis techniques (Baraer et al., 2009; Cable et al., 2011).

The hydrochemical tracer approach is reliant upon several key assumptions. The most fundamental is that the hydrochemical signatures of various end members are sufficiently distinct. Similarly, the approach assumes that the tracer being employed is conservative within the study watershed, meaning that no additional isotopic fractionation or solute-altering chemical reaction has taken place along the flow path between source and mixing point (Mark et al., 2005; Baraer et al., 2009). The chemical characteristics of the mixed stream water must solely be a function of the proportions of the respective end members that have been mixed into it rather than any post-mixing chemical processes, otherwise the mass of the solute in the mix will not be representative of the proportional input from each end member (Christophersen et al., 1990). Hydrochemical tracer approaches also assume that chemical characteristics defining each end member capture the range of natural hydrochemical variation that each water source might experience. For example, ‘glacier meltwater’ is typically a mixture of waters
originating from different ablation processes and englacial pathways that are subject to differential isotopic fractionation and chemical reactions (Sharp et al., 1995; Nolin et al., 2010), while meltwater derived from different glaciers within a single watershed may be chemically-distinct due to factors such as bedrock geology, ice flow rate and sub-glacial drainage patterns that can be unique to each glacier (Yuanqing et al., 2001). Groundwater signatures may be similarly variable given that solute concentrations are influenced by the specific geology in the immediate vicinity of the flow paths, something that is often highly heterogeneous in mountain environments (Brown et al., 2006). This assumption of minimized end member variability can also be a limiting factor in efforts to use hydrochemical tracers to describe the seasonal variation of glacial meltwater contributions to discharge, since any temporal variation in the mixed water chemistry must be assumed to represent changing proportional contributions from each end member (e.g. Maurya et al., 2011).

Despite the limitations of these assumptions, the hydrochemical tracer approach has a number of notable advantages over other techniques. First, tracer analyses do not require the detailed, often long-term glaciological and meteorological observations needed for each of the other approaches since one sampling suite is sufficient to provide a reasonable snapshot of the watershed if made during baseflow conditions. Second, they do not require an explicit calculation of hydrological parameters that can be very difficult to accurately measure in the field, such as groundwater exchange and evapotranspiration (Mark et al., 2005; Kong and Pang, 2012). Third, obtaining hydrochemical data is easy and inexpensive, even in remote watersheds (Mark and Seltzer, 2003; Nolin et al., 2010),
notwithstanding the costs of laboratory analysis that may present financial challenges for researchers/institutions with limited resources. Fourth, depending upon the sampling design and hydrochemical characteristics of the watershed, hydrochemical tracers can be very effective at capturing variation in glacial meltwater contributions at high temporal and spatial resolutions (Brown et al., 2010; Kong and Pang, 2012).

Given the requisite assumptions of this approach, some studies are limited to a simplified partitioning of watershed discharge without explicit terms of uncertainty. For example, Mark and Seltzer (2003), using both isotopes and solutes, only classify water as glacial meltwater or precipitation-derived runoff, while Fujita et al. (2007), using solutes (as measured by electroconductivity), differentiate only glacial meltwater and soil water. It can be very difficult to know with high confidence whether or not the hydrochemical signatures of various components are sufficiently uniform to support the assumption of end member uniqueness (Nolin et al., 2010), especially when a relatively small number of samples are used to characterize each component within the watershed. It can be similarly difficult to know whether or not a tracer is conservative, especially in highly dynamic, geologically-heterogeneous mountain watersheds (Mark and Seltzer, 2003). An additional area of uncertainty is associated with the hydrochemical differentiation of glacier ice and seasonal snow melt (Cable et al., 2011).

Stable isotopes of water ($^{18}$O and $^2$H) (e.g. Mark and McKenzie, 2007; Nolin et al., 2010; Cable et al., 2011) and various solutes (e.g. major ions such as Ca$^{2+}$, Na$^+$, Cl$^-$ and SO$_4^{2-}$) (e.g. Mark et al., 2005; Brown et al., 2006) are the tracers most commonly employed in end-member mixing analysis. Stable isotopes are useful because different
hydrological components are exposed to different fractionation processes as they transit the water cycle (Kendall and McDonnell, 1998). The relationship between $^{18}$O and $^2$H within a water sample, known as deuterium-excess, is also a useful tracer since it is strongly controlled by the amount of evaporation to which the water has been exposed (Maurya et al., 2011). Solute concentrations are appropriate tracers because different components of the water cycle tend to be dominated by different ions. For example, precipitation tends to have high proportional concentrations of Cl$^-$, since atmospheric vapor evaporated from salty oceans will contain this ion, but low proportional concentrations of ions such as Ca$^{2+}$ and Mg$^{2+}$ that are largely derived from bedrock. Because many solute concentrations are controlled by both rock-type and residence time in the geologic system, an observed change in the solute concentration is often a strong indication of a change in dominant water source within the watershed (Brown et al., 2006). Because stable isotopes are especially effective for distinguishing glacier meltwater from precipitation and snowmelt while solutes are most effective for differentiating groundwater from other hydrological components, many studies incorporate both tracer approaches in their analyses (e.g. Mark and Seltzer, 2003; Baraer et al., 2009; Maurya et al., 2011; Kong and Pang, 2012). Electrical conductivity has also been used as a tracer, since it reflects the overall ionic concentration of the water (Fujita et al., 2007; Maurya et al., 2011; Kong and Pang, 2012) but there is disagreement about whether or not it meets the requirement for being conservative in the watershed (Sharp et al., 1995; Moore et al., 2008).
Hydrological models

Hydrological modeling represents the most frequently-applied approach to quantifying the proportional contribution of glacial meltwater. Models generally employ a set of nested equations that solve the water balance while simulating the spatial and temporal variation of various hydrological components such as precipitation, groundwater fluxes, seasonal snowmelt and ice melt. Because models are designed to use local meteorological, glaciological and hydrological data to simulate hydrological processes, they can improve our understanding of observed processes within a watershed (Verbunt et al., 2003) and can help pinpoint areas where knowledge is lacking, additional measurements are needed, and uncertainty is greatest (Pellicciotti et al., 2012). Models are also very useful for testing hypotheses such as how discharge responds to changing climate (e.g. Koboltschnig et al., 2007) and/or different water management decisions (e.g. Jeelani et al., 2012).

There are two general classes of hydrological models (Farinotti et al., 2012). Physically-based models are based on the governing physical principles that drive hydrological response to climatic and other biophysical conditions. These models often produce results with the highest temporal resolution and the lowest uncertainties, however they generally require a great deal of input data, are computationally-intense (Koboltschnig et al., 2008), and thus are usually limited in application to smaller watersheds where extensive monitoring provides verification (Huss, 2011; Boscarello et al., 2012). Conceptual models use statistical relationships based on past hydro-climatic observations to simulate hydrological behavior without resolving small-scale physical
processes (Hagg et al., 2011). This approach simplifies the amount of input data needed (excluding, for example, wind and radiative flux data), making them more appropriate for use in watersheds in remote areas where limited data have been accumulated. Conceptual models are, however, more prone to the problem of ‘equifinality’ (Hagg et al., 2011), the condition whereby different combinations of model parameters produce the same output, that is a primary source of uncertainty in hydrological modeling (Beven, 2006).

Furthermore, because conceptual models are developed for specific locations and epochs, they are not transferable in space or time. While some researchers develop new glacio-hydrological models specifically for their study (e.g. Schaefli et al., 2005; Rees and Collins, 2006; Jeelani et al., 2012), most incorporate glacier melt modules into existing hydrological models such as HBV and its variants (Shahgedanova et al., 2009; Gao et al., 2012; Jost et al., 2012), SRM (Immerzeel et al., 2010; Nolin et al., 2010) or PREVAH (Koboltschnig et al., 2007; Koboltschnig et al., 2008) (Table 2.3). Some modeling studies do not explicitly quantify the proportional contribution of glacial meltwater but rather describe only overall discharge patterns (e.g. Mukhopadhyay and Dutta, 2010); these are nonetheless included in this review since they are subject to the same assumptions and uncertainties.

Models can operate at temporal resolutions ranging from hourly (e.g. Verbunt et al., 2003; Koboltschnig et al., 2008; Prasch et al., 2013) to monthly (e.g. Juen et al., 2007; Mukhopadhyay, 2012), and spatial resolutions ranging from as little as 25 m (e.g. Schaefli et al., 2005) to many kilometers (e.g. Comeau et al., 2009; Schaner et al., 2012), both of which greatly influence the nature of the information provided by the model.
Table 2.3. Hydrological models adapted for studies quantifying the contribution of glacier meltwater to watershed discharge.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Class</th>
<th>Authors(a)</th>
<th>Spatial Discretization(b)</th>
<th>Time-Step</th>
<th>Standard Input Data(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEST-WB</td>
<td>Conceptual</td>
<td>• Boscarello et al., 2012</td>
<td>Gridded (500 m)</td>
<td>Hourly</td>
<td>Air temperature; precipitation; runoff; snow cover; topography; soil characteristics; glacier area</td>
</tr>
<tr>
<td>HBV</td>
<td>Conceptual</td>
<td>• Hagg et al., 2007 (HBV-ETH) (f)</td>
<td>HRU</td>
<td>Daily</td>
<td>Air temperature; precipitation; runoff; topography; land cover; glacier area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Akhtar et al., 2008 (f)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Stahl et al., 2008 (f)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Shahgedanova et al., 2009 (HBV-ETH) (f)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Hagg et al., 2011 (f)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Gao et al., 2012 (HBV-Light) (f)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Jost et al., 2012 (HBV-EC) (f)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GERM</td>
<td>Conceptual</td>
<td>• Huss et al., 2008 (f)</td>
<td>Gridded (25 m)</td>
<td>Daily</td>
<td>Air temperature; precipitation; runoff; topography; land cover; glacier volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Huss et al., 2010 (f)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Farinotti et al., 2012 (f)</td>
<td></td>
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<td></td>
<td></td>
<td>• Gabbi et al., 2012 (f)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSM-SOCONT</td>
<td>Conceptual</td>
<td>• Schaeffli et al., 2005</td>
<td>HRU</td>
<td>Daily</td>
<td>Air temperature; precipitation; potential evapotranspiration; runoff; glacier area; glacier mass balance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Horton et al., 2006 (f)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Schaeffli and Huss, 2011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITGG-2.0 R</td>
<td>Physically-based</td>
<td>• Juen et al., 2007 (f)</td>
<td>HRU</td>
<td>Monthly</td>
<td>Air temperature; precipitation; runoff; solar radiation; albedo; atmospheric emissivity; proportion of sublimation to melting; glacier area</td>
</tr>
<tr>
<td>J-2000</td>
<td>Conceptual</td>
<td>• Nepal et al., 2012 (f)</td>
<td>HRU</td>
<td>Daily</td>
<td>Air temperature; precipitation; sunshine hours; wind speed; relative humidity; soil characteristics; glacier area</td>
</tr>
<tr>
<td>OEZ</td>
<td>Conceptual</td>
<td>• Hagg et al., 2007 (f)</td>
<td>HRU</td>
<td>Monthly</td>
<td>Air temperature; precipitation; runoff; topography; land cover; glacier area; glacier mass balance</td>
</tr>
<tr>
<td>PREVAH</td>
<td>Conceptual</td>
<td>• Koboltschnig et al., 2007</td>
<td>HRU</td>
<td>Hourly</td>
<td>Air temperature; precipitation; humidity; wind speed; sunshine duration; solar radiation; land cover; runoff; glacier area; glacier mass balance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Koboltschnig et al., 2008</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PROMET</td>
<td>Physically-based</td>
<td>• Prasch et al., 2012 (f)</td>
<td>Gridded (1 km)</td>
<td>Hourly</td>
<td>Air temperature; precipitation; topography; land cover; glacier area</td>
</tr>
<tr>
<td>SNOWMOD</td>
<td>Conceptual</td>
<td>• Singh et al., 2006 (f)</td>
<td>HRU</td>
<td>Daily</td>
<td>Air temperature; precipitation; runoff; glacier area</td>
</tr>
</tbody>
</table>

(a) (f) indicates an additional scenario-based modeling of future glacier meltwater contribution component.
(b) HRU = Hydrological Response Units. For gridded spatial discretization, the highest applied grid-cell resolution is given.
(c) Includes data used for model calibration (usually runoff and/or glacier mass balance)
Models with shorter time-steps require more detailed input data and greater computing power/time (Verbunt et al., 2003), which may be limiting factors as the size of the modeled watershed increases. The coarse spatial resolutions necessary for modeling large watersheds typically require a greater number of simplifying assumptions and more generalized parameters (Schaner et al., 2012).

Model parameters fall into two categories: empirical parameters determined from field measurements or statistical relationships that generally have some physical basis; and calibration parameters determined during the model tuning process (Zhang et al., 2011b). As the number of calibration parameters increases, model uncertainty increases in response to the elevated risk of equifinality (e.g. Konz et al., 2007; Gao et al., 2012).
Model performance is thus a function of empirical parameter quality, with uncertainty increasing as data become less temporally or spatially complete (Gao et al., 2012; Mukhopadhyay, 2012; Nepal et al., 2013). A lack of data also leads to increased uncertainty due to necessary reductions in model complexity and increases in calibration parameters. Recent research has focused on improving modeling in otherwise data-poor watersheds by developing techniques for acquiring data via remote sensing and improving downscaling of macro-scale datasets (Konz and Seibert, 2010; Prasch et al., 2013).

As with other methodological approaches to quantifying the contribution of glacier meltwater, researchers must make explicit their key assumptions and simplifications, for example assumptions about the accuracy of extrapolated climate data, the routing of meltwater through downstream hydrological systems (e.g. Comeau et al., 2009) or the explicit conditions causing ablation (Farinotti et al., 2012). Modeling studies may assume that the data used to calibrate and validate the model are error-free and thus that discrepancies between simulated and measured outputs are due to problems with model parameterization rather than potential measurement error (e.g. Prasch et al., 2013). Conversely, it can also be tempting to overly trust the model rather than field measurements when there are large discrepancies between the two, even when there is no direct evidence that the measurements are erroneous (e.g. Mukhopadhyay and Dutta, 2010).

There are numerous sources of uncertainty in the hydrological modeling approach, including those associated with model structure, those associated with
parameterization of the model, and those associated with equifinality. Structural uncertainty is enhanced for conceptual models that are not explicitly constrained by guiding physical processes, for example a glacier evolution model that does not incorporate ice flow mechanics (e.g. Farinotti et al., 2012). Indeed, because different models forced with the same parameter set may produce considerably different results (e.g. Hagg et al., 2007), selection of the most appropriate model remains a key challenge (Huss et al., 2010). One of the most critical structural decisions a researcher using the modeling approach must make is whether to employ an energy balance or temperature-index melt module. The greater simplicity and lower data requirements of the temperature-index approach make it an attractive option, and though temperature does correlate with other important factors such as radiation and wind patterns, their exclusion will increase uncertainty (Gabbi et al., 2012). So-called ‘enhanced temperature-index’ models that incorporate radiative fluxes can mitigate this uncertainty somewhat (Verbunt et al., 2003; Pellicciotti et al., 2012), though it is a lack of this sort of data that forces the use of temperature-index approaches in the first place. It should be noted that the temperature-index approach is generally not applicable in tropical climates since moisture and radiative fluxes control ablation rather than sensible heat (Juen et al., 2007).

Parameter uncertainty is related to the same data measurement uncertainties that plague the direct discharge measurement, glaciological and hydrological balance approaches: a dearth of weather data collected in the higher elevations of watersheds (Pellicciotti et al., 2012); an inability to accurately measure precipitation, especially snow accumulation (Hagg et al., 2007; Boscarello et al., 2012) and the need to interpolate
precipitation measurements across highly heterogeneous mountain landscapes (Koboltschnig and Schoner, 2011); a lack of empirical evapotranspiration data (Horton et al., 2006; Koboltschnig et al., 2008); and uncertainty about the accuracy of stream discharge measurements, especially at higher flows (Nepal et al., 2013). Pellicciotti et al. (2012) suggest that model parameterization may be a larger source of uncertainty than has generally been recognized, while Blöschl and Montanari (2010) argue that uncertainty assessment remains an area of weakness and that this is an area where researchers must make progress. Greater attention to parameter sensitivity has been suggested as one approach to meeting this challenge (Nepal et al., 2013).

Glaciological parameters are a particular source of uncertainty in hydrological modeling approaches. This is partly due to the inherent challenge of trying to resolve both the hydrological balance and glacier mass balances simultaneously (Schaefli and Huss, 2011), but also because existing glacier volumes are often highly generalized, especially in macro-scale modeling applications (Gabbi et al., 2012). Many researchers have concluded that mass balance data are essential for reducing equifinality and improving model performance (Braun and Aellen, 1990; Koboltschnig and Schoner, 2011; Schaefli and Huss, 2011), though the lack of such data is one reason a researcher might employ a hydrological model rather than using a glaciological approach. The ability to incorporate limited mass balance data (as little as a single year) along with just a few days of melt-season discharge information has been shown to greatly reduce uncertainty in model performance (Konz and Seibert, 2010), though Schaefli and Huss (2011) caution that glacier-wide mass balance data derived from a single measurement
point are prone to considerable error. The geodetic approach to reconstructing mass balance offers an alternative, but this too is reliant upon the existence of high-quality data covering multiple years. As with other approaches, differentiating between ice melt and seasonal snow melt can also be a challenge, though the existence of remotely-sensed data such as the MODIS snow-cover product can help improve parameter sets where they are scale appropriate (Koboltschnig et al., 2008; Pellicciotti et al., 2012).

Equifinality is a troublesome source of uncertainty because it occurs when the model appears to have accurately simulated reality without having actually replicated the true relationship among model parameters. Equifinality is especially common when glacier mass balance processes are poorly parameterized, since other model parameters are likely to be erroneously adjusted in order to better match measured discharge (Schaefl et al., 2005; Konz and Seibert, 2010). Researchers suggest calibrating the model against multiple empirical parameter sets rather than the usual single set (typically discharge), since doing so permits a better assessment of model consistency (Verbunt et al., 2003; Pellicciotti et al., 2012). Various random sampling techniques have been employed to identify the most likely combination of calibration parameter values, with the best parameter set identified using a statistical correlation test (e.g. Schaefl et al., 2005; Finger et al., 2012; Gao et al., 2012; Nepal et al., 2013). However, Pellicciotti et al. (2012) note that different types of correlation tests could yield different ‘best’ parameter sets, thus introducing yet another source of uncertainty.

Many studies employing hydrological modeling incorporate an additional scenario-based component to describe potential future glacier meltwater contributions
within a watershed, and some make this their sole objective (e.g. Loukas et al., 2002; Akhtar et al., 2008; Huss et al., 2008). Such scenario-based modeling is subject to additional uncertainties about the future behavior of hydro-climatic systems due to: unanswered questions about the rate and intensity of future climate change (Huss et al., 2010); the response of glaciers to climate change (Immerzeel et al., 2010); and the response of watersheds to glacier change and other shifting climatic conditions (Farinotti et al., 2012).

**Discussion**

Our survey of the literature reveals that the methodological approaches available for a specific study are constrained by both social (e.g., monitoring capacity) and environmental (e.g. climate, geology) conditions in the study area; and that the methodological approach selected for the study limits the nature of the conclusions that can be drawn as a result. Researchers considering potential approaches for their own studies need to be aware of these constraints before settling upon any particular research design.

A fundamental decision that researchers must make at the outset is how they will define ‘glacial meltwater’ (Gao et al., 2012; Jost et al., 2012). Some studies report the contribution from glacierized areas, including both ice melt as well as water generated by seasonal snowpack in the glacier’s ablation zone and on bare surfaces (e.g. Nepal et al., 2013) while others exclude seasonal snowmelt from the estimate (e.g. Stahl et al., 2008). This distinction is important because the volume of water generated by seasonal snowmelt on a glacier surface can be a significant proportion of the discharge generated
by the glacierized portion of the watershed (Verbunt et al., 2003; Huss, 2011) and may actually dominate discharge early in the melt season (Pelto, 2008). Though most studies do not differentiate between glacier ‘melt’ and ‘wastage’ (Hopkinson and Young, 1998), this distinction is important because glacial meltwater influences watershed yield at different temporal scales. Wastage represents the hydrological consequence of negative mass balance and thus describes the impact of glacial meltwater on interannual time scales, whereas melt describes both wastage and the water stored and released by the glacier within a single hydrological year and thus the seasonal buffering of watershed yield at intra-annual time scales (Hopkinson and Young, 1998; Gao et al., 2012). Because different techniques have different capabilities for differentiating between ice melt and seasonal snow melt, and between glacier melt and glacier wastage, researchers must decide upon their intent before selecting their methodological approach. These variable definitions for glacial meltwater mean that conclusions drawn from one study may not be directly comparable to those of another.

Researchers should account for the spatial and temporal variability of glacial meltwater contribution in their research design. Given the importance of the glacial compensation effect to watershed hydrology, quantification of seasonal variability is especially important lest the study misinterpret the relative importance of glacial meltwater at key times during the hydrological year (e.g. Jeelani et al., 2012). Glaciological and hydrological balance equation approaches often rely on data representing conditions over an entire year and thus may be limited in their ability to describe these seasonal variations. Direct discharge measurement and hydrochemical
tracers approaches provide discrete estimates of meltwater contribution, thus
measurements need to be repeated multiple times to capture its seasonal variation.
Hydrological models are effective at identifying variation, even when run at monthly
time-steps. The proportional contribution of glacial meltwater is also a direct function of
the location within the watershed at which total discharge is being measured. While some
researchers calculate discharge at a logical watershed pour-point such as a major river
confluence, others use locations where there happens to be a stream gauge with discharge
data of sufficient quality (e.g. Singh et al., 1997). The problem this presents is that the
proportional contribution estimated at that point may not accurately reflect conditions
elsewhere in the watershed, particularly at a key location such as a specific irrigation
intake canal. Those techniques that depend upon measured downstream discharge data,
such as glaciological and hydrological balance approaches and some hydrological
modeling approaches, may be particularly prone to this limitation.

Finally, researchers must be cognizant of the other conditions that can limit the
range of methodological options available to them. The two most significant constraints
guiding the selection of a technique, which are often tightly interwoven, are watershed
accessibility and the availability of existing hydrologic, glaciologic and climatologic data.
Approaches that yield estimates with better spatial and temporal resolution and with less
overall uncertainty are almost always limited to readily accessible watersheds where
monitoring infrastructure has already been put in place, and data management capacities
are more highly developed (e.g. Verbunt et al., 2003; Gascoin et al., 2011; Pelto, 2011).
While a number of creative data interpolation techniques have been employed to leverage
existing data sets collected from outside the study area (e.g. Juen et al., 2007; Marshall et al., 2011), these data sources will still result in greater uncertainty about actual conditions within the study watershed. The development of techniques that are applicable in ungauged watersheds has been one key area of research (Konz et al., 2007; Huss, 2011). Hydrochemical tracer methods (e.g. Mark and McKenzie, 2007; Maurya et al., 2011) and hydrological models parameterized from global-scale data sets (e.g. Immerzeel et al., 2010; Mukhopadhyay and Dutta, 2010) present potential opportunities in this regard, though each introduces its own uncertainty to the study.

Areas for future research emphasis

There will be many sources of uncertainty regardless of the methodological approach taken to estimate the proportional contribution of glacier meltwater to total watershed discharge. Future research must thus address the dual needs of providing information about the glacio-hydrological conditions in specific watersheds where the hydrological impact of glacier meltwater is considerable, as well as identifying new techniques for reducing methodological uncertainties. Miller et al. (2012) suggest several specific lines of research that will help address uncertainty, including improving our ability to quantify the spatial variability of glacial and seasonal snow melt, improving our understanding of current and future streamflow patterns, and continuing to improve the performance of glacio-hydrological models. Sorg et al. (2012) argue that fully-distributed, physically-based models are better able to simulate the complexities of watershed hydrology and the transient shifts in hydrological and glaciological conditions that can be expected due to climate change, thus further refinement of these models and
reductions in computational and data limitations should be priorities. A frequent obstacle to modeling and most other approaches is a lack of high-quality meteorological, hydrological and glaciological data, underscoring the ongoing need for additional monitoring networks involving both the research community and appropriate water management authorities. Improved dissemination of data collected from short-term monitoring efforts would also benefit the research community, since these data are especially valuable in places where no long-term monitoring program has been established (Pellicciotti et al., 2012). Because predictive modeling of future glacio-hydrological conditions requires well-constrained estimates of current glacier geometry and mass balance behavior, as well as reasonable predictions of future glacier geometry and extent, emphasis on ice-thickness surveys in many mountain regions would also be highly useful (Stahl et al., 2008; Marshall et al., 2011; Gabbi et al., 2012).

There is tension within the literature between the desire to investigate small watersheds, where conditions are more homogenous and thus uncertainty is generally lower, and larger watersheds where studies are relevant to a greater number of people. However, despite the desire to generalize findings from a small sample of watersheds, the high temporal and spatial heterogeneity of mountain climatic, hydrological and glaciological systems makes necessary the investigation of a wide array of watersheds, especially as these systems respond to global climate change (Baraer et al., 2012). Furthermore, it is worth reemphasizing that glacial meltwater can be a critical hydrological component in small, headwaters watersheds even when its contribution is
negligible at the macro-scale (Comeau et al., 2009; Miller et al., 2012) and the water resources implications of glaciers are worth investigating in these areas as well.

Three other areas of potential future research emphasis are worth noting. First, given the signal role of glacial meltwater in buffering stream flow during dry periods – especially during periods of intense heat and/or extended drought – there is considerable value in specifically investigating the contributions of glacial meltwater in these hydrologically-significant years (e.g. Koboltschnig et al., 2007). Second, there has been very little research about the relationship between glacial meltwater and nearby groundwater systems. Despite the common assumption that there is minimal infiltration in high, rocky mountain watersheds, there is evidence that groundwater systems can play a substantial hydrological role in glacierized watersheds (Favier et al., 2008; Baraer et al., 2009; Andermann et al., 2012). Given enhanced melting expected in most mountain areas over the next century, understanding these linkages is important. Third, considering the importance of projecting future discharge under the shifting glacial conditions of global climate change, there will be increasing value in returning to previously investigated watersheds to validate earlier predictions with direct measurements, especially as time progresses.

Finally, echoing the detailed recommendations of Viviroli et al. (2011), we believe that more emphasis should be placed on integrating this area of research with the specific needs of watershed stakeholders. When stakeholders are engaged in the research design and are provided specific results in a useable format, the socio-economic motivations for investigating glacio-hydrological systems are better met (Miller et al.,
Given the high spatial and temporal variability of glacial meltwater contributions, we suggest that research should investigate the current and potential future hydrological significance of meltwater at specific locations such as hydroelectric facilities and important water diversions so that managers of this infrastructure can better adapt research results into their planning and operations (e.g. Jeelani et al., 2012). We also wish to emphasize the value of transdisciplinary research in improving our ability to understand watershed hydrology in mountain areas (e.g. Mark et al., 2010; Bury et al., 2011), given the tight coupling of natural and human systems in this environment.

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Chapter 3: Detecting patterns of climate change at Volcán Chimborazo, Ecuador by integrating instrumental data, public perceptions and glacier change analysis

Introduction

The people of Andean Ecuador face a suite of potential risks due to climate change, including decreased food production, increased exposure to vector-borne diseases, and less reliable water supplies (IPCC 2014). People in the rural, agrarian communities of the region are especially vulnerable because their persistent economic
and political marginalization (e.g. Hentschel and Waters 2002, Jokisch 2002, Craps et al. 2004, Farrow et al. 2005) tends to leave them with limited capacity to document environmental change and develop feasible mitigation strategies. This is especially true at a time when the unprecedented climate change that is unfolding (Mora et al. 2013) exceeds anything within cultural memory (Rhoades, Rios and Ochoa 2008). A fundamental obstacle for those seeking to assess patterns of climate change in Andean Ecuador is the lack of detailed, long-term meteorological data for the region (Vuille et al. 2008), which is especially problematic given the high biogeophysical heterogeneity that is characteristic of this landscape (Buytaert et al. 2010). Instead, a synthesis of available empirical data with information from other sources, such as evidence from sensitive features such as glaciers and anecdotal reports from local residents, will be necessary if we are to improve our understanding of local manifestations of climate change.

In data-sparse regions of the world, qualitative information derived from surveying people’s perceptions of climate change has been successfully used to identify local-scale trends that are not evident within regional-scale analyses (West, Roncoli and Ouattara 2008, Marin 2010). Similarly, glacier change analysis has been used to infer local patterns of climate change in areas where detailed meteorological records and glacier mass balance data are lacking, including in the tropical Andes (Ceballos et al. 2006, Salzmann et al. 2013). While it can be risky to make sweeping statements about glacier response to climate change without establishing clear mass-balance records (Hoelzle et al. 2007), the high sensitivity of tropical glaciers to climatic perturbations (Kaser and Osmaston 2002, Vuille et al. 2008) suggests that there is minimal decoupling
of ice surface area and climatic behavior here. In Andean Ecuador, glacier equilibrium line altitudes tend to closely match the mean 0°C isotherm so that ablation zones (typically the lower 20% of a tropical glacier) consistently experience above-freezing conditions. Small changes in air temperature thus manifest in a shifting snowline elevation, which drives variations in glacier melt as the ice surface albedo responds to the presence or absence of fresh snow (Favier et al. 2004a). Similarly, if the interval between precipitation events increases or the duration of precipitation events decreases, the amount of time glacier tongues are in a snow-free, low albedo state will increase, and the rate of ice melt will accelerate. Because ablation occurs year-round in Ecuador’s thermally-homogenous tropical climate, glaciers here will respond very rapidly if temperature or precipitation patterns change. Given their limited size and thickness, this will result in concomitantly rapid changes in ice surface geometry.

In Andean Ecuador, detailed climatological and glacier mass balance data have only been methodologically-collected at Volcán Antisana, ~130 km northeast of Chimborazo, where a long-term monitoring program was established in 1994 (Francou et al. 2000, Favier et al. 2004a, Favier, Wagnon and Ribstein 2004b, Francou et al. 2004, Cáceres et al. 2006, Cadier et al. 2008, Favier et al. 2008, Villacís 2008, Collet 2010). However, glacier mass balance behavior at Antisana may not be indicative of Chimborazo’s given the heterogeneous nature of precipitation seasonality and intensity in the Ecuadorian Andes (Pourrut et al. 1995, Farrow et al. 2005). In particular, Antisana’s closer proximity to the Amazon Basin, from which most of the region’s precipitation is derived, means that precipitation patterns and glacier changes recorded there may be
inconsistent with the recent behavior of the more semi-arid Chimborazo climate. Already, there is evidence that local-scale climate patterns in Andean Ecuador may contradict apparent regional trends (Rhoades et al. 2008). Thus, while the monitoring efforts at Antisana may provide a more detailed and complete dataset, there is risk in assuming that those data speak to conditions at Chimborazo simply because they are scientifically rigorous.

The objective of this research is to describe the recent, local-scale patterns of climate change at Volcán Chimborazo, Ecuador through an integration of available climatological data, qualitative data provided by local residents, and information derived from a detailed analysis of recent glacier change (1986-2013) on the mountain. Specifically, I identify existing climatological records for the region and analyze apparent trends in temperature and precipitation, report on the perceptions of recent climate change as experienced by people living in the agrarian communities at the foot of the mountain, and document the extent and spatial patterns of glacier surface area change between 1986 and 2013. Our expectation is that this mixed approach will provide insights into patterns of climate change at Chimborazo that would otherwise be unavailable, and will demonstrate that it is possible to effectively document climate change even in the absence of ‘ideal’ empirical data.

A secondary objective of this work is to construct a detailed, up-to-date glacier inventory for Volcán Chimborazo in order to provide useful baseline data that can be used in future climate change analyses. Systematic mapping of Chimborazo’s glaciers was first attempted by the national mapping agency Instituto Geográfico Militar (IGM) as
part of the development of a nationwide 1:50000 topographic series (Cáceres 2010), however the 1962 aerial photograph used in this project featured fresh snowfall to elevations several hundred meters below actual ice lines, which confounded glacier mapping and led to a significant overstatement of glacier coverage (B. Caceres, pers. comm.). Glacier assessments that rely on this source (Jordan and Hastenrath 1998, Cáceres 2010) are thus similarly inaccurate. Additionally, inconsistent nomenclature has long been a problem in identifying Chimborazo’s individual glaciers, in part because their geometry has evolved considerably since the early 20th century. There are considerable discrepancies among existing descriptions and mapping efforts (e.g. Hastenrath 1981, Clapperton and McEwan 1985, Jordan and Hastenrath 1998, Jordan and Buchroithner 2009, Cáceres 2010) and the data currently cataloged in the World Glacier Inventory (WGI; WGMS and NSIDC 2012) incorporates several errors. I present this inventory to correct these errors and to clarify ongoing confusion.

**Study Area**

The Ecuadorian Andes are divided into two parallel ranges averaging 4000-4500 m in elevation that are punctuated by a series of stratovolcanoes which rise to 5000 meters and above. Volcán Chimborazo (6268 m.a.s.l.; 1.47ºS, 78.82ºW), the southern-most volcano in the Cordillera Occidental (western range), is the highest of these peaks (Figure 3.2). The summit of Chimborazo’s 90 km² massif is mantled by a ~55 m-thick icecap (Ginot et al. 2002), from which glaciers radiate outward in all directions. Chimborazo is considered to be dormant, with its last eruption estimated to have occurred ~420 and 700 CE (Barba et al. 2008). Settled, agriculturally-productive areas begin at
Figure 3.2. Overview map of the Chimborazo region. Focus group communities are labeled.

~4000 m.a.s.l. and extend outward from the lower slopes of the mountain, especially to the south and east in the Rio Chimborazo and Rio Guano watersheds.

Chimborazo’s tropical climate is thermally-homogenous, with only a ~2°C variation in mean temperature between the coolest months (July and August) and the
warmest months (November and December; Figure 3.3). Precipitation seasonality is pronounced, with the annual oscillation of the Intertropical Convergence Zone (ITCZ) resulting in two wet seasons, one long (February – May) and one short (October – November). Convective precipitation is common during the two intervening ‘dry’ seasons (June – September and December – January). Despite its relative proximity to the Pacific Ocean, moisture generally arrives from the Amazon Basin on northeasterly winds and highly heterogeneous, topographically-driven precipitation patterns are apparent (Figure 3.4). On Volcán Chimborazo itself, there is a strong northeast (up to 2000 mm yr-1) to southwest (less than 500 mm yr-1) precipitation gradient. Four elevation-dependent climate zones exist within close proximity of the mountain (Pourrut et al. 1995). The
Alpine climate describes those areas above ~4500 m.a.s.l. where sub-freezing temperatures and snowfall are dominant. The Equatorial High Mountain climate is cool and damp, with mean annual temperatures between 0°C and 12°C, mean annual precipitation greater than 600 mm (except on leeward slopes) and no annual moisture deficit. The Equatorial Semi-Humid Temperate climate features mean annual temperatures between 12°C and 22°C and mean annual precipitation of at least 600 mm while the semi-arid Equatorial Dry Temperate climate features mean annual temperatures between 12°C and 22°C, mean annual precipitation less than 600 mm and a potential
annual moisture deficit of up to 600 mm (GADPCH 2011). Interannual climatic variability can be considerable and is primarily driven by the El Niño – Southern Oscillation (ENSO), with El Niño (La Niña) bringing warmer (cooler) and drier (wetter) conditions (Vuille, Bradley and Keimig 2000).

Since 1939, mean atmospheric temperatures in the tropical Andes (Ecuador, Peru and Bolivia) have increased 0.10°C decade⁻¹ (0.68°C total; Vuille et al. 2008), and within Ecuador specifically, mean minimum and maximum daily temperatures have both increased while the mean daily temperature range has decreased (Quintana-Gomez 2000). At Volcán Antisana, mean temperature increased 0.18°C decade⁻¹ between 1980 and 2005 (Villacís 2008). Precipitation trends have been more difficult to discern over large scales in the tropical Andes due to high interannual variability, topographic heterogeneity and low measurement certainty (Vuille et al. 2008). For example, Vuille et al. (2003) identify a general increase in precipitation between 1950 and 1994 in the tropical Andes north of central Peru and Haylock et al. (2006) document evidence that both total precipitation and precipitation intensity in Andean Ecuador trended upwards between 1960 and 2000. Pourrut and Nouvelot (1995), meanwhile, identify a slight drying trend at Quito over the 20th century (through 1988) and Rhoades et al. (2008) note local-scale heterogeneity in precipitation trends in the area of Volcán Cotacachi, north of Quito. Other regional scale analyses are suggestive of increasing precipitation, including apparent increases in humidity (Vuille et al. 2003) and convective cloud cover (Vuille et al. 2008).
**Data and Methods**

*Instrumental Climatological Data*

I obtained climatological time series data from a series of weather stations established and maintained by the Ecuadorian government agency Instituto Nacional de Meteorología e Hidrología (INAMHI). I identified five monthly precipitation and two monthly temperature time series from stations within 50 km of Chimborazo that were established prior to 1986 (the baseline year of our glacier change analysis; Table 3.1 and Figure 3.2). Because of extensive data gaps I was unable to use data from the precipitation gauge nearest the mountain (Urbina). Furthermore, because the only two suitable temperature stations are located within 2 km and 60 m elevation of one another, these data are significantly autocorrelated. I reconstructed data gaps by first creating a correlation matrix between stations, then interpolated data from the station with the highest correlation using simple linear regression. To determine overall trends in precipitation and temperature, I calculated the average departure from the monthly mean.

Table 3.1. INAMHI weather stations used to analyze climatic trends in the Chimborazo region.

<table>
<thead>
<tr>
<th>Station</th>
<th>Code</th>
<th>Elev. (m.a.s.l.)</th>
<th>Distance from Chimborazo (km)</th>
<th>Start Date</th>
<th>Interpolation %</th>
<th>Correlating Station</th>
<th>Correlation r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedro Fermin Cevallos</td>
<td>M128</td>
<td>2910</td>
<td>25.9</td>
<td>Precip: Jul 78</td>
<td>5.2</td>
<td>Precip: Pilahuin</td>
<td>.814</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temp: Jul 78</td>
<td>5.8</td>
<td>Temp: Querochaca</td>
<td>.955</td>
</tr>
<tr>
<td>Querochaca</td>
<td>M258</td>
<td>2850</td>
<td>26.1</td>
<td>Temp: Nov 85</td>
<td>0.0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Pilahuin</td>
<td>M376</td>
<td>3314</td>
<td>20.8</td>
<td>Precip: Aug 64</td>
<td>1.4</td>
<td>Tisaleo</td>
<td>.834</td>
</tr>
<tr>
<td>Tisaleo</td>
<td>M377</td>
<td>3266</td>
<td>21.1</td>
<td>Precip: Aug 64</td>
<td>7.7</td>
<td>Pilahuin</td>
<td>.834</td>
</tr>
<tr>
<td>San Juan – Chimborazo</td>
<td>M393</td>
<td>3220</td>
<td>17.9</td>
<td>Precip: Jan 80</td>
<td>2.1</td>
<td>Guano</td>
<td>.755</td>
</tr>
<tr>
<td>Guano</td>
<td>M408</td>
<td>2620</td>
<td>25.6</td>
<td>Precip: Jan 80</td>
<td>2.3</td>
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<td>.755</td>
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</tbody>
</table>
(1980-2011 for precipitation; 1986-2011 for temperature) for all stations during each month then analyzed trends using the Mann-Kendall non-parametric test (Lettenmaier, Wood and Wallis 1994). Prior to trend analysis, each time series was interrogated for auto-correlation using the Durbin-Watson test (Durbin and Watson 1950, Durbin and Watson 1951) and none was found to score outside acceptable bounds (Farebrother 1980). Because precipitation seasonality is a dominant feature of the Chimborazo climate, I analyzed trends for each of the four seasons separately. I downloaded monthly Multivariate ENSO Index data from the NOAA Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/enso/mei/#Home) and processed the data to apply the three-month lag in atmospheric response to ENSO over the Ecuadorian Andes (Francou et al. 2004).

I also attempted to utilize NCEP Climate Forecast System Reanalysis (CFSR) data in this study. CFSR is a high resolution (~38 km²; 64 atmospheric levels) data set which reconstructs a variety of ocean-atmosphere parameters, including atmospheric temperature and humidity, in monthly time steps back to 1979 (Saha et al. 2010). Unfortunately, the model generates a spurious increase in mean precipitation rates from east to west in the Ecuadorian Andes, which contradicts actual conditions. This suggests that the model is unable to resolve the complex topography of the parallel Andean cordilleras and is thus unusable for local scale analyses.

Public Perceptions of Recent Climate Change

I conducted 59 semi-structured household surveys in 25 different communities within San Andres Parroquia, the township-level administrative unit located in the upper
Rio Guano watershed southeast of Volcán Chimborazo. Sampled households were selected using a randomized GIS polygon technique to divide the parroquia into discrete subunits (Bury et al. 2011). I then used GPS to identify the polygon centroid location in the field, and approached the nearest adult (age 18+) to solicit participation in the survey. I conducted surveys in Spanish (with assistance from a translator) during daylight hours in May and June of 2012. I ultimately contacted households with a total of 294 resident individuals (2.2% of parroquia population); comparison of survey demographic data with 2010 census data (INEC 2010) suggests that I achieved an acceptable representation of the total parroquia population (Table 3.2). The survey instrument (Appendix A) was approved by the Institutional Review Board at The Ohio State University and was field-tested to reduce confusing wording and potential bias. Though the survey was primarily designed to explore household livelihood activities, I asked specific questions about

Table 3.2. Comparison of survey demographic data to San Andres Parroquia census data (INEC, 2010)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Survey n (a)</th>
<th>2012 Survey Value</th>
<th>2010 Census Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>-</td>
<td>294 (b)</td>
<td>13481</td>
</tr>
<tr>
<td>Male</td>
<td>59</td>
<td>54.2%</td>
<td>48.0%</td>
</tr>
<tr>
<td>Female</td>
<td>59</td>
<td>45.8%</td>
<td>52.0%</td>
</tr>
<tr>
<td>Married</td>
<td>59</td>
<td>83.1%</td>
<td>58.3%</td>
</tr>
<tr>
<td>Single</td>
<td>59</td>
<td>6.8%</td>
<td>25.2%</td>
</tr>
<tr>
<td>Divorced/separated</td>
<td>59</td>
<td>3.4%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Widowed</td>
<td>59</td>
<td>6.8%</td>
<td>6.0%</td>
</tr>
<tr>
<td>Born in San Andres Parroquia</td>
<td>59</td>
<td>81.4%</td>
<td>90.5%</td>
</tr>
<tr>
<td>No formal education</td>
<td>83 (c)</td>
<td>12.1%</td>
<td>13.4%</td>
</tr>
<tr>
<td>Higher than primary education</td>
<td>83 (c)</td>
<td>20.5%</td>
<td>36.0%</td>
</tr>
</tbody>
</table>

(a): Survey n varies because not all respondents answered questions related to economic activities.
(b): Total number of residents in the 59 households included in the survey.
(c): Includes data provided by married respondents about their spouses.
(d): The survey value represents the percentage of respondents who report that at least one household member engages in this activity while the census value reports the percentage of all individuals who engage in this activity. A direct comparison is thus impossible, and these values are provided for informational purposes only.
a perceptions of temperature, precipitation, hydrological and cryospheric change in the region. Questions were initially phrased without reference to specific time intervals, though answers were clarified to ensure that responses reflected long-term (decade-plus) experiences. Responses were tabulated only when respondents had resided in the area as adults for at least 10 years and were analyzed based on household location and various livelihood characteristics.

I also conducted four focus groups with irrigators of the Las Abras irrigation system, the largest in the upper Rio Guano watershed with over 1500 member households. Groups were held in the communities of Tintatacto (3400 m.a.s.l.), San Pablo (3150 m.a.s.l.), Basacón (3050 m.a.s.l.), and Tapi (2800 m.a.s.l.; see Figure 3.2), each representing one of the system’s four sub-districts. Participants were recruited with the assistance of the president of the Las Abras users association, with representatives from each district first volunteering to participate then recruiting additional members from within their respective districts. In all, 22 individuals participated among the four groups, with both men and women present at each. Discussions were conducted over 60-90 minute periods on late weekday afternoons during May and June, 2012. Though nine household survey participants were members of the Las Abras system, there was no overlap with participants in the focus group. The focus group questionnaire (Appendix B) consisted of eight questions, the first of which explicitly inquired about perceptions of climate change in the region over participants’ lifetimes (all were natives of the area). The questionnaire was also approved by the Institutional Review Board at The Ohio State
University and was presented in Spanish (with assistance from a translator). Each group was digitally recorded and transcribed by either a fluent (Tapi and San Pablo) or native (Tintacto and Basacón) Spanish speaker. I translated each transcript with occasional assistance from a native Spanish speaker.

Glacier Change Analysis

I used multi-temporal analysis of remotely-sensed imagery to document glacier change at Volcán Chimborazo between 1986, 2000 and 2013, a technique that has proven to be very effective for monitoring glacier change in places where direct glacier measurements are unavailable (Paul et al. 2002, Kargel et al. 2005, Bamber and Rivera 2007). Images used in this analysis were obtained from a variety of sources, including Landsat imagery, aerial photography and the RapidEye satellite platform (Table 3.3). Because Chimborazo is frequently cloud-cloaked and can receive accumulating snow below the ice line at any time, it was necessary to mosaic multiple images to fully map the mountain’s glaciers. Because of the rarity of suitable images, the interval between the first and last image in a mosaic can approach one year.

Table 3.3 Catalog of data sources used for area glacier mapping. Image dates are in mm/dd/yy format. Glacier numbers are cross-referenced with glacier names in Table 3.5.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Platform</th>
<th>Image Date</th>
<th>Resolution (m)</th>
<th>Glaciers Mapped</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Landsat-5</td>
<td>01/18/86</td>
<td>30</td>
<td>7, 9, 10, 14 (part)</td>
</tr>
<tr>
<td></td>
<td>Landsat-5</td>
<td>02/03/86</td>
<td>30</td>
<td>3, 4, 5, 6, 12, 14 (part), 17 (part), 18 (part), 19 (part), 23</td>
</tr>
<tr>
<td></td>
<td>Landsat-5</td>
<td>09/15/86</td>
<td>30</td>
<td>1, 2, 17 (part), 18 (part), 19 (part), 20, 22</td>
</tr>
<tr>
<td>2000</td>
<td>IGM Aerial</td>
<td>11/13/00</td>
<td>0.6</td>
<td>All (part of 4)</td>
</tr>
<tr>
<td></td>
<td>Landsat-7</td>
<td>01/03/01</td>
<td>15</td>
<td>4 (part)</td>
</tr>
<tr>
<td>2013</td>
<td>RapidEye</td>
<td>08/21/12</td>
<td>5</td>
<td>1 (part), 2, 3 (part), 4 (part), 5 (part), 6 (part), 7 (part), 10 (part), 12 (part), 14 (part), 18 (part), 19 (part), 20 (part), 22 (part)</td>
</tr>
<tr>
<td></td>
<td>Landsat-7</td>
<td>04/10/13</td>
<td>15</td>
<td>9, 10 (part), 12 (part), 14 (part); 23 (part)</td>
</tr>
<tr>
<td></td>
<td>Landsat-7</td>
<td>04/27/13</td>
<td>15</td>
<td>3 (part), 4 (part), 10 (part)</td>
</tr>
<tr>
<td></td>
<td>Landsat-8</td>
<td>06/21/13</td>
<td>15</td>
<td>1 (part), 17 (part), 18 (part), 19 (part), 20 (part), 22 (part)</td>
</tr>
<tr>
<td></td>
<td>Landsat-7</td>
<td>06/29/13</td>
<td>15</td>
<td>1 (part), 3 (part), 5 (part), 6 (part), 7 (part), 23 (part)</td>
</tr>
</tbody>
</table>
I used 1986 as our baseline because this is the first year in which freely available, Landsat-5, 30 m resolution imagery is available. The 2000 glacier map is derived from a 0.6 m resolution black and white aerial photograph obtained by the Ecuadorian Instituto Geográfico Militar (IGM). Because this image is completely cloud-free and was taken on a day in which there was minimal non-glacial snow cover, it afforded the highest possible mapping accuracy and thus served as the base scene to which all other images are co-registered. The photograph was orthorectified (RMSE < 1 m) using a combination of 60 differentially-corrected GPS (DGPS) ground control points (mean horizontal and vertical precision < 0.05 m.) and a 5 meter photogrammetric digital elevation model (DEM; Jordan et al. 2010). I verified the vertical accuracy of this DEM using 84 DGPS check points collected from non-glacial, bedrock areas (mean vertical precision = 0.039 m). Because the original mean offset of the DEM was -13.0 m (σ = 8.7 m), with a systematic and spatially-patterned bias towards elevation underestimation (96% of check points), I corrected the DEM by adding the original surface to an estimated-error raster derived from the control points using an Inverse Distance Weighting algorithm. I used nine additional DGPS check points to assess the accuracy of the corrected DEM and found a mean offset of -0.1 m (σ = 3.1 m). Because the tongues of glaciers 4 (Reschreiter) and 6 (Theodor Wolf) fell outside the IGM aerial photograph, a pan-sharpened Landsat-7 scene acquired less than two months later was used to complete these ice edges. For 2013 glacier boundaries, a 5 m resolution RapidEye scene acquired August 2012 was used when possible, though large areas of fresh snow rendered some ice edges impossible to discern. For these boundaries, pan-sharpened Landsat-7 and Landsat-8 scenes from April
and June 2013 were used. Because Chimborazo is situated in the middle of its Landsat scene (row 10, path 61), the failure of the Landsat-7 scan line corrector instrument did not impact this study. The tongues of glaciers 2 (Abraspungo), 3 (Hans Meyer), 4 (Reschreiter), 5 (Carlos Zambrano), 6 (Theodor Wolf), 10 (Nicolas Martinez), 12 (Carlos Pinto), 18 (Escombros), and 20 (Stubel) were mapped using DGPS in the first half of 2012. All images used in this analysis were projected in UTM 17S (datum WGS84).

I employed the Normalized Difference Snow Index (Hall, Riggs and Salomonson 1995) with an empirically-determined threshold of 0.7 (based on visual glacier boundaries in the RapidEye image) to automatically generate an initial glacier surface map from the Landsat imagery (Racoviteanu et al. 2009, Paul et al. 2013b). I then exported this output to ArcGIS 10.0 and created binary rasters (glacier = yes/no) for each scene. I carefully examined each image to identify areas of non-glacial snow and cloud cover, then converted each binary raster (Landsat-5 at 1:6000, all other images at 1:3000) to create vector glacier boundary lines, while ice edges derived from the IGM and RapidEye imagery were manually digitized. Debris covered ice was readily discernable in both of these images, with DGPS data also used to correct these features for the 2013 map. Unfortunately, delineation of debris covered ice using the 30 m resolution Landsat-5 imagery was impossible for the 1986 analysis. Lacking any additional data, I assumed that 2000 debris-covered ice extents reasonably represent 1986 extents and thus incorporated them in our 1986 glacier polygon. Because of this, the reported increase in debris-covered area between 1986 and 2000 is due only to the development of supraglacial debris on previously clean ice. Figure 3.5 shows examples from each of the
image types used in this analysis. I calculated glacier area change for each epoch by comparing the measured area value for each polygon per the guidelines of Racoviteanu et al. (2009).

Typically, the recommended approach for assessing mapping uncertainty is to have multiple analysts independently digitize a sample of glaciers (Paul et al. 2013a). This technique simultaneously accounts for both types of glacier classification uncertainty: digitizing uncertainty (a function of an analyst’s ability to precisely digitize along pixel edges) and glacier interpretation uncertainty (a function of an analyst’s ability to discern glacier ice from other features). In this instance, however, my extensive field experience would result in a biased set of results when other analysts without the same on-the-ground knowledge of Chimborazo’s glaciers attempted to interpret glacier boundaries from the source imagery (especially for the 2013 analysis). To estimate digitization uncertainty, I instead followed the technique of DeBeer and Sharp (2007) and
created a buffer around the external ice perimeter (i.e. not along internal ice divides) with a width determined by the resolution of the image used to digitize that segment of glacier. For the IGM aerial image (0.6 m), I set the buffer equal to one pixel width. For the Landsat (30 m), pan-sharpened Landsat (15 m) and RapidEye (5 m) images, the buffer is set equal to ½ pixel width since manual digitization eases as pixel width increases. For glacier perimeters field-mapped using GPS, I assume a buffer width of 0.5 m. I then divided the total area of the buffer by the total ice surface area. I calculated glacier interpretation uncertainty by manually digitizing any area inside or outside the defined glacier polygon and its associated digitization uncertainty buffer that was potentially misclassified. I then divided the total uncertainty area by the total ice surface area to arrive at the proportional uncertainty term. Because errors of omission and commission will partly cancel one another, the true glacier interpretation error is likely somewhat overstated. Positional uncertainty (e.g. Bolch et al. 2008) was excluded because each image used in this analysis was co-registered to the orthorectified IGM aerial photograph (F. Paul, pers. comm.). Final uncertainty was calculated by taking the root sum of the square of each of the two classification uncertainty terms. Overall glacier change uncertainty for each epoch was calculated as the root sum of the square of the combined uncertainties for two bookending years.

Delineation of ice divides is not always straightforward when glaciers radiate outward from a single summit ice cap. Here, I automatically derived ice divides and various topographic parameters from the 5 m photogrammetric DEM using ArcGIS 10.0 spatial analysis tools. I then manually corrected areas where the automated delineation
conflicted with observed glacier behavior. For glacier identification, I generally employed the delineations and naming conventions of Jordan and Buchroithner (2009), though I do not differentiate one lobe of glacier 14 (Humboldt) as the distinct Marco Cruz Glacier. Glacier numbers were adapted from the current World Glacier Inventory numbering system to maintain as much consistency as possible. Separate GLIMS glacier IDs were assigned in accordance with specifications of that project (Raup and Khalsa 2010). The updated inventory has been submitted to both the WGI and GLIMS databases. I used ArcGIS 10.0 to determine both glacier hypsometry and mean glacier aspect, the latter using the methodology of Paul et al. (2010). The high resolution of our DEM and the hummocky terrain of many glacier surfaces resulted in spurious mean slope calculations using ArcGIS 10.0 zonal functions, so I instead calculated this parameter using a Δ-Elevation approach (Jiskoot et al. 2009) that divides the flow line length by the glacier’s total elevation range (excluding intervening terrain when detached sections exist). Flow lines were determined using a cost-distance algorithm (Kienholz et al. 2013). These results were then compared to observed behavior and were manually corrected where large discrepancies were apparent.

Results

Instrumental Climate Change Since 1986

At the two INAMHI temperature gauges nearest Volcán Chimborazo (Querochaca and Pedro Fermin Cevallos, both ~26 km northeast of the summit), mean annual temperature increased 0.11°C decade⁻¹ between 1986 and 2011 (0.26°C total), though the trend is not statistically-significant (p = .10; Figure 3.6). At Querochaca and
Pedro Fermin Cevallos, of the nine years prior to 2011, only 2007 and 2008 were cooler than the 1986-2011 mean. Both of these years occurred during the 2007-2009 La Niña event, which generally creates below-normal temperatures in the Ecuadorian Andes. Notably, mean annual temperature remained above normal during 2010 and 2011 despite this being one of the strongest La Niña events since 1950. Assuming an atmospheric lapse rate of 0.6°C per 100 m, this level of warming results in a 50 m increase in freezing level height, a value consistent with other estimates for the region (Bradley et al. 2009, Rabatel et al. 2013).
The INAMHI instrumental data do not indicate any statistically-significant seasonal precipitation trends in the Chimborazo region between 1980 and 2011, with one exception (Table 3.4; Figure 3.7). At the two northern stations, Pilahuin (21 km north) and Tisaleo (21 km northeast), an increasing precipitation trend is apparent during the short dry season (December and January). Though the probability is < .7, and thus it is not recognized as a statistically-significant trend, it is worth noting that there is evidence of decreasing precipitation during the long wet season at Guano (26 km southeast). A weak (-.206) but statistically-significant (p < .01) relationship exists between below

Figure 3.7. Aggregated departure from mean seasonal precipitation, 1980-2011, for the Chimborazo region and its relationship with the Multivariate ENSO Index (MEI).
Table 3.4. Precipitation measurements and trends, 1980-2011. When the Mann-Kendall Statistic (S) > 0, an increasing trend is suggested; when S < 0, a decreasing trend is suggested. Trends were recognized when the probability ≥ .95.

(a) Long wet season (Feb-May)

<table>
<thead>
<tr>
<th>Station</th>
<th>Elev. (m)</th>
<th>Distance from Chimborazo (km)</th>
<th>Mean seasonal precip. per day (mm)</th>
<th>Precip. trend</th>
<th>Prob. (1 – α)</th>
<th>Mann – Kendall statistic (S)</th>
<th>Durbin-Watson autocorrelation value</th>
<th>Months w/ interpolated data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilahuin</td>
<td>3314</td>
<td>20.8</td>
<td>2.46</td>
<td>No Trend</td>
<td>.8523</td>
<td>91</td>
<td>1.999</td>
<td>0.8</td>
</tr>
<tr>
<td>Tisaleo</td>
<td>3266</td>
<td>21.1</td>
<td>2.54</td>
<td>No Trend</td>
<td>.7284</td>
<td>57</td>
<td>2.207</td>
<td>8.9</td>
</tr>
<tr>
<td>Pedro Fermin Cevallos</td>
<td>2910</td>
<td>25.9</td>
<td>1.83</td>
<td>No Trend</td>
<td>.7850</td>
<td>72</td>
<td>1.752</td>
<td>3.2</td>
</tr>
<tr>
<td>Guano</td>
<td>2620</td>
<td>25.6</td>
<td>1.87</td>
<td>No Trend</td>
<td>.6888</td>
<td>-46</td>
<td>2.098</td>
<td>1.6</td>
</tr>
<tr>
<td>San Juan – Chim.</td>
<td>3220</td>
<td>17.9</td>
<td>2.67</td>
<td>No Trend</td>
<td>.6119</td>
<td>16</td>
<td>1.727</td>
<td>4.0</td>
</tr>
</tbody>
</table>

(b) Long dry season (June-Sept)

<table>
<thead>
<tr>
<th>Station</th>
<th>Elev. (m)</th>
<th>Distance from Chimborazo (km)</th>
<th>Mean seasonal precip. per day (mm)</th>
<th>Precip. trend</th>
<th>Prob. (1 – α)</th>
<th>Mann – Kendall statistic (S)</th>
<th>Durbin-Watson autocorrelation value</th>
<th>Months w/ interpolated data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilahuin</td>
<td>3314</td>
<td>20.8</td>
<td>1.71</td>
<td>No Trend</td>
<td>.9318</td>
<td>121</td>
<td>1.657</td>
<td>3.2</td>
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<tr>
<td>Tisaleo</td>
<td>3266</td>
<td>21.1</td>
<td>1.86</td>
<td>No Trend</td>
<td>.7999</td>
<td>76</td>
<td>1.912</td>
<td>10.5</td>
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<tr>
<td>Pedro Fermin Cevallos</td>
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<td>25.9</td>
<td>1.38</td>
<td>No Trend</td>
<td>.7435</td>
<td>61</td>
<td>1.379</td>
<td>4.8</td>
</tr>
<tr>
<td>Guano</td>
<td>2620</td>
<td>25.6</td>
<td>0.67</td>
<td>No Trend</td>
<td>.6957</td>
<td>48</td>
<td>1.714</td>
<td>3.2</td>
</tr>
<tr>
<td>San Juan – Chim.</td>
<td>3220</td>
<td>17.9</td>
<td>0.84</td>
<td>No Trend</td>
<td>.6023</td>
<td>6</td>
<td>1.638</td>
<td>1.6</td>
</tr>
</tbody>
</table>

(c) Short wet season (Oct-Nov)

<table>
<thead>
<tr>
<th>Station</th>
<th>Elev. (m)</th>
<th>Distance from Chimborazo (km)</th>
<th>Mean seasonal precip. per day (mm)</th>
<th>Precip. trend</th>
<th>Prob. (1 – α)</th>
<th>Mann – Kendall statistic (S)</th>
<th>Durbin-Watson autocorrelation value</th>
<th>Months w/ interpolated data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilahuin</td>
<td>3314</td>
<td>20.8</td>
<td>1.79</td>
<td>No Trend</td>
<td>.6069</td>
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<td>21.1</td>
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<td>No Trend</td>
<td>.6105</td>
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<td>2.41</td>
<td>No Trend</td>
<td>.6080</td>
<td>-13</td>
<td>2.113</td>
<td>1.6</td>
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</tbody>
</table>

(d) Short dry season (Dec-Jan)

<table>
<thead>
<tr>
<th>Station</th>
<th>Elev. (m)</th>
<th>Distance from Chimborazo (km)</th>
<th>Mean seasonal precip. per day (mm)</th>
<th>Precip. trend</th>
<th>Prob. (1 – α)</th>
<th>Mann – Kendall statistic (S)</th>
<th>Durbin-Watson autocorrelation value</th>
<th>Months w/ interpolated data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilahuin</td>
<td>3314</td>
<td>20.8</td>
<td>1.59</td>
<td>Increasing</td>
<td>.9728</td>
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<tr>
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<td>1.58</td>
<td>Increasing</td>
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<td>0.99</td>
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<td>2.003</td>
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<td>San Juan – Chim.</td>
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<td>17.9</td>
<td>1.72</td>
<td>No Trend</td>
<td>.6787</td>
<td>43</td>
<td>2.113</td>
<td>0</td>
</tr>
</tbody>
</table>

**Perceptions of Recent Climate Change in San Andres Parroquia**

In contrast to the instrumental data, people living in San Andres Parroquia have a near- unanimous perception that precipitation has decreased and that area springs, streams, and ponds are diminishing. Of survey respondents that identified changes in precipitation patterns (79% of all respondents), 95% perceive that there is less rainfall now than in decades past. Similarly, of those identifying shifts in surface water availability (94% of all respondent), 92% say that there is less water now than before. Participants in all four of the focus groups were also unanimous in their belief that the local climate had become noticeably drier. This perception of increased aridity is not limited to specific climate zones in the parroquia, and is shared by irrigators and non-irrigators alike. As one non-irrigator stated, “when I was little, everything was green. Now, (pointing to dry soil), it’s like this. What will happen in ten years?” (Household Interview 23, 1 June 2012). The comments of one irrigator were typical: “The climate has changed a great deal … in [the long dry season] the land is now drier. Now, it merely rains a little,” (Tintatacto Focus Group, 9 June 2012). An irrigator living in a lower-elevation area was even more adamant: “Right now, the annual cycle is 80% dry season. The wet season is gone,” (Tapi Focus Group, 4 June 2012). Numerous residents observe that trees in the region are more stressed, the quality of grasses used for animal feed has
declined, and that crops fail more frequently, all of which combine to reduce incomes and make life more difficult: “We suffer because when there is no rain, there are no crops,” (Household Interview 37, 4 June 2012).

Another frequent observation is that the climate has become more variable and that previously predictable patterns of precipitation are breaking down. While only 44% of all survey respondents discussed climate variability, 100% of those who did stated that rainfall unpredictability is a growing problem. This same concern was also raised in each of the four focus groups. This is a critical concern for Chimborazo farmers, since rainfall seasonality is what guides the annual cycles of sowing and harvesting. “Before, people knew when it would rain and when it wouldn’t rain,” one farmer explained, “now, people don’t know what the weather will be and so they don’t know when to plant,” (Household Interview 16, 3 June 2012).

While there is strong instrumental evidence that the atmospheric temperature has increased, residents are generally less able to discern this apparent change. Only 24% of surveyed household commented on shifting temperatures, and there was no consensus as to atmospheric warming or cooling. Multiple farmers did note that, as one described, “the sun is stronger, and when it does rain, the rain dries quickly,” (San Pablo Focus Group, 21 May 2012). Such a change could be driven by one of several factors (or combinations thereof), including decreased atmospheric humidity or increased wind velocities, however this observation does lend support to the instrumental evidence for increasing temperatures. One observation upon which nearly everyone agrees is that glaciers on Volcán Chimborazo are shrinking and the mountain’s snowline is retreating (80% of all
survey respondents and 95% of respondents commenting upon cryospheric change). While the direct relationship between glacier meltwater runoff and regional water supply may be limited (see Chapter 5), local farmers identify a strong connection between the two, and concern about these changes is a frequent refrain: “Chimborazo is not like it was before. There used to be a lot more ice but now it is drying out,” (Household Interview 22, 1 June 2012).

Glacier Area Change Between 1986 and 2013

Between 1986 and 2013, glacier surface area at Volcán Chimborazo decreased by 21% ± 9% (Figure 3.8, Table 3.5) and, as of 2013, stands at 11.1 km² ± 3% divided between 17 distinct glaciers (Table 3.6). During this epoch, the rate of glacier shrinkage has been -0.07 km² yr⁻¹ (-0.8% yr⁻¹), however since 2000 the rate has increased to -0.11 km² yr⁻¹ (-1.2% yr⁻¹). These rates are similar to those recorded at Volcán Antisana, where Collet (2010) calculated a rate of -1.6% yr⁻¹ between 1987 and 2007, and Caceres (2010), looking at Glacier 15 specifically, calculated a rate of -1.5% yr⁻¹ between 1993 and 2008 and -2.6% yr⁻¹ between 2000 and 2008. At Volcán Cotopaxi (~100 km NE of Chimborazo), estimated shrinkage rates were -1.3% yr⁻¹ between 1979 and 1997 (Jordan et al. 2005) and 0.9% yr⁻¹ between 2001 and 2009 (Collet 2010).

The mean minimum elevation of clean ice for all glaciers has increased 180 m since 1986, with 120 m of that increase happening after 2000. The mean lowest elevation of clean ice for all glaciers is presently 5320 m.a.s.l., though this is partly controlled by near-vertical topography in some glaciersheds. Excluding three glaciers that terminate at the brink of cliff bands near 5600 m.a.s.l., the mean minimum elevation increase was
Figure 3.8. Changes in glacier surface area on Volcán Chimborazo, 1986 – 2013. Because debris-covered ice cannot be discerned from 1986 Landsat TM imagery, debris-covered ice present in 2000 is assumed to have been present in 1986 (see text for further discussion). Glacier numbers are cross-referenced with glacier names in Table 3.5.
Table 3.5. Summary of glacier change characteristics between 1986, 2000 and 2013 at Volcán Chimborazo. The last two digits (in bold) of the World Glacier Inventory ID refer to the glacier identifiers in Figure 3.8. Relative change in debris-covered area values reported as NA indicate that no debris-covered ice exists for that epoch; the (*) values reported for the Carlos Zambrano Glacier indicate that a calculation is impossible since no debris-cover existed in 1986 or 2000. Debris-cover percentages reported for 1986 are based on glacier edges established from 2000 imagery that are assumed to have been unchanged since 1986 (see text for explanation).

<table>
<thead>
<tr>
<th>Glacier Name</th>
<th>Total Area (km²)</th>
<th>Relative Change in Area (%)</th>
<th>Relative Change in Debris-Covered Area (%)</th>
<th>Change in Minimum Elevation of Clean Ice (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>01</td>
<td>1.2</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Abraspungo</td>
<td>02</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Hans Meyer</td>
<td>03</td>
<td>2.3</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Reschreiter</td>
<td>04</td>
<td>2.9</td>
<td>2.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Carlos Zambrano</td>
<td>05</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Theodor Wolf</td>
<td>06</td>
<td>1.1</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Garcia Moreno</td>
<td>07</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Boussignault</td>
<td>09</td>
<td>0.06</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>Nicolas Martinez</td>
<td>10</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Carlos Pinto</td>
<td>12</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Humboldt</td>
<td>14</td>
<td>1.0</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Walther Sauer</td>
<td>23</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Totorillas</td>
<td>17</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Escombros</td>
<td>18</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Thielmann</td>
<td>19</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Stuebel</td>
<td>20</td>
<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Reiss</td>
<td>22</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total (Mean)</td>
<td>14.1 ± 9%</td>
<td>13.2 ± 2%</td>
<td>11.1 ± 3%</td>
<td>-7 ± 9%</td>
</tr>
</tbody>
</table>
Table 3.6. Volcán Chimborazo Glacier Inventory, 2013. The last two digits (in bold) of the World Glacier Inventory ID refer to the glacier identifiers in Figure 3.8. Glacier length is calculated only for those glaciers without disconnected ice. Minimum elevation includes disconnected ice.

<table>
<thead>
<tr>
<th>Glacier Name</th>
<th>World Glacier ID</th>
<th>GLIMS Glacier ID</th>
<th>Total Area (km²)</th>
<th>Mean Aspect (˚)</th>
<th>Min. El. (Clean Ice) (m)</th>
<th>Debris-Covered Ice (%)</th>
<th>Detached Ice (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>EC1Q00011001</td>
<td>G281181E01466S</td>
<td>0.9</td>
<td>348</td>
<td>4995</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Abraspungo</td>
<td>EC1Q00011002</td>
<td>G281187E01458S</td>
<td>0.5</td>
<td>15</td>
<td>4950</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>Hans Meyer</td>
<td>EC1Q00011003</td>
<td>G281199E01452S</td>
<td>1.3</td>
<td>27</td>
<td>4875</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Reschreiter</td>
<td>EC1Q00011004</td>
<td>G281196E01462S</td>
<td>2.6</td>
<td>67</td>
<td>4780</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Carlos Zambrano</td>
<td>EC1Q00011005</td>
<td>G281195E01471S</td>
<td>0.9</td>
<td>72</td>
<td>4900</td>
<td>18</td>
<td>35</td>
</tr>
<tr>
<td>Theodor Wolf</td>
<td>EC1Q00011006</td>
<td>G281204E01470S</td>
<td>0.9</td>
<td>55</td>
<td>4880</td>
<td>49</td>
<td>82</td>
</tr>
<tr>
<td>Garcia Moreno</td>
<td>EC1Q00011007</td>
<td>G281206E01475S</td>
<td>0.1</td>
<td>74</td>
<td>5175</td>
<td>0</td>
<td>84</td>
</tr>
<tr>
<td>Boussignault</td>
<td>EC1Q00011009</td>
<td>G281203E01476S</td>
<td>0.03</td>
<td>136</td>
<td>5450</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Nicolas Martinez</td>
<td>EC1Q00011010</td>
<td>G281202E01482S</td>
<td>0.7</td>
<td>149</td>
<td>4785</td>
<td>74</td>
<td>0</td>
</tr>
<tr>
<td>Carlos Pinto</td>
<td>EC1Q00011012</td>
<td>G281194E01482S</td>
<td>0.6</td>
<td>159</td>
<td>4680</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>Humboldt</td>
<td>EC1Q00011014</td>
<td>G281187E01476S</td>
<td>0.9</td>
<td>170</td>
<td>4900</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>Walther Sauer</td>
<td>EC1Q00011023</td>
<td>G281179E01477S</td>
<td>0.2</td>
<td>185</td>
<td>5610</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totorillas</td>
<td>EC1Q00011017</td>
<td>G281179E01474S</td>
<td>0.2</td>
<td>238</td>
<td>5650</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Escombros</td>
<td>EC1Q00011018</td>
<td>G281180E01470S</td>
<td>0.5</td>
<td>226</td>
<td>4820</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Thielmann</td>
<td>EC1Q00011019</td>
<td>G281172E01467S</td>
<td>0.2</td>
<td>250</td>
<td>5345</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stubel</td>
<td>EC1Q00011020</td>
<td>G281172E01464S</td>
<td>0.4</td>
<td>295</td>
<td>5055</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>Reiss</td>
<td>EC1Q00011022</td>
<td>G281176E01463S</td>
<td>0.2</td>
<td>337</td>
<td>5755</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total (Mean)</td>
<td></td>
<td></td>
<td>11.1 ± 3%</td>
<td>(5095)</td>
<td>27</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

205 m, and for the six glaciers that terminated below 5000 m.a.s.l. in 1986, the mean minimum elevation increase was 230 m. The overall mean elevation of Chimborazo’s glacier ice increased 45 m, from 5415 m.a.s.l. in 1986 to 5460 m.a.s.l. in 2013. Clean ice reaches a minimum elevation of 4780 m.a.s.l. on glacier 4 (Reschreiter), the mountain’s largest in terms of surface area. The hypsometric distribution of glacier ice in both 1986 and 2013, as well as the distribution of glacier change between 1986 and 2013, is presented in Figure 3.9. Note that the decrease in mean minimum elevation recorded between 2000 and 2013 for glacier 12 (Carlos Pinto; 45 m) and glacier 18 (Escombros; 13 m) is likely a product of digitization uncertainty.
Since 1986, the tongues of the glaciers 1 (Spruce), 4 (Reschreiter), 6 (Theodor Wolf) and 9 (Boussignault) have become detached from their accumulation areas, and, at present, eight of Chimborazo’s glaciers feature disconnected ice masses. Of these, the tongues of five, glaciers 1 (Spruce), 4 (Reschreiter), 6 (Theodor Wolf), 12 (Carlos Pinto) and 18 (Escombros), are fully debris-covered and appear to be stagnant. Glacier 7 (Garcia Moreno), which in 1986 was one of two glaciers with disconnected upper and lower clean ice segments, has now disintegrated into four pieces, all of which have surface areas of ~0.02 km² or less. Overall, 19% of Chimborazo’s glacial ice is disconnected from the main ice cap.
The overall proportion of debris-covered ice increased from ~17% in 1986 to 20% in 2000 and 27% (on 11 glaciers) in 2013. Proportional debris coverage has increased at all elevation bands below 5500 m.a.s.l. since 1986 and debris-covered ice area between 4800 and 5500 m.a.s.l. has increased 190% (Figure 3.10). Since 2000, the maximum elevation of debris cover has only increased from 5475 m.a.s.l. to 5490 m.a.s.l., however the elevation below which half of all ice is debris-covered increased from ~5150 m.a.s.l. to ~5500 m.a.s.l. While the proportion of debris-covered area increased on all debris-covered glaciers, the actual debris-covered surface area decreased between 2000 and 2013 on the glaciers 1 (Spruce; -13%), 12 (Carlos Pinto; -3%), 18 (Escombros; -13%).

Figure 3.10. Hypsometric distribution of debris-covered ice on Volcán Chimborazo in 1986 and 2013.
and 20 (Stubel; -11%) due to ice loss along glacier edges. Debris-covered ice presently terminates at a mean minimum elevation of 4820 m.a.s.l., with the detached, stagnant terminus of glacier 4 (Reschreiter) reaching the lowest elevation of any Chimborazo ice at 4485 m.a.s.l.

**Discussion**

The disparity between the instrumental records from regional weather stations and perceptions of recent climate change on the part of local residents raises some important questions. The divergence of instrumental and perceptual evidence for increasing temperatures isn’t surprising since tropical climates generally feature low seasonal temperature variability and a lack of thermal extremes, two factors that influence humans’ perceived temperature sensitivities. However, the discrepancy between what local rain gauges have recorded and the strong and widespread perception that there is less rainfall now compared to the past is more problematic. Are people in the Chimborazo region conflating other socio-environmental stressors such as increased water demand, degrading soil quality, or market-based impacts on agricultural productivity with climate change? Other research in the tropical Andes has documented similar mismatches between local perception and empirical hydroclimatic data (Mark et al. 2010, Murtinho et al. 2013), and in both cases the stress caused by increased water demand has been posited as an explanation. As Murtinho et al.(2013) noted, people without access to rain gauges will tend to use stream levels as a proxy for precipitation, so increased upstream withdrawals could lead to a perception of drying even when precipitation is unchanged. Similarly, could perceptions be unduly influenced by the fact...
that inquiry was being made by a foreign ‘climate change researcher’? That is certainly possible, though a well-designed survey instrument should reduce this effect such that responses aren’t nearly unanimous in one direction or the other, as they are in this study.

Alternatively, could the discrepancy be the result of inaccuracies in the empirical data? INAMHI’s rain gauge network is comprised of a collection of totalizing gauges where water depth is measured monthly and then converted into a precipitation depth by a local resident (B. Caceres, pers. comm.). ‘Gauge-induced’ measurement bias has been documented in precipitation datasets worldwide due to wind factors, wetting of internal gauge walls and evaporation from such gauges (Legates and Willmott 1990). Similarly, improper gauge siting relative to surrounding features could induce measurement error, as could improper methodologies on the part of person making the monthly measurements. When rain gauge networks suffer from uneven spatial coverage in a highly heterogeneous climatic landscape like Chimborazo’s, such systematic errors could become hidden within the larger data collection. Another possible explanation is that precipitation events have become less frequent but more intense. If this were the case, farmers might perceive climatic drying because of both the increased interval between rains as well as the lower effective soil moisture that results from more rapid surface runoff. Totalizing rain gauges, measured monthly, would be unable to capture this shift if the total measured monthly precipitation remained roughly unchanged. Both tropical climate models (O’Gorman 2012) and precipitation data from elsewhere in Andean Ecuador (Haylock et al. 2006) support an intensifying precipitation hypothesis, and one
farmer notes that, “the dry season has become longer, and when it does rain, the rains are now more intense,” (Household Interview 54, 10 June 2012).

The recent behavior of Chimborazo’s glaciers may help clarify the situation. The lack of a regionally-coherent precipitation pattern to match the regionally-coherent pattern of glacier shrinkage rates has been suggested as evidence that atmospheric warming is the primary driver of recent ice loss in the tropical Andes (Rabatel et al. 2013). However, while atmospheric warming since 1986 can account for a ~50 m increase in freezing level height, mean minimum clean ice elevation for Chimborazo’s 14 non-cliff-terminating glaciers increased by 205 m over the same time period. While some ice loss is likely due to climatic disequilibrium already present in the mid-1980s, this suggests that decreased precipitation – frequency, if not amount – is also responsible for the Chimborazo’s glacier shrinkage. Decreasing precipitation enhances ice loss both by reducing mass input as well as by permitting low ice-surface albedo conditions to persist for longer periods of time. Because radiative and turbulent fluxes often cause snow to melt even well above the freezing level height, this means that a considerable proportion of Chimborazo’s ice is potentially impacted by this reduced albedo effect. Various topographic effects also play a role in glacier area change, and I performed a correlation analysis using Kendall’s $\tau$ to quantify the potential impact of these factors at Chimborazo (Table 3.7). Debris-cover percentage and glacier slope (especially the presence of cliff bands) do influence spatial patterns of ice loss, however, the uniformity with which the minimum clean ice elevation of Chimborazo’s glaciers exceeded the increase in freezing level height (105 m was the least amount by which a non-cliff-terminating glaciers
Table 3.7. Correlation analysis (Kendall’s $\tau$, 1-tailed) exploring the relationship between glacier area change (1986-2013) and topographic variables derived from 1986 glacier extents and the 5 m DEM. Bold values are significant at $p < 0.05$.

<table>
<thead>
<tr>
<th></th>
<th>Total Ice Area</th>
<th>Max Elevation</th>
<th>Min Elevation (Clean Ice)</th>
<th>Median Elevation</th>
<th>Slope</th>
<th>Aspect</th>
<th>Debris Cover %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>-0.2570</td>
<td>-0.2790</td>
<td>0.2000</td>
<td>-0.0190</td>
<td>0.4860</td>
<td>-0.0100</td>
<td>-0.4900</td>
</tr>
<tr>
<td>$p$</td>
<td>0.091</td>
<td>0.075</td>
<td>0.150</td>
<td>0.461</td>
<td>0.006</td>
<td>0.481</td>
<td>0.008</td>
</tr>
</tbody>
</table>

increased) suggests that topographic effects alone cannot explain the remaining ice retreat.

A confounding factor in identifying a climate change signal from Chimborazo’s recent glacier shrinkage is the possible impact of periodic tephra deposition from Volcán Tungurahua, a 5000 m.a.s.l. mountain 40 km E of Chimborazo that has been active since October 1999. Tephra deposition can have a significant effect on glacier ablation processes by either enhancing melt by decreasing snow/ice albedo, or diminishing melt by insulating the ice from incoming shortwave radiation, even at depths as little as 5 mm (Driedger 1980, Brock et al. 2007, Rivera et al. 2012). Data available from the NOAA Volcanic Ash Advisory Center (http://www.ospo.noaa.gov/Products/atmosphere/vaac/), shows that between October 1999 and August 2012, there were 350 different days in which ground or satellite observation confirmed that a tephra plume passed over Chimborazo, with an additional 764 days in which wind trajectories could have transported tephra over the mountain but no confirmation was possible. Because most of these events likely resulted in a discontinuous layer of very fine material (Bustillos 2010), the tendency would be to enhance rather than diminish ablation, at least temporarily. However, it is noteworthy that Chimborazo’s glacier shrinkage rate is consistent with
those of Antisana and Cotopaxi despite those mountains being subject to tephra much less frequently. A possible explanation is that Chimborazo’s greater elevation (510 m higher than Antisana; 371 m higher than Cotopaxi) and extensive areas of debris-covered ice (absent elsewhere) counteract the tephra effect, though it is also possible that most tephra events are too light and/or are too quickly buried by fresh snow to have a significant impact.

Integrating all of this information, it is reasonable to conclude that Chimborazo’s local climate has become both warmer and drier since the 1980s, and that rainfall seasonality has become less distinct. Though the trend is not quite statistically-significant, the 0.11°C decade⁻¹ warming recorded northeast of the mountain is consistent with the 0.10°C decade⁻¹ temperature increase evident since 1939 across the tropical Andes as a whole (Vuille et al. 2008). The tropical Andes are thermally-homogenous, and altitude is the dominant factor influencing the spatial patterns of temperature at any point in time. As such, there is little reason to expect unique patterns of temperature change at the local scale. Residents have not been sensitive to the temperature change, though this is expected given the lack of thermal extremes in the local climate. Farmers have noted that ground moisture dries more quickly than in the past and that the sun is ‘stronger’, and this too is consistent with a warming atmosphere. The shrinkage of Chimborazo’s glaciers, especially the upward movement of minimum clean ice elevations, is also suggestive of increased temperatures, though other factors are also driving this change.

Despite the absence of corroborating data from local rain gauges, there is also compelling evidence that precipitation has either decreased in quantity or decreased in
frequency while increasing in intensity, at least in the Rio Guano watershed (where the INAMHI gauge also hints at a decrease in long wet season precipitation). Farmers – whose very livelihoods depend on predictable moisture – are very sensitive to changing rainfall patterns and the near ubiquity with which people perceive rainfall to have decreased (especially in the long dry season) and become more seasonally-variable weakens any argument that people are simply conflating socio-environmental challenges such as increased water demand with climate change. Many farmers (especially non-irrigators) have already been forced to make livelihood adaptations due to decreased agricultural productivity (see chapters 4 and 5), and multiple communities have been forced to develop new potable water sources due to reduced discharge from existing springs (see Chapter 5), both of which are consistent with a reduction in effective rainfall. There is also a potential link between a local decrease in precipitation quantity and/or frequency and recent glacier change, one that becomes more plausible since atmospheric warming and topographic factors can’t account for the amount by which minimum clean ice elevations have increased (though the influence of tephra from Volcán Tungurahua introduces uncertainty to this evidence).

Conclusion

In this study, I have attempted to overcome the limitations of data scarcity by integrating available instrumental records with information gleaned from local residents and recent glacier behavior to identify patterns of climate change at Volcán Chimborazo, Ecuador. The empirical data derived from INAMHI’s weather station network indicates that the local mean annual temperature increased 0.11°C decade⁻¹ between 1986 and 2011
(0.26°C total) while precipitation trends have remained unchanged aside from a short wet season increase in precipitation to the north of the mountain. Based on these instrumental records alone, we would thus conclude that climate change at Chimborazo has followed the same general pattern as has been identified elsewhere in the inner tropical Andes. However, while the perceptions of local residents do not contradict the evident atmospheric warming, they do describe a different response in local precipitation. In a household survey conducted in San Andres Parroquia, a rural, agrarian administrative district in the upper Rio Guano watershed southeast of the mountain, 95% of those perceiving a change in precipitation (79% of all respondents) state that there is less rainfall now than in decades past while 92% of those who have notice a change in surface water availability (94% of all respondents) say there is less water now than before. Participants (22 total) in four focus groups held with local irrigators were also unanimous in their belief that the local climate had become noticeably drier. It is impossible to pinpoint a single explanation for the inability of INAMHI rain gauges to record such a change, however, while qualitative information is not usually assigned the same cachet as empirical data, I believe the ubiquity of these opinions among farmers, who are highly sensitive to changes in precipitation, suggests that, in this instance, the qualitative information is in fact more robust.

Because tropical glaciers are highly sensitive to climate change, I also analyzed recent glacier change at Volcán Chimborazo to glean additional information about local patterns of climate change. I also used this opportunity to create an up-to-date glacier inventory for the mountain that can be used as a baseline for future analyses. Between
1986 and 2013, Chimborazo lost 21% ± 9% of its ice surface area, which now stands at 11.1 km² ± 3%. Over this interval, the average annual rate of change has been -0.8% yr⁻¹, though this rate has increased to -1.2% yr⁻¹ since 2000. The proportion of debris-covered ice increased from ~17% to 27% and the mean minimum elevation of clean ice has increased 180 m to 5320 m.a.s.l (205 m for when three cliff-terminating glaciers are excluded). Since 1986, the tongues of four glaciers have detached from their accumulation zones. Overall, eight of the mountain’s 17 glaciers now feature detached tongues and five of these are fully debris-covered and apparently stagnant.

While the 0.26°C atmospheric warming evident since 1986 can account for a ~50 m increase in freezing level height, the four-fold greater increase in the mean minimum clean ice elevation of Chimborazo’s glaciers indicates that atmospheric warming alone cannot account for glacier change. Furthermore, while debris-cover percentage and glacier slope do influence spatial patterns of ice loss, the uniformity by which ice retreat exceeds the probable increase in freezing level height among Chimborazo’s radial collection of glaciers (at least 105 m for all non-cliff-terminating glaciers) suggests that topographic effects alone cannot account for the remaining glacier change. Instead, given the compelling anecdotal evidence for decreased precipitation, I believe that this factor, which reduces mass input while enhancing melt through the preservation of low ice-surface albedo conditions, has also been an important driver of recent glacier change. It is also likely that repeated dustings of tephra from nearby Volcán Tungurahua since late 1999 have also played a role in the ice loss, though the coherence of Chimborazo’s ice
loss rates with those recorded elsewhere in Ecuador suggests that the overall effect may be minor.

My conclusions about recent climate change at Chimborazo are less scientifically rigorous than those derived from a comprehensive network of monitoring stations and robust glacier mass balance monitoring programs. However, if we utilized only the sparse data available locally and instead relied more heavily on the information generated at Volcán Antisana, we would have an incomplete understanding of the local patterns of climate change, especially with regards to the shifting precipitation patterns that are so critical for livelihoods here. It is evident that the naturally high spatial heterogeneity of precipitation in Andean Ecuador is being translated into differential patterns of climate change that vary at quite local scales. Given that detailed, locally-specific information is not forthcoming at Chimborazo – nor in most other mountain regions of the developing world – this research shows that integrating information from a variety of empirical and non-empirical sources provides valuable information about local manifestations of climate change that would otherwise remain unrecognized.

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Chapter 4: Patterns of mountain livelihood vulnerability and adaptation in a changing world: A case study from Chimborazo Province, Ecuador

Figure 4.1. Volcán Chimborazo, towering above the agrarian community of Calshi.
Introduction

The compounding impacts of globalizing economies and global climate change represent considerable challenges to human society, and agrarian, developing world communities are among those facing the most acute vulnerability to these overlapping processes (Adger 2003; O'Brien and Leichenko 2000). Agrarian communities in mountain areas are especially at risk for significant livelihood disruption, given the high sensitivity of mountain areas to climate change (Beniston 2003; Kohler and others 2010; Viviroli and others 2011), and their tendency to be economically and politically marginalized compared to lowland constituencies (Funnell and Parish 2001; Marston 2008). Indeed, given the rates and scales at which socioeconomic, environmental, and climatic change (henceforth termed ‘global change’) is occurring worldwide, there is considerable concern about the capacity of agrarian mountain communities to adapt to evolving stressors (Diaz and others 2012; Eriksson and others 2009; Jodha 2000).

Vulnerability describes the degree to which an entity is susceptible to harm from, or unable to cope with, some perturbation or stressor (Adger 2006; Parry and others 2007). Vulnerability to global change can be conceptualized as a product of interacting domains (e.g. socioeconomic or environmental) and spheres (e.g. endogenous or exogenous) that together describe the conditions creating risk for a given system (Füssel 2007). For example, the vulnerability of a particular agrarian mountain community to global change may be a function of its economic status (endogenous socioeconomic), soil quality (endogenous environmental), exposure to international aid (exogenous socioeconomic) and/or exposure to shifting rainfall patterns (exogenous environmental),
among many other environmental, demographic, economic, and social factors, making evident just how spatially and temporally differentiated vulnerability can be (Cutter 1996; Liverman 1994; Turner and others 2003). A frequent, if unintentional, narrative is that agrarian mountain communities suffer from uniformly high vulnerability to global change (e.g. Barua and others 2013; Gentle and Maraseni 2012; Vergara and others 2010; Xu and others 2009). However, these factors may vary considerably from one household to the next. For example, the specific production decisions (i.e. which crops are planted, which livestock is raised) and access to resources (i.e. amount of land owned, location of land, access to irrigation; Young and Lipton 2006), presence or absence of remittance income from emigrated family members (Jokisch 2002) and status as a net producer or buyer of food (Skjeflo 2013) all influence the degree to which a household is susceptible to harm or unable to cope with the stressors of global change. As such, it seems likely that vulnerability within agrarian mountain communities may actually be highly heterogeneous.

There is a growing body of literature describing ongoing and future global change vulnerability in agrarian tropical Andean communities (Mulligan and others 2010; Perez and others 2010; Rhoades and others 2008; Vergara and others 2010; Young and Lipton 2006), and recent household-level analyses in Bolivia (de la Riva and others 2014; McDowell and Hess 2012; Valdivia and others 2010) and Peru (Bury and others 2011; Mark and others 2010) have begun to capture the heterogeneity that exists at this scale. To this point, however, there has been little examination of vulnerability at such fine scales in Andean Ecuador, and what does exist tends to overly generalize the risks facing
agrarian households as well as their capacity for adaptation (Leidy and Reyes 2012). In this research, I examine vulnerability and adaptation to global change in several agrarian communities in order to better understand the spatial patterns of these processes in Andean Ecuador. I focus this research on the residents of San Andres Parroquia, a 179 km² administrative district in Chimborazo Province that lies at the base of glacier-capped Volcán Chimborazo (6268 m.a.s.l.), Ecuador’s highest peak. People here frequently express concern about the combined forces of global change – especially climate change – and there is widespread belief that life here is more challenging than in the past.

Because vulnerability is a function of the complex and dynamic interrelationships of so many socioeconomic and environmental factors, vulnerability is not easily captured by a single, simple metric (Adger 2006; Gallopín 2006; Skjeflo 2013; Turner and others 2003). In this research, I answer these questions by employing a livelihoods approach to assessing vulnerability and adaptive capacity. At the household level, livelihoods are a function of relative access to social, economic, and environmental resources (Bebbington 1999), which are the same endogenous and exogenous factors that determine vulnerability. As such, livelihoods and vulnerability can be expected to operate at similar scales (McDowell and Hess 2012), making the former a useful proxy for the latter. Here, I define livelihood vulnerability as the susceptibility of a household to a worsening of perceived socioeconomic well-being. I use ‘perceived socioeconomic well-being’ quite intentionally, for, as will be illustrated below, a forced adjustment in livelihood activities may be viewed as socially detrimental even when it results in improved access to tangible amenities.
In the following section, I introduce the Chimborazo landscape and review some of the key factors that influence livelihood decisions and control exposure to livelihood vulnerability in Andean Ecuador. After a brief description of the data and methods used in this research, I then document the social and environmental drivers of livelihood vulnerability presently being experienced by people in San Andres Parroquia as a result of global change and report on the adaptation strategies that households employ in response to these challenges. I follow this with a discussion about some of the implications of my research findings, then attempt to develop a picture of expected future patterns of livelihood vulnerability as a function of continued global change. I conclude by summarizing the key points of this research and reflecting on the high heterogeneity of vulnerability in mountain landscapes and the resulting need for global change research to emphasize local scale analyses.

Geographic Setting

Chimborazo Province is located in the central Ecuadorian Andes, approximately 150 km south of the capital city of Quito (Figure 4.2). San Andres Parroquia, home to 13,500 people residing in approximately 3700 different households (INEC 2010), is highly agrarian and residents here are highly reliant on water originating from Volcán Chimborazo. Settled, agriculturally-productive areas in the parroquia extend from 4000 m.a.s.l. on the lower slopes of the mountain (the lower limit of regular nightly frosts) down to 2950 m.a.s.l. at the fringe of the rapidly-growing provincial capital, Riobamba. The area above 4000 m.a.s.l. has been designated a ‘faunal protection reserve’, one of eight classifications for Ecuadoran national parks (Himley 2009). As with other mountain
landscapes, this considerable altitudinal range (over a lateral distance of only 20 km) results in high climatic, topographic and biophysical heterogeneity.

Temperature and precipitation both vary with altitude, with the local climate becoming increasingly warm and dry with decreasing elevation. In fact, the variation in
mean annual temperature between the highest and lowest-elevation communities is greater than the intra-annual temperature variation in any one location at this tropical latitude. There are typically two distinct wet seasons (Oct-Nov; Feb-May), and while moisture is usually sufficient in the Equatorial High Mountain climate zone typical of higher elevations, below 3100 m.a.s.l., the Equatorial Dry Temperate climate is semiarid, with annual precipitation less than 600 mm (Pourrut and others 1995) and an average annual moisture deficit of up to 600 mm (GADPCH 2011). There is tremendous spatial variability in precipitation quantity in Andean Ecuador (Farrow and others 2005), and there is also considerable inter-annual precipitation variability (usually a function of the El Niño – Southern Oscillation; Francou and others 2004) such that seasonal droughts are common. Since 1939, atmospheric temperatures in the tropical Andes have increased ~0.7°C (Vuille and others 2008) and there is evidence that both total precipitation and precipitation intensity in Andean Ecuador trended upwards between 1960 and 2000 (Haylock and others 2006). Climatological data from weather stations located within 50 km of Volcán Chimborazo indicate a 0.26°C temperature increase since the mid-1980s but generally do not identify changes in local precipitation patterns (see Chapter 3). Volcán Chimborazo’s ice surface area has decreased 21% ± 9% since 1986 (see Chapter 3).

Soils in Andean Ecuador tend towards high spatial variability (even at micro scales; Dercon and others 2003) and the soil transition that occurs at ~3400 m.a.s.l. (see Figure 4.2) is a distinct aspect of agricultural production in the parroquia. At higher elevations, soils are generally dark and loamy, with high moisture retention capacities
and high organic content. At lower elevations, the soil is sandy and highly erodible, with low moisture retention capacities and low organic content. Below 3100 m.a.s.l., the combination of poor soils and potential moisture deficits results in agricultural production being significantly less reliable than it is at higher elevations. This inverts the traditional agro-economic situation in the Andean highlands, where wealthier (usually mestizo or white) landowners farm at lower elevations where the climate tends to be more moderate and the risk of crop-killing frosts are reduced, while more marginalized (usually indigenous) landowners farm riskier, higher elevation plots (Stadel 1989). While this ethnic-elevation gradient remains apparent in the parroquia, it is decreasingly pronounced and appears to have been subsumed by an ethnic-urban dichotomy (mestizo/white-urban; indigenous-rural) that is even more strongly evident in the province.

Slightly more than half of adults in San Andreas Parroquia work in the agricultural sector (INEC 2010), and approximately 90% of households earn at least some portion of their income from crop and/or animal production. As is common in many mountain areas, agricultural activities here have a strong vertical component, with individual households often farming parcels scattered across multiple ecological belts within a short horizontal distance (Stadel 1986). By leveraging the biogeophysical heterogeneity of the landscape, households throughout the Andes lower risk and accommodate climatic variability by having diversified agricultural economies, including utilizing multiple fields in different locations, planting a variety of crops, and using a variety of seed stock (Stadel 2008; Young and Lipton 2006). In San Andres Parroquia, the typical household farms less than 3 hectares of land and produces 3 or 4 different
crops, such as potatoes, beans, and carrots at higher elevations, and barley and maize at lower elevations. Most households maintain a portfolio of mixed crop and livestock production, and milk is a key income source. Pigs, chickens and cuyes are also common, but are generally maintained for household consumption rather than as income sources. Alpaca and llama are relatively uncommon here. Throughout Andean Ecuador, unequal land distribution remains a remnant of the hacienda land-tenure system that existed here prior to the mid-20th century (Bebbington 1993a; Korovkin 1997). Though less extreme than elsewhere in the region (e.g. Stadel 1986), this pattern remains evident in the parroquia.

Because the seasonal variability and interannual unpredictability of precipitation represents a significant source of stress in Andean agricultural livelihoods (Stadel 1989), access to irrigation water is a strong predictor of agrarian livelihood well-being. About half of San Andres Parroquia households have access to irrigation. These households are potentially able to double or triple agricultural production, which may represent the difference between household sustainability and abject poverty (Boelens and Doornbos 2001). Throughout Andean Ecuador, access to irrigation water is tightly intertwined with broader issues of local geography (Waldick 2003), economic status (Dávila and Olazával 2006), community membership (Boelens and Zwart eveen 2005; Knapp 1991), political power (De Vos and others 2006; Hoogesteger 2012) and even ethnic identity (Andolina 2012; Cremers and others 2005). While irrigation management systems thus represent a fundamental component of community governance, increased demographic pressure, agricultural degradation, and the processes of migration, globalization and rural
urbanization are straining these systems (Boelens and others 2005), as are changing hydro-climatic conditions. These challenges, combined with persistent economic and political instability, have resulted in a tumultuous history of water resources management in Ecuador (Boelens and others 2013; Ruf 2003).

There continue to be strong inequalities in the allocation of water resources and water infrastructure development. While smallholder farmers comprise 88% of irrigators, they only have legal access to 6-20% of available water supply, while the top 1-4% of irrigators (typically surviving haciendas and agro-industrial operations) control 50-60% of the irrigation supply (Galárraga-Sánchez 2000). Government investment in irrigation has been similarly unbalanced in recent decades; a 1992 national evaluation found that farms of less than 1 ha (60% of all farmers) receive only 13% of the state expenditure on irrigation, while large landowners, comprising 6% of farmers receive 41% of these benefits (Cremers and others 2005). Unsurprisingly, this confluence of factors results in water rights being highly contested (Dávila and Olazával 2006), and the combination of high (and increasing) demand, limited (and decreasing) supply, inefficient management and problematic infrastructure (Evans and others 2003) have served to enhance water stress. One of the primary sources of water conflict has been the tendency of the national water management authority to authorize new water concessions without firm hydrological data. As early as the mid-1980s all rivers draining into the central Andean valley were considered to be fully allocated (Knapp 1991), however only in 2012 did authorities in Chimborazo Province initiate a formal water resources inventory.
Crucially, those households that are fortunate enough to have irrigation are now experiencing increasingly unreliable water supplies, meaning that their long-standing security against climatic variability is becoming more tenuous and their own vulnerability to further hydroclimatic change more pronounced. The Las Abras irrigation system, which is fed by runoff from Volcán Chimborazo and is the largest in the parroquia – both in terms of length (28 km) and number of users (~1500 households) – exemplifies this growing problem (see Chapter 5). The system has a legal concession for 60% of the discharge of the Rio Mocha at the canal intake, which, when originally codified, equated to 909 L s⁻¹. Diminishing watershed yield has subsequently forced the irrigation schedule to be reduced such that the maximum total allocation is currently 440 L s⁻¹. This adaptation, which has presented hardship for many users, is now itself proving to be insufficient for the hydrological realities of the watershed, and over the last six months of 2012 the canal was unable to meet total demand 80% of the time. As a result, some Las Abras users often do not receive their share of water when it is scheduled to be delivered. Since most households are allocated water for a specific period of time each week, non-delivery means that they must wait for their next turn the following week to receive water.

Land scarcity is also a persistent constraint on agricultural production in Andean Ecuador (Bebbington 1993a; Stadel 1986). Land scarcity is partly a function of land inequalities dating from the hacienda era, and partly a function of local traditions of equal land inheritance among children (both sons and daughters; Jokisch 2002). After land reform in 1964 and 1973, most households purchased parcels totaling 3 to 5 ha (Jokisch
2002), which represented the maximum amount of land most people could afford even though this was often insufficient for producing more than subsistence-level income (Bebbington 1993b). Now, after multiple generations of further inheritance-related subdivision, parcels in the parroquia are often transacted in sub-hectare units called *quadras* (0.64 ha). Continued population pressure and government restrictions on sub-*quadra* subdivision now results in very high land prices (up to US$5000 per *quadra*) and most families cannot afford to expand their crop production except by sowing in communal pastures, and sometimes, even in the officially-protected Chimborazo Faunal Protection Reserve.

Declining soil productivity has been recognized as a problem throughout Andean Ecuador, and has been linked to the land reform process that transferred land from the large hacienda owners to individual families (Bebbington 1993a). Under the hacienda system, most land was dedicated to pasture with only small areas devoted to crops, which permitted long fallow periods and the conservation of soil nutrients on the majority of the land. After land redistribution, most of the land was converted to individual crop plots and intensified farming has reduced or eliminated fallow periods. With insufficient quantities of animal manure to meet the fertilizing needs of the region, most farmers have been forced to increase their reliance on agrochemicals. The high cost of agrochemicals can force high elevation potato farmers to pioneer new plots farther upslope as the soil becomes degraded (Sarmiento 2002). As higher, steeper hillsides are cleared, however, there are notable negative consequences, including a drop in the local water table and
increased soil erosion. Farmers are then forced to move yet further uphill, and the process is repeated.

While smallholder agriculture remains the dominant economic activity, external employment has played an important role in regional livelihoods in recent decades (Bebbington 1993b; Knapp 1991), and in some areas of Andean Ecuador, agriculture is no longer the primary mode of income generation (Bebbington 1993a). Economic opportunities in San Andres Parroquia are limited; external employment for rural inhabitants like those of San Andres Parroquia typically requires emigration – seasonal or permanent – to Riobamba, other urban areas in Ecuador, and even international destinations such as the United States and Spain. Emigration strongly influences both the economic and social condition of rural Andean households (Jokisch 2002; Jokisch and Pribilsky 2002). On one hand, remittances from emigrated family members have become a significant component of the local economy and a key component in households’ ability to reduce economic vulnerability (Gray and Bilsborrow 2014), while on the other, emigration results in increased personal hardships for both the emigrants and the families they leave behind (Bebbington 1993b) and is seen as contributing to increasing social problems such as reduced community participation, an erosion of civility and increased crime (Bebbington 1993a). In any case, rural Andean Ecuador remains mired in poverty, and Chimborazo Province is considered the most socially-vulnerable of Ecuador’s provinces (Dávila and Olazával 2006; Farrow and others 2005). Here, 80% of the population live in poverty, 50% live in extreme poverty and 60% of children suffer from chronic malnutrition. One of the key obstacles to improved economic development is
limited education; in San Andres Parroquia, 64% of adults have no more than primary school education while 13% have no formal education whatsoever (INEC 2010).

In summary, people in Andean Ecuador face a suite of environmental challenges (and opportunities) and socioeconomic obstacles to livelihood sustainability. Andean societies have developed a range of adaptive strategies to leverage the environmental variables of their landscape in their favor; however, the forces of global change, including economic integration with the global economy and exposure to accelerating climate change, are testing their resilience to the factors that increase livelihood vulnerability. In light of these evolving conditions, I ask three specific questions about livelihood vulnerability in San Andres Parroquia:

1. Which socioeconomic and environmental stressors are driving perceptions of increasing vulnerability and how do these vary at the household level?
2. How have households adapted in response to shifting perceptions of vulnerability and what factors influence differential adaptive capacity at the household level?
3. How are vulnerability and adaptive capacity likely to evolve as the forces of global change persist or accelerate in the years ahead, and how heterogeneous are these conditions likely to be, given differential socioeconomic and environmental endowments among households?

Methods and Data

In order to answer questions about household livelihood stressors, perceptions of vulnerability and adaptive capacity, I conducted a total of 59 semi-structured household
surveys in 25 different communities within the parroquia. My sample was selected using a randomized GIS polygon technique to divide the parroquia into discrete subunits (Bury and others 2011). I then used GPS to identify the polygon centroid location in the field, and approached the nearest adult (age 18+) to solicit participation in the survey. While most participants were interviewed at their place of residence, a few were interviewed at farm plots that were located some distance from their homes. In all instances, interviews were held at locations where household livelihood activities take place. I collected GPS data at each interview site, though I generalize this on resulting maps in order to preserve household anonymity. I conducted surveys during daylight hours all on days of the week.

A total of 294 individuals reside within sampled households (2.2% of parroquia population), and comparison of survey demographic data with 2010 census data (INEC 2010) suggests that I have achieved an acceptable representation of the total parroquia population (Table 4.1). The survey instrument was approved by the Institutional Review Board at The Ohio State University and was field-tested to reduce confusing wording and potential bias (Appendix A). I conducted the surveys in Spanish (with assistance from a translator) in May and June of 2012. I also conducted several key-informant interviews with local and provincial government officials between 2010 and 2012 to gain a wider perspective on socioeconomic conditions in the region, as well as with local irrigation managers to better understand allocation and performance issues in local systems.

My survey extracted both quantitative and qualitative livelihood information about household demographics, economic activities, social support resources, agricultural activities, and, where appropriate, irrigation practices and performance. I identified 43
variables describing these conditions for which we analyzed each household’s survey responses. Table 4.2 describes these variables and summarizes results for the entire sample population. I next analyzed household locations using a GIS database incorporating soil survey information obtained from the Ministry of Agriculture (MAGAP) and local climate data obtained from the Institute of Hydrology and Meteorology (INAMHI) to identify spatial patterns in survey responses. I then grouped households into groups of irrigators/non-irrigators and good soils/poor soils and used a paired-difference analysis ($t$-tests) on a subset of 21 key variables to identify significant differences among households in each group pair. While soil quality is locally identified as an important determinant of agricultural prosperity, I note that soil quality is, like climate, elevation dependent and thus difficult to separate from temperature and humidity.
Table 4.2. Summary of descriptive statistics of surveyed San Andres Parroquia households. Variables in bold were included in the Independent Samples T Test means comparison for irrigator/non-irrigator and good soil/poor soil households.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>n (a)</th>
<th>Percentage of Observations</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey Information</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>resage</td>
<td>Respondent age</td>
<td>59</td>
<td>-</td>
<td>46.8 ± 15.9</td>
</tr>
<tr>
<td>resgen</td>
<td>Respondent gender</td>
<td>59</td>
<td>M: 54.2</td>
<td>45.8</td>
</tr>
<tr>
<td>resmar</td>
<td>Respondent marital status</td>
<td>59</td>
<td>Married: 83.1</td>
<td>Single: 6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Divorced/Separated: 3.4</td>
<td>Widowed: 6.8</td>
</tr>
<tr>
<td>resstat</td>
<td>Respondent status in household</td>
<td>59</td>
<td>Head of household/spouse: 88.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adult child of head of household: 11.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Employee of head of household: 0.0</td>
<td></td>
</tr>
<tr>
<td>Household Demographics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>totnem</td>
<td>Total number of household members</td>
<td>59</td>
<td>-</td>
<td>5.0 ± 2.9</td>
</tr>
<tr>
<td>totadult</td>
<td>Total number of adults (age ≥ 15) in household</td>
<td>59</td>
<td>-</td>
<td>3.5 ± 1.9</td>
</tr>
<tr>
<td>totchild</td>
<td>Total number of children (age &lt; 15) in household</td>
<td>59</td>
<td>-</td>
<td>1.4 ± 1.8</td>
</tr>
<tr>
<td>totdmen</td>
<td>Total number of adult men (age ≥ 15) in household</td>
<td>59</td>
<td>-</td>
<td>1.6 ± 1.1</td>
</tr>
<tr>
<td>totdwom</td>
<td>Total number of adult women (age ≥ 15) in household</td>
<td>59</td>
<td>-</td>
<td>2.0 ± 1.2</td>
</tr>
<tr>
<td>childratio</td>
<td>Child Dependency Ratio (number of children / number of household members)</td>
<td>59</td>
<td>-</td>
<td>0.21 ± 0.23</td>
</tr>
<tr>
<td>resedu</td>
<td>Highest education attained by respondent</td>
<td>46</td>
<td>No formal education: 13.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Some primary school: 10.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Completed primary school: 54.3</td>
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<td></td>
<td></td>
<td></td>
<td>Some secondary school: 6.5</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Completed secondary school: 6.5</td>
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<td></td>
<td>Some university: 4.3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Completed university: 0.0</td>
<td></td>
</tr>
<tr>
<td>resyrcomm</td>
<td>Number of years respondent has lived in their current community</td>
<td>58</td>
<td>-</td>
<td>36.5 ± 21.2</td>
</tr>
<tr>
<td>prolifeom</td>
<td>Proportion of life spent in current community (resyrcomm / resage)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Economic Activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aginc</td>
<td>Household earns regular income from agricultural activities on their own owned/rented land</td>
<td>58</td>
<td>Yes: 89.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No: 10.3</td>
<td></td>
</tr>
<tr>
<td>nonaginc</td>
<td>Household earns regular income from any activity other than agriculture on their own owned/rented land</td>
<td>58</td>
<td>Yes: 70.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No: 29.3</td>
<td></td>
</tr>
<tr>
<td>econact</td>
<td>Summary of economic activity of household</td>
<td>57</td>
<td>Ag. income from own land only: 28.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non-ag. income only (b): 10.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mixed ag. / non-ag. income: 61.4</td>
<td></td>
</tr>
<tr>
<td>nonagincnum</td>
<td>Number of household members who regularly earn non-ag. income</td>
<td>40</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.8 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>assetscore</td>
<td>Household Asset Index (c)</td>
<td>56</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.9 ± 2.2</td>
<td></td>
</tr>
<tr>
<td>car</td>
<td>Household owns at least 1 car</td>
<td>59</td>
<td>Yes: 30.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No: 69.5</td>
<td></td>
</tr>
<tr>
<td>Household Support</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sibChim</td>
<td>At least 1 adult sibling lives in Chimborazo or Tungurahua Province</td>
<td>57</td>
<td>Yes: 79.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No: 15.1</td>
<td></td>
</tr>
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</table>

Continued
Table 4.2 (Continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>n (a)</th>
<th>Percentage of Observations</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>childChim</td>
<td>At least 1 adult child lives in Chimborazo or Tungurahua Province</td>
<td>53</td>
<td>Yes: 47.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>No: 5.3</td>
<td></td>
<td>No adult children: 47.4</td>
<td>-</td>
</tr>
<tr>
<td>remit</td>
<td>Regularly receives remittance payments from outside household</td>
<td>58</td>
<td>Yes: 13.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>No: 86.2</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Agricultural Activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>parcel</td>
<td>Location of parcels relative to house</td>
<td>56</td>
<td>All adjacent to house: 39.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Some are walking distance away: 32.1</td>
<td></td>
<td>All are walking distance away: 10.7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Some/all are driving distance away: 17.9</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>parsize</td>
<td>Total size of all parcels, in hectares</td>
<td>53</td>
<td>-</td>
<td>2.1 ± 2.0</td>
</tr>
<tr>
<td>avparcsiz</td>
<td>Average size of parcels, in hectares</td>
<td>51(8)</td>
<td>-</td>
<td>1.1 ± 1.4</td>
</tr>
<tr>
<td>agtype</td>
<td>Type of agricultural activity pursued by household</td>
<td>52</td>
<td>Crop production only: 11.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Livestock/milk production only: 21.2</td>
<td></td>
<td>Crop and livestock/milk production: 67.3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>cropprod</td>
<td>Number of different crop types grown at time of survey</td>
<td>52</td>
<td>-</td>
<td>3.4 ± 1.7</td>
</tr>
<tr>
<td>numcow</td>
<td>Number of cows owned by household</td>
<td>48(6)</td>
<td>-</td>
<td>4.9 ± 5.6</td>
</tr>
<tr>
<td>numsheep</td>
<td>Number of sheep owned by household</td>
<td>32</td>
<td>-</td>
<td>5.6 ± 4.1</td>
</tr>
<tr>
<td>numharm</td>
<td>Number of horses owned by household</td>
<td>6</td>
<td>-</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td>numbuurro</td>
<td>Number of burros owned by household</td>
<td>20</td>
<td>-</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>numpigg</td>
<td>Number of pigs owned by household</td>
<td>37</td>
<td>-</td>
<td>1.6 ± 0.9</td>
</tr>
<tr>
<td>numalpllama</td>
<td>Number of alpacas and/or llamas owned by household</td>
<td>7</td>
<td>-</td>
<td>1.6 ± 0.5</td>
</tr>
<tr>
<td>numcuy</td>
<td>Number of cuyes owned by household</td>
<td>39</td>
<td>-</td>
<td>19.0 ± 19.1</td>
</tr>
<tr>
<td>numrabbit</td>
<td>Number of rabbits owned by household</td>
<td>17</td>
<td>-</td>
<td>8.5 ± 4.8</td>
</tr>
<tr>
<td>numchick</td>
<td>Number of chickens owned by household</td>
<td>36</td>
<td>-</td>
<td>6.0 ± 5.0</td>
</tr>
<tr>
<td>animdiv</td>
<td>Number of different animal types owned by household at time of survey</td>
<td>58</td>
<td>-</td>
<td>4.4 ± 1.9</td>
</tr>
<tr>
<td>milknum</td>
<td>Households earns regular income by selling milk</td>
<td>58</td>
<td>Yes: 63.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>No: 36.2</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>milkquan</td>
<td>Quantity of milk sold per week; in L</td>
<td>36(6)</td>
<td>-</td>
<td>154.1 ± 214.9</td>
</tr>
<tr>
<td>cropprod</td>
<td>Current crop production compared to past crop production</td>
<td>39</td>
<td>No Change: 0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Better than in the past: 0.0</td>
<td></td>
<td>Worse than in the past: 100.0</td>
<td>-</td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>irrig</td>
<td>Household uses irrigation water</td>
<td>58</td>
<td>Yes: 47.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>No: 52.5</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>irrigavail</td>
<td>Availability of irrigation water</td>
<td>27</td>
<td>Unlimited in time/quantity: 81.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Regulated in time/quantity: 18.5</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>irrigsuf</td>
<td>Sufficiency of irrigation supply</td>
<td>26</td>
<td>Always sufficient: 30.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Always water; sometimes insufficient: 34.6</td>
<td></td>
<td>Sometimes no water: 34.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

(a): n varies to reflect the number of households answering in the affirmative or, in some cases, the number of respondents who provided information
(b) Includes day labor income performed on farms owned by other people.
(c) Household Asset Index is a relative score determined by the number of the following real goods of which the household owns at least one: automobile, motorcycle, television, radio, cell phone, refrigerator, hot water shower.
(d) Excludes one household that is a significant outlier. This household of 13 adults has pooled resources to obtain 40 hectares of land and 106 cows, and produces 2800 L milk per week.
as a differentiating factor. Qualitative statements from each survey were also compiled
and analyzed in relation to a household’s spatial location, primary economic activity, and
irrigation status. I created an indicator called the household asset score to roughly assess
the relative economic well-being of different households. This score is tabulated by
counting the presence of at least one automobile, motorcycle, television, radio, cell
phone, refrigerator, and hot water shower such that a household with each of these
amenities would have a score of 8, while a household with none would have a score of 0.
I excluded one household from the quantitative analysis because it was a significant
outlier in terms of income and assets, however I incorporated qualitative information
from this survey into our discussion of household adaptation strategies.

Results

Social and Environmental Drivers of Livelihood Vulnerability

Households in San Andres Parroquia identify multiple environmental (e.g. climatic variability, soil productivity, insect plague) and social (e.g. market uncertainties, land scarcity) stressors that influence productivity as primary drivers of livelihood vulnerability. There is deep and widespread concern that many of these stressors are shifting in a way that threatens agrarian livelihoods. Though agriculture in Andean Ecuador has long been unprofitable and limited to subsistence-level yields (Jokisch 2002), residents overwhelmingly report that agricultural productivity is in decline and that households are now more vulnerable than they have been in the past. The comment of one farmer was typical: “crop production is much worse than it used to be and a farming livelihood is now much less secure,” (Household Interview 68, 6 June 2012).
Extreme weather and climatic uncertainty are always critical trajectories of vulnerability in agrarian households, and the livelihood risks most frequently identified by residents here are killing frosts (60%) and drought (55%). However, households are especially concerned about a general drying trend that they see as being the single greatest factor in reduced agricultural productivity in the region. When asked to describe regional climate change in the past decade-plus, 95% of those perceiving a change in precipitation (79% of all respondents) state that there is less rainfall now than in decades past while 92% of those who have notice a change in surface water availability (94% of all respondents) say there is less water now than before (see Chapter 3). Many households report that rains are becoming increasingly unpredictable and that this too has added to the sense of increased livelihood vulnerability in the parroquia: “These changes mean that it is harder to predict agricultural production,” states one farmer (Household Interview 27, 27 May 2012). These perceptions directly contradict the instrumental precipitation data from the region, which indicate that precipitation trends have generally remained unchanged in recent decades.

Nearly 20% of surveyed households identify degrading soils as one of the notable local environmental changes over the past few decades, and there is widespread belief that acceptable crop yields are now impossible unless special treatments are applied. This perception is shared by both irrigators and non-irrigators and is independent of soil zone in the parroquia. “In the past, harvests were better and there was no need to use chemical fertilizers like there is today,” (Household Interview 41, 6 June 2012). This need to purchase fertilizer, pesticides and other treatments is a significant financial burden for
households already struggling to maintain even modest livelihoods, and a lack of capital for doing so is the single most widely cited obstacle (30% of households) to improving household incomes. Says one farmer, “the need for chemicals means a high initial investment, which makes farming harder than it used to be,” (Household Interview 23, 1 June 2012) while another reports, “the expense of buying seeds and fertilizers in order to produce a sufficient crop is a challenge. Often, we need to obtain a bank loan, but we must use our animals, land, and house as collateral and we risk losing these if we are unable to repay the loan,” (Household Interview 22, 1 June 2012).

Pests, especially those affecting potato crops (35%) and land scarcity (10%) were also identified by residents as important livelihood risks. Pests are viewed as being increasingly problematic, especially by non-irrigators ($p < .05$; medium effect size), which indicates a relationship between moisture stress and susceptibility to insect damage. Land scarcity is viewed not only as a constraint on household crop yields, but also one of the drivers of declining soil productivity since many households don’t have the luxury of fallowing their land in order to naturally restore nutrients.

**Household Adaptations to Shifting Livelihood Vulnerabilities**

Chimborazo’s drying climate has only enhanced the longstanding perception that irrigation is essential for profitable agrarian livelihoods in the parroquia, and several key indicators suggest that, to this point, irrigating households have been better shielded from the area’s expanding trajectories of social and environmental vulnerability. Irrigators have more diverse crop ($p < .1$) and livestock ($p < .01$) portfolios than do non-irrigators, which results in higher incomes as well as a level of insurance against drought and other
extreme weather events that non-irrigators do not enjoy (Table 4.3). Irrigators (56%) are less likely to require external employment than are non-irrigators (87%) ($p < .05$); especially in the warmer, drier, poor soil zone where access to irrigation is a primary determinant in whether or not a purely agrarian livelihood remains possible. Here, no non-irrigating household persists without income from external employment. Household asset scores indicate differential economic well-being between irrigators (3.3) and non-irrigators (2.5), though this is not statistically-significant ($p < .18$). Asset scores clearly illustrate why external employment is essential for non-irrigators: those with outside income have a mean asset score of 2.9 while those few who maintain an exclusively agrarian livelihood have a mean score of 0.8. It is also noteworthy that irrigators are

Table 4.3. Comparison of irrigators and non-irrigators for selected livelihood variables. Bold values are significant at $p < 0.05$. Non-irrigator $n = 30$; Irrigator $n = 28$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Non-Irrigator Mean</th>
<th>Irrigator Mean</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>resage</td>
<td>46.67</td>
<td>47.54</td>
<td>0.836</td>
</tr>
<tr>
<td>totmem</td>
<td>5.17</td>
<td>4.43</td>
<td>0.290</td>
</tr>
<tr>
<td>childratio</td>
<td>0.25</td>
<td>0.18</td>
<td>0.267</td>
</tr>
<tr>
<td>resedu</td>
<td>1.65</td>
<td>2.50</td>
<td><strong>0.039</strong></td>
</tr>
<tr>
<td>resyrcomm</td>
<td>34.76</td>
<td>38.64</td>
<td>0.497</td>
</tr>
<tr>
<td>prolificom</td>
<td>0.73</td>
<td>0.79</td>
<td>0.524</td>
</tr>
<tr>
<td>econact</td>
<td>2.55</td>
<td>2.07</td>
<td><strong>0.048</strong></td>
</tr>
<tr>
<td>sibChim</td>
<td>1.00</td>
<td>0.79</td>
<td>0.100</td>
</tr>
<tr>
<td>childChim</td>
<td>1.39</td>
<td>1.43</td>
<td>0.825</td>
</tr>
<tr>
<td>remit</td>
<td>0.10</td>
<td>0.18</td>
<td>0.423</td>
</tr>
<tr>
<td>car</td>
<td>0.27</td>
<td>0.32</td>
<td>0.654</td>
</tr>
<tr>
<td>assetscore</td>
<td>2.50</td>
<td>3.28</td>
<td>0.173</td>
</tr>
<tr>
<td>parcloc</td>
<td>2.07</td>
<td>2.00</td>
<td>0.810</td>
</tr>
<tr>
<td>parcsizesize</td>
<td>1.85</td>
<td>1.72</td>
<td>0.316</td>
</tr>
<tr>
<td>avparcsizesize</td>
<td>1.23</td>
<td>1.02</td>
<td>0.591</td>
</tr>
<tr>
<td>cropdiversity</td>
<td>2.92</td>
<td>3.81</td>
<td>0.061</td>
</tr>
<tr>
<td>animaldiversity</td>
<td>3.73</td>
<td>5.04</td>
<td><strong>0.007</strong></td>
</tr>
<tr>
<td>numcow</td>
<td>4.26</td>
<td>5.40</td>
<td>0.484</td>
</tr>
<tr>
<td>numsheep</td>
<td>5.94</td>
<td>5.19</td>
<td>0.610</td>
</tr>
<tr>
<td>numcuy</td>
<td>13.59</td>
<td>22.76</td>
<td>0.148</td>
</tr>
<tr>
<td>milkquan</td>
<td>113.39</td>
<td>194.83</td>
<td>0.259</td>
</tr>
</tbody>
</table>
much more likely to have continued their education beyond the primary level than are non-irrigators \( p < .05 \). I interpret this as a legacy of the enhanced economic stability that irrigation provides, since the next level of education, \textit{collegio}, requires tuition and children in economically-tenuous households are more likely to be forced into family-support roles at a younger age.

Households in San Andres Parroquia commonly view acquisition of irrigation rights as their ideal adaptation strategy for addressing the range of livelihood vulnerabilities they face, and a greater proportion of non-irrigators (24%) identify the lack of reliable water as a primary obstacle to improved financial stability than identify a lack of jobs (20%) or land scarcity (12%). One farmer states, “having irrigation water would change our lives. It would allow us to increase our production of cash crops such as potatoes, cabbage and lettuce, and would allow us to raise a milk cow,” (Household Interview 5, 16 May 2012). Another explained, “having water would be wonderful! If I could irrigate, I would plant more beans because they grow more rapidly, can be harvested more frequently, and will earn me a better income,” (Household Interview 23; 1 June 2012). In all, 96% of non-irrigators state that having irrigation would increase their income, 27% believe that irrigation would greatly reduce their livelihood uncertainty, and 12% claim that, if they had irrigation, household members would give up their external employment and return to agriculture full-time. “I would prefer to work the land full-time rather than work in construction,” notes one man who can only tend his fields on weekends, “but I could only do so if I had irrigation,” (Household Interview 45, 3 June 2012).
The increasing precipitation variability that people here observe means that they cannot plan for a lack of water since they don’t always know in advance when this will occur. Instead, households can, “only get by as best as possible,” (Household Interview 21, 6 June 2012). Including other irrigation systems, 69% of irrigators we surveyed in the parroquia state that they do not receive their allocation at least some of the time. This problem is especially acute for down-canal irrigators, meaning that those farmers who are already most disadvantaged by climate and soil conditions are also those least likely to receive their full allocation of irrigation water. As a result, irrigators and government officials report that unauthorized water use is increasingly common and that incidences of inter- and intra-community water conflict are on the rise. Many irrigators express serious concern about the potential consequences of losing their water supplies. Some suggest that they would simply have to accept smaller yields, others recognize that they would have to change their modes of agricultural production, while still others acknowledge that, without irrigation, they would have to make more drastic livelihood adaptations. Without irrigation, says one farmer, “life would be harder for everyone and more people might be forced to emigrate. Already, there are fewer farmers than there used to be and some people from our community have had to move away,” (Household Interview 4, 16 May 2012).

The hypothetical adaptations suggested by irrigators concerned about their water supplies are rooted in the actual decisions that many households, especially non-irrigators, have already been forced to make as agrarian livelihoods in San Andres Parroquia have become increasingly strained. One such strategy is to reduce economic
dependence on crop production and instead emphasize livestock-related activities. While a mixed crop/livestock portfolio has always been the dominant approach to agricultural production, numerous households report that they have made a conscious decision in recent years to sow less seed and instead increase their investment in animals, especially milk cows. As one farmer explains, “milk production is a lower risk activity, and I’m paid every 15 days” (Household Interview 21, 6 June 2012), while another farmer noted that dairies will often provide cash advances against future milk production, which is very helpful when a household experiences an economic shock (Household Interview 27, 27 May 2012). In all, 71% of households who pursue agricultural activities sell milk on a regular basis and, given the economics of milk production, it is easy to understand why. As of June, 2012, milk earned US$0.32/L; given a weekly milk production of 70 L (the median production rate of surveyed households), a household would earn US$97 per month (28% of Ecuador’s 2011 gross median monthly wage for all sectors; ILO 2012). At present, nearly a quarter of households sell milk as their only means of agricultural production, and this number is likely to rise. “Ideally, I won’t plant more crops but instead will buy more animals,” commented one farmer when asked about his strategy for reducing livelihood vulnerability (Household Interview 39, 30 May 2012), though the expense of purchasing animals remains an obstacle. The transition to livestock doesn’t necessarily eliminate the perceived need for irrigation either, since most farmers see irrigation as the key for improving forage and thus increasing the number of cows their land can support. Indeed, it is noteworthy that only 1 of the 11 livestock-only households I surveyed is located below 3400 m.a.s.l., suggesting that the combination of poor soils
and drier climate at lower elevations inhibit forage growth such that this may not be a viable livelihood adaptation strategy in these areas.

While there is a longstanding tradition of seasonal labor migration on the part of agrarian households in Andean Ecuador, household reliance on external employment to supplement or even replace agricultural income is another adaptation strategy that appears to be increasingly common. As one community leader noted, “Our community’s economy has changed quite a bit. In the past, farming was the dominant activity but now the majority of people undertake other activities, (Key Informant Interview, 22 July, 2012). In San Andres Parroquia, 72% of households we surveyed now draw some or all of their income from external employment. Underemployment is rife, however, and 77% of those who pursue external employment are limited to temporary and/or transient opportunities such as day labor or construction work. This lack of stable income is one reason why household asset scores for households who earn all of their income from external employment (2.6) are only marginally higher than those for households who earn all of their income from agricultural production (2.4), and lack of available jobs is widely viewed as a primary obstacle to improving livelihood well-being.

Long-term emigration of at least some household members has been a common adaptive response to acute socioeconomic and environmental stressors in Andean Ecuador for some decades (DePaoli 2011; Jokisch and Pribilsky 2002), and in many cases, the remittance payments returned by emigrants provide the greater proportion of total household income for the families remaining behind (Gray and Bilsborrow 2014; Jokisch 2002). In San Andres Parroquia, 14% of surveyed households receive regular
remittance payments, with emigrant family members typically settled domestically in the larger Ecuadorian cities such as Quito or Guayaquil or internationally in either the United States or Spain. Elsewhere in Andean Ecuador, access to remittance payments has been identified as an important factor in creating differential wealth within rural communities (Jokisch 2002); here, however, there is no difference in either the amount of land owned or the household asset score between those that receive remittance payments and those that do not, suggesting that these households only use emigration as a means to stay solvent rather than as a means for financial growth.

Discussion

One of the most surprising findings of this research is the discrepancy between what local rain gauges have recorded and the strong and widespread perception that there is less rainfall now compared to the past. While the scientific community tends to value empirical data much more highly than anecdotal qualitative data, there is compelling evidence that it is the instrumental record generated by the sparse network of rain gauges in the region that is misinterpreting local precipitation patterns (see Chapter 3). This finding illustrates how pure reliance on sparse instrumental data to determine where and how climate change impacts are occurring may force us to miss the true nuances of climate change and the way people react in response, especially in highly complex mountain landscapes. The implications of this are significant: if we do not adequately understand local patterns of climate change, then our ability to identify and address shifting patterns of livelihood vulnerability is constrained and we then miss opportunities to anticipate who will be most impacted by climate change in the future.

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While irrigation may be viewed as a panacea for many of the challenges facing non-irrigating farmers, there are few opportunities for developing new irrigation systems or for purchasing shares in existing systems in the parroquia, which greatly limits the viability of irrigation as an adaptation option. A few small irrigation systems have been substantially expanded in recent years, typically with help from international donor agencies, however the fundamental constraint is that there is little unallocated water left in the parroquia, and what water is available is being used to improve provision of even more essential potable water systems. Because of the combination of diminishing supply and increasing demand, many communities’ existing potable water sources are increasingly insufficient, and there has been a recent push to claim and exploit most of the few remaining undeveloped springs on Volcán Chimborazo’s slopes for potable usage. Springs on Chimborazo’s southern slopes have been especially impacted, and communities there are constructing new systems, such as a new 14 km pipeline serving the residents of Santa Lucía and Silvería, to exploit the few remaining springs in the more humid Rio Mocha watershed on the northeast flank of the mountain. Because water supplies are scarce, most existing irrigation systems are fully-allocated and tightly regulated. Farmers wanting to obtain irrigation must thus negotiate to purchase land that has an existing, transferable irrigation share. Given the scarcity of both land and water, such opportunities are extremely limited and well outside the financial capacity of most households. One farmer summarized this challenge: “irrigation is available for people who were born here, but I don’t live in this community so there’s no water available for my land,” (Household Interview 68, 6 June 2012).
For communities in the parroquia, exploitation of groundwater for irrigation is not a feasible option without significant outside investment since the main aquifer is as much as 100 m below the surface. Furthermore, recent analysis suggests that this aquifer provides only ‘fossil’ water that is as much as 8000 years old (Bigo 2013), so even if such investment were forthcoming, this would not be a sustainable long-term solution. The city of Riobamba, which derives all of its domestic water supply from this aquifer (its wells are located in the parroquia at the community of Llío), is already exploring alternative, distant sources as well as ways to actively promote reduced urban water consumption (Key Informant Interview, 4 March, 2010). Similarly, while water is ample in the mountains east of Riobamba, the cost to develop diversion infrastructure would require at least national-level investment. Though the provincial government has invested at least $15 million since 2009 to upgrade existing irrigation infrastructure and improve management (Key Informant Interview, 18 April 2012), households express frustration that the provincial – and, especially – national governments aren’t doing more. As one farmer concludes: “Our reality is that we don’t have enough water, we can’t grow enough, and there isn’t enough government assistance” (Household Interview 22, 1 June 2012).

While the land scarcity problem is overshadowed by changing precipitation patterns and degraded soil productivity as the primary drivers of increased livelihood vulnerability in San Andres Parroquia, it also has important implications for local farmers’ adaptive capacity to these accumulating stressors. While the dispersal of parcels across different ecological belts is an important traditional adaptive strategy in the region,
this land ownership pattern is now as much due to the vagaries of land markets as it is a conscious strategy to minimize risk, which means that parcels are often more scattered than would otherwise be desirable. This presents challenges in terms of time/expense of transportation and potential loss of community-based social capital. As one older resident laments, “many of the people who own land here live far away, so there’s no sense of community anymore,” (Household Interview 31, 21 May 2012). In the end, land scarcity means that many households find themselves land-rich but dollar-poor, unable to grow enough on their small parcels to make a profit and unable to purchase additional land due to high market prices.

Though external employment can improve a household’s economic situation, the lack of available work in the region means that pursuing this strategy often requires considerable disruption, as household members – typically male – are forced to seek work in Riobamba or even further afield. People express unhappiness about these social implications. As one community leader explained, “Life in general is more difficult than it used to be and it is getting worse. Because there is much less agricultural production, people must seek work elsewhere and the community is less close-knit as a result. There is less community collaboration than there used to be,” (Key Informant Interview, 22 July 2012). External employment is viewed in a somewhat negative light and a cultural tension about the shifting reliance on non-agrarian livelihood activities is evident. While several people commented that farming is much harder than are other types of work and that they feel disadvantaged by their inability to enjoy the modern amenities of urban living, many people who do pursue external employment express frustration that they no
longer have the freedom to simply live off their own land. As one farmer who is forced to
work in construction during the week also explained, “I still work my parcels because my
parents worked very hard for this land and I want to honor that as well as maintain the
farming tradition.” (Household Interview 45, 3 June 2012).

Disruptive as it may be, emigration is nonetheless an adaptation strategy that can
be employed to alter a household’s economic status. For example, the head of one of the
most financially-successful households I surveyed explained that he was only able to
invest in additional land and animals because he had built significant savings after a
decade of migrant farm labor in Spain (Household Interview 11, 27 May 2012).

However, while recent research elsewhere in Andean Ecuador has refuted the notion that
emigration leads to abandonment of agricultural land (Gray and Bilsborrow 2014), there
is clear evidence that considerable areas of formerly productive land in the lowest
elevation regions of the parroquia have been vacated and residents say that some of the
negative social consequences of emigration, including increased crime and decreased
civility (Bebbington 1993a) are increasingly apparent here. The cultural loss associated
with emigration remains a strong deterrent to emigration, however. “Other people
sometimes wonder why we don’t leave this area since life is difficult here, but we prefer
to live here because we love the land” (Household Interview 50, 3 June 2012).

Characterizing Future Livelihood Vulnerability

Amelioration of the primary social and environmental stressors identified by
residents of San Andres Parroquia – shifting hydroclimatic conditions, degrading soil
productivity and increasing land scarcity – is unlikely for the foreseeable future. Indeed,
the anticipated effects of 21st century climate change in the tropical Andes, including a potential 4°C increase in mean annual surface temperature (Urrutia and Vuille 2009), an intensifying hydrological cycle (Buytaert and others 2011), and a higher frequency of extreme El Niño events (Cai and others 2014) is likely to accelerate households’ exposure to enhanced livelihood vulnerability in much of the region (Marengo and others 2011; Rhoades and others 2008; Young and Lipton 2006). However, as this research illustrates, this area – like most mountain landscapes – is highly heterogeneous both environmentally and socially. Complex topography creates complex patterns of slope and solar exposure, soil quality is highly variable, steep elevation gradients result in steep temperature gradients, and precipitation patterns vary dramatically over very short distances (Figure 4.3). Some households are more highly educated, have easier access to labor and commodity markets due to their relative proximity to improved roads and public transportation, have been able to obtain more stable external employment, and/or have stronger familial support structures than do other households, and, of special importance here, some households have access to irrigation while others do not. Taken together, these (and many other) factors combine to form a complex tapestry of vulnerability and adaptive capacity to global change that makes broad generalization of future livelihood vulnerability extremely difficult.

Nonetheless, because access to irrigation and soil quality appear to be the two most dominant variables in determining agricultural production, I can use these factors to develop a picture of expected future patterns of livelihood vulnerability as a function of global change. To this end, I have created a local ‘vulnerability matrix’ that describes
Figure 4.3. The spatial pattern of seasonal aridity, as measured in the annual number of consecutive months with less than 60 mm mean precipitation, in central Andean Ecuador (adapted from Farrow and others 2005).

how soil quality and access to irrigation (or lack thereof) interweave to influence the risks facing households in the parroquia (Figure 4.4). For those households that are located in higher elevation ‘good’ soil zones (i.e. those that are dark and loamy, with high moisture retention capacities and high organic content) and have access to irrigation, I find that the future risk of increased livelihood vulnerability due to global change is relatively low. While these households are will face challenges posed by increased hydroclimatic variability, their favorable soils and the generally cooler, wetter climate at higher elevations will moderate some of these effects. Similarly, though irrigation schedules are tightly regulated and irrigators in both soil zones report insufficient water supply,
Figure 4.4. Vulnerability matrix for surveyed households in San Andres Parroquia, as a function of access to irrigation and soil quality. Green boxes indicate those households where the future risk of increased livelihood vulnerability due to climate change is relatively low compared to other households; yellow indicates moderate risk of increased vulnerability; red indicates high risk of increased vulnerability.

upstream irrigators are more likely to receive water than downstream irrigators simply by virtue of having access to available supply first. Households located in good soil zones but that do not have access to irrigation face a moderate risk of increased livelihood vulnerability due to global change. Without irrigation, these households are likely to face higher risk of drought in the future, however their favorable soils and higher-elevation climate provides some protection against this risk. Indeed, households located at the highest habitable elevations of the parroquia actually view changing climatic conditions to be advantageous. As one farmer who lives above 3600 m.a.s.l. commented, “I prefer the weather now to that of the past. Warmer and drier is a better climate at this location,” (Household Interview 28, 30 May 2012). This sentiment reflects the reality that climate change, at least as it has thus far manifested, is not universally detrimental and that some
mountain areas may actually benefit in the decades ahead (at least unless/until temperatures or precipitation shift more dramatically).

Counterintuitively, I also find that households that lack irrigation in lower elevation ‘bad’ soil zones (i.e. that are sandy and highly erodible, with low moisture retention capacities and low organic content) are generally at only moderate risk of increased livelihood vulnerability due to global change. While they should be expected to suffer the most agricultural disruption due to global change, many of these households actually have reduced exposure to direct impacts because they have already adapted to shifting conditions by limiting their economic reliance on agricultural production. Within this group of households, only one survey participant maintains exclusive reliance on agrarian activities while 20% of households draw income exclusively from external employment (compared to 3% in good soil zones). Furthermore, based on apparent patterns of abandoned farmland and the perceptions of survey participants, it appears that households in this vulnerability category are more likely to have already pursued emigration strategies than have non-irrigators in poor soil zones or irrigators in either soil zone. While most households in this group do rely to some extent on agricultural production, their exposure to non-agricultural economic networks outside of their communities likely presents alternative adaptation opportunities.

In my analysis, I find that irrigators residing in bad soil zones are the group most at risk of increased livelihood vulnerability due to global change and that this risk is potentially quite high. Though 63% of these households also incorporate external employment into their economic portfolio, 20% continue to rely exclusively on
agricultural production and it is only because of their access to irrigation that this has remained possible. However, as irrigation supplies becomes less reliable, the likelihood that a household will suffer an economically-devastating crop loss increases. This problem is especially acute in the poor soil zones because these households are typically at the lowest end of their irrigation systems, where losses due to distribution inefficiencies and unauthorized water use accumulate to the greatest extent. When available water supplies are no longer able to allow households to overcome their dual obstacles of unfavorable climate and poor soils, members will be forced to look elsewhere for income. Because irrigators as a group have attained higher levels of education, such an economic transition may be somewhat less difficult than it has been for non-irrigating households. However, considering the dearth of available jobs in the region, future global change is likely to introduce significant hardship to many of these families unless a dramatic increase in irrigation infrastructure investment is made by the Ecuadorian government.

Conclusions

Agrarian households in San Andres Parroquia face a range of socioeconomic and environmental stressors that, together, are enhancing the perception that livelihood vulnerability is increasing. Evolving hydroclimatic conditions and a near ubiquitous sense of increased water stress are the most prominent factors people here identify, though degrading soil productivity, increased pests and land scarcity are also identified as drivers of reduced well-being. These factors affect nearly all households to some extent, though the intensity of their impact varies from one household to the next. Households
respond to their perceived increased vulnerability by adjusting their agricultural activities, especially in favor of milk production, and/or seeking external employment opportunities. While both strategies have been in the adaptation portfolio of Andean communities for several generations, considerable barriers to implementation, such as the need for economic capital to purchase animals, limited education, minimal non-agricultural skills, and a dearth of stable employment opportunities, persist. Emigration, though a common adaptation strategy in Andean Ecuador since the 1990s, is highly disruptive and carries considerable social costs at the individual, household and community levels. Obtaining access to irrigation is a high-impact adaptation strategy and it remains an idealized option for many farmers; however, because all reasonably accessible surface water in the parroquia is now fully allocated, this strategy is no longer viable for most households.

Most socioeconomic and environmental forecasts suggest that the forces of global change – in particular, climate change – will exert increasing pressure on Andean livelihoods in the years ahead. Already, livelihood vulnerability is increasing, though the severity is differentiated among households and is spatially heterogeneous. There is ample evidence that, as with agrarian communities elsewhere in the tropical Andes, climate change specifically is having a considerable impact on livelihoods and household stability in Andean Ecuador. Of particular concern is the potential future livelihood vulnerability of households that continue to rely on irrigated agriculture as their primary means of income. Whereas these families have been somewhat insulated from those stressors that have already forced non-irrigators (especially in unfavorable soil and
climatic zones) to make dramatic livelihood alterations, increasingly unreliable water supplies are putting their economic viability at risk, too. This is one of the key messages that we can derive from the experiences of people in San Andreas Parroquia: access to irrigation is not necessarily a buffer against vulnerability to climate change, since external conditions (i.e. poor soils, increasingly unpredictable irrigation supply) can trump in-situ previously available adaptations (increasing irrigation; changing crop types).

The other key message that we can take from this research is that household livelihood vulnerability to global change is just as heterogeneous as are other social and environmental conditions in San Andres Parroquia and thus we cannot simply conclude that everyone living in rural Andean Ecuador is equally vulnerable. Some households are at greater risk for livelihood disruptions than are others, and these people do not live in single homogenous blocks (Figure 4.5). This conclusion calls into question some of the assumptions upon which much of the discourse about global change impacts in rural mountain regions is built, and it should force us to rethink how we perceive vulnerability and adaptation in these places. Rather than approaching vulnerability as a homogenous condition, we must seek to analyze vulnerability and adaptive capacity at highly localized scales in order to understand the nuances inherent to such highly complex social and natural landscapes.
Figure 4.5. Future risk of increased livelihood vulnerability due to climate change of surveyed households based on soil quality and access to irrigation.
References


Figure 5.1. The Boca Toma, where 60% of the Rio Mocha’s discharge is diverted into the Las Abras irrigation system.
Introduction

Glaciers throughout the tropical Andes are steadily losing mass in response to climate change (Burns and Nolin 2014; Cáceres 2010; Ceballos and others 2006; Jordan and others 2005; Rabatel and others 2013; Ribeiro and others 2013), and there is mounting concern about the potential consequences for water resources of this ice loss (Bradley and others 2006; Chevallier and others 2011; Vergara 2007). Glaciers are of particular value in a water resources context because they store a proportion of the precipitation falling over a watershed and modulate downstream discharge over daily to multi-century time scales (Fleming and Clarke 2005; Hock 2005; Jansson and others 2003). In glacierized mountains where precipitation is typically highly seasonal, this “glacier compensation effect” ensures a dependable water supply throughout the dry season and, on an interannual basis, mitigates the impact of extended drought (La Frenierre and Mark 2014; Lang 1986; Rothlisberger and Lang 1987). In the tropical Andes, this reliable water supply makes glacier meltwater runoff a crucial resource for downstream irrigation, power generation and domestic water consumption.

Research conducted in Peru’s heavily glacierized Cordillera Blanca illustrates the hydrological impact of tropical glaciers (Mark and McKenzie 2007; Mark and others 2005; Mark and Seltzer 2003). In the small (58 km²), modestly glacierized (3%) Querococha watershed, for example, glacier meltwater was found to contribute between 35 – 58% of mean annual discharge, and, in dry years, nearly 100% of dry season discharge. While watershed yields initially increase in response to persistent ice loss, the shrinking ice mass is ultimately unable to sustain elevated flows and, eventually,
discharge volume decreases while discharge variability increases (Baraer and others 2012). The impact of a diminished glacier compensation effect is apparent in modeling conducted in another watershed in the same region (Juen and others 2007). In the Llanganuco catchment (86 km², 34% glacierized), a potential 75% reduction in glacier area by 2080 results in a 10 – 26% increase in wet season discharge and an 11 – 23% decrease in dry season discharge. Anticipating the consequences of complete glacier loss from the Cordillera Blanca, Baraer et al. (2012) estimate that dry season flows in the upper Rio Santa, which drains the entire western flank of the range (4800 km², 7% glacierized), would decrease by as much as 30%.

Glaciers aren’t the sole source of water in mountain watersheds, of course, and even in highly glacierized catchments like those of the Cordillera Blanca, groundwater may be the dominant contributor to watershed discharge throughout the year (Baraer and others 2009). However, the relationship between glacier meltwater and groundwater recharge is likely complex and dynamic (Favier and others 2008) and there remains a great deal of uncertainty about the implications of glacier loss for this component of the hydrological system.

Though small compared to those of the Cordillera Blanca, the glaciers of Ecuador’s Volcán Chimborazo can be expected to play a similar role in local watershed hydrology. To date, however, there has been little investigation into the hydrologic significance of Chimborazo’s glaciers. There have been no comprehensive efforts to measure the rate and extent of the mountain’s glacier retreat or to quantify glacier melt as a component of total watershed discharge. There is minimal existing infrastructure for
any discharge monitoring, and climatologic measurements are sparse. The net effect of these conditions is that there is very limited local capacity for modeling Chimborazo’s hydrologic systems, predicting the response of those systems to climate change, and for anticipating the impact of glacier loss on current and future water management practices. Because people in the Chimborazo region are highly dependent upon irrigation, this limited capacity, combined with a relatively low standard of economic development, suggests that there are people here who may be highly vulnerable to evolving hydrological conditions and that they may be poorly positioned to adapt without significant socioeconomic disruption.

Here, I present the results of an integrative study that quantifies glacier meltwater runoff as a water resource in the Chimborazo region and explores how water users here are responding to various manifestations of hydrological change. I use as a case study the Las Abras irrigation system, the largest in the immediate vicinity of Volcán Chimborazo and likely the most reliant upon glacier meltwater runoff. I first analyze the system’s spatial and temporal patterns of supply and demand to determine if water scarcity is becoming a discernible problem. I then quantify the proportional contribution of glacier meltwater runoff to the total supply entering the irrigation system to better understand the hydrological role of Chimborazo’s glaciers and the possible implications of their continued retreat. Finally, I examine the impacts irrigation practices of Las Abras users to assess the potential impact of an increasingly unreliable water supply. My motivation for undertaking this work is two-fold: 1) to demonstrate the utility of such an integrative approach for local-scale climate change impact assessment; and 2) to rigorously examine
the relationship between glacier loss and water scarcity so that Chimborazo’s irrigators will be in a better position to understand, mitigate, and adapt to the effects of climate change on their water supply.

**Geographic Setting**

Volcán Chimborazo (1.47°S, 78.82°W) is located in the central Ecuadorian Andes, approximately 150 km south of the capital, Quito, near the boundary of Chimborazo and Tungurahua provinces (Figure 5.2). Within Ecuador, the Andes are comprised of two parallel ranges, the eastern Cordillera Oriental and the western Cordillera Occidental, which are punctuated by a series of towering stratovolcanoes; dormant Chimborazo is the highest of these (6268 m.a.s.l.) and the southern-most in the Cordillera Occidental. Areas above 4000 m.a.s.l. on the mountain have been designated a ‘faunal protection reserve’, while the lower slopes – especially those to the south and east – are intensively farmed and dotted by small, primarily indigenous communities. Riobamba, the capital and largest city in Chimborazo Province (population ~150,000), is located 25 km southeast of the mountain.

Chimborazo’s equatorial situation results in minimal intra-annual temperature variation and distinct precipitation seasonality. There are generally two wet seasons, one long (February – May) and one short (October – November) and two intervening dry seasons (June – September and December – January). Despite its relative proximity to the Pacific Ocean, moisture generally arrives from the Amazon Basin on northeasterly winds and a pronounced northeast (up to 2000 mm yr\(^{-1}\)) to southwest (less than 500 mm yr\(^{-1}\)) precipitation gradient is evident. Three elevation-dependent climate zones exist within
Figure 5.2. Map showing the location of Volcán Chimborazo and the Las Abras system in Chimborazo Province, Ecuador, local climate zones, and the glacier meltwater runoff status of the mountain’s 17 glacial catchments.

the vicinity of the mountain (Pourrut and others 1995). The Alpine climate describes those area above ~4500 m.a.s.l. where sub-freezing temperatures and snowfall are
dominant. The Equatorial High Mountain climate is cool and damp, with mean annual temperatures between 0°C and 12°C, mean annual precipitation greater than 600 mm (except on leeward slopes) and no annual moisture deficit. The semi-arid Equatorial Dry Temperate climate, found below ~3100 m.a.s.l. on the southeast side of Chimborazo, features mean annual temperatures between 12°C and 22°C, mean annual precipitation less than 600 mm and a potential annual moisture deficit of up to 600 mm. Interannual climatic variability can be considerable and is primarily driven by the El Niño – Southern Oscillation (ENSO), with El Niño (La Niña) bringing warmer (cooler) and drier (wetter) conditions (Vuille and others 2003).

Chimborazo’s glaciers, like all tropical glaciers, are highly sensitive to climate change (Kaser and Osmaston 2002), and the mountain’s 21% reduction in ice area since 1986 (see Chapter 3) indicates that climatic conditions are indeed different than in decades past. Available instrumental records from the region suggest that temperatures have increased 0.11°C decade⁻¹ since at least 1980 (consistent with the tropical Andes as a whole; Vuille and others 2008), but that precipitation has remained largely unchanged outside of a slight increase in precipitation during the short dry season in the region north of the mountain. Residents living east and south of the mountain are, however, in near unanimous agreement that precipitation is now less frequent (and less predictable) than in decades past and that local springs, streams and ponds are drying up (see Chapter 3).

Chimborazo’s seventeen glaciers, which presently cover ~11 km², are located in the headwaters of four different river systems, all of which eventually drain into the Amazon River system. The Rio Mocha (NE flank) and Rio Colorado (NW flank) both
flow northward into Tungurahua Province, while the Rio Guano (SE flank) and Rio Chimborazo (SW flank) flow south into Chimborazo Province. Despite its glacial coverage and the year-round nature of tropical glacier ablation, surface meltwater runoff is not constant in most of Chimborazo’s watersheds (Figure 5.2). Only four of the seventeen glaciers – including the mountain’s two largest, the Reschreiter (2.55 km²) and the Hans Meyer (1.33 km²) – produce year-round surface discharge, nearly all of which drains via the Rio Mocha. Meltwater from a small lobe of the Hans Meyer Glacier drains via the Rio Colorado, however this will cease to be the case within a few decades if present rates of ice loss are maintained. Another glacier in the Rio Colorado watershed, along with two in the Rio Chimborazo watershed, generate meltwater when warm, sunny conditions persist for several days, though such conditions may only happen a handful of times per month even in the dry season. All remaining glaciers, including those located within the Rio Guano watershed, rarely generate surface meltwater runoff.

All four of Chimborazo’s watersheds feature extensive areas of páramo, the biologically-rich grasslands endemic to the tropical Andes above ~3500 m.a.s.l. Páramos, which are characterized by soils of high infiltration capacity, hydraulic conductivity and storativity, are very efficient at regulating watershed discharge and are of considerable hydrological importance throughout Andean Ecuador (Buytaert and others 2006; Buytaert and others 2011). Large areas of páramo wetlands (bofadales) are present in the upper Rio Mocha watershed (Figure 5.3), and the páramos located here, as well as those in the upper Rio Guano watershed, are considered to be of very high societal value given the large number of downstream communities reliant on their ecological services.
Figure 5.3. False color satellite image of the upper Rio Mocha watershed, captured by the RapidEye satellite platform on August 21, 2012. Bright pink areas within the demarcated watershed boundary are bofadas, páramo wetlands that are very efficient at regulating discharge. (Bustamante and others 2011). Human encroachment into páramos is a growing problem in Ecuador, and activities such as intensive livestock grazing, de- (and re-) forestation, and expanding cultivation can have significant downstream hydrological consequences (Farley 2007; Harden and others 2013; Wigmore and Gao 2014).

There are numerous springs in all four watersheds, and continuous discharge in the Chimborazo and Guano rivers is only sustained downstream of these features. In the
Rio Guano watershed, the main springs are located near San Pablo, more than 1500 m lower and 10 km distant from the nearest glacier. The largest of these, which discharges 285 L s\(^{-1}\), provides the city of Riobamba with half of its domestic water supply though engineers with the municipal water management authority, Empresa Municipal de Agua Potable y Alcantarillado de Riobamba (EMAPAR), state that discharge is in noticeable decline (pers. comm., Mar 4, 2010). Above these springs, the tributaries of the Rio Guano only flow during and immediately after moderate to heavy precipitation events. A study commissioned by EMAPAR provides the first, preliminary description of aquifers in the Rio Guano watershed (Bigo 2013). A shallow, unconfined surface aquifer averaging 30-100 m in depth exists within a debris-avalanche deposit and is likely the source of the watershed’s primary springs. Deuterium analysis suggests that most water in this aquifer infiltrates between 3500 – 4000 m.a.s.l. A second, deeper, confined aquifer also exists, and wells in this formation provide the city with the remainder of its water supply. \(^{14}\)C dating of two water samples drawn from this aquifer indicate that it may be a non-renewable, fossil resource as much as 8000 years old.

Small aquifers exist within the unsorted glacial deposits found higher on Chimborazo’s slopes (down to ~3600 m.a.s.l. in the Rio Mocha and ~3900 m.a.s.l. in the Rio Guano watersheds), and many of the springs located high in these catchments are associated with old moraines. The steep gradients in these features and the high hydraulic conductivities characteristic of such material suggest that groundwater residence time is relatively short. Such springs in the Rio Guano watershed have traditionally been exploited as potable water sources for the highest communities of the area, however their
increasing inability to meet demand has resulted in a significant recent push to develop springs in the upper Rio Mocha watershed and most such sources are now being diverted.

Given the limited role of glacier meltwater runoff in Chimborazo’s other watersheds, this study focuses specifically on the upper Rio Mocha catchment, a 30.4 km² basin that is ~13% glacierized (Figure 5.3). I define this watershed as the area upstream of Boca Toma, the diversion point for the Las Abras system. The watershed ranges in elevation from 3895 m.a.s.l. at the canal headgate to 6268 m.a.s.l. at Chimborazo’s summit. The northern flank of the watershed is defined by the 5018 m.a.s.l. summit of the steep and more highly-eroded Volcán Carihuairazo. Aside from small copses of *polylepis*, the watershed is treeless, with páramo grasses and *bofadales* dominant below 4600 m.a.s.l. and rock, snow and ice above. The Reschreiter Glacier and the majority of the Hans Meyer Glacier flow into the watershed, with the lowest 16% of the Reschreiter being debris-covered and thus able to sustain ice at much lower elevations (4480 m.a.s.l.) than would otherwise be climatically possible. There may also be very small remnants of glacier ice near the summit of Carihuairazo, though their combined area is well under 1% of the watershed area and any meltwater contribution from these ice bodies would be of minimal hydrological consequence.

Despite its size, relatively little surface meltwater is generated by the Hans Meyer Glacier, and on most days all of this water is diverted into the small Rasourco irrigation system. Because of this, the upper Rio Mocha watershed and glacierized areas subsequently reported here excludes the Hans Meyer glacier and the 2.5 km² area above this diversion. Surface runoff from a 2.0 km² non-glacierized area in the Gavilán Muchim
sub-catchment is also captured by the Rasourco system, and is similarly excluded from this analysis. In this study, I thus assume that all glacier meltwater entering the Las Abras system is generated by the Reschreiter Glacier and is drained by Gavilán Muchim, whose 7.5 km² sub-catchment (excluding the area noted above) is 34% glacierized.

The Las Abras Irrigation System

The Chimborazo region remains a fundamentally agrarian landscape, and as many as 90% of households here obtain at least a portion of their income from agricultural production (see Chapter 4). The seasonal variability and interannual unpredictability of precipitation is a key stressor affecting agricultural production (Stadel 1989), especially below 3400 m.a.s.l. in the Rio Guano watershed, where unfavorable soil conditions exacerbate the effect of the area’s semi-arid climate. Access to irrigation water is thus a strong predictor of agrarian livelihood well-being. Irrigation increases crop yield and allows for the production of high value crops such as cabbage, broccoli and carrots that, in many areas, cannot be sustained on natural precipitation alone. Crucially, irrigation also permits crop production even during the long dry season, which may represent the difference between household sustainability and the abject poverty which remains widespread in the region (Boelens and Doornbos 2001; INEC 2010; Santos 2003). The scarcity of water and the economic importance of irrigation mean that it is imbued with considerable social power (Andolina 2012; Boelens and Zwartveen 2005; Hoogesteger 2012; Knapp 1991), and there remain considerable inequalities in water allocation and infrastructure development (Cremers and others 2005; Galárraga-Sánchez 2000). Water rights are, unsurprisingly, highly contested (Dávila and Olazával 2006; De Vos and
others 2006), and the combination of high (and increasing) demand, limited (and
decreasing) supply, inefficient management and problematic infrastructure (Evans and
others 2003) have combined to enhance water stress throughout Andean Ecuador.

The Las Abras irrigation system, the oldest and largest originating on Volcán
Chimborazo, is a 31 km long canal that diverts water from the Rio Mocha to provide
irrigation to agrarian communities in the Rio Guano watershed. The system serves 1540
households who irrigate a total of ~1100 ha of farmland. Las Abras was officially
registered in 1938, though parts of the canal have existed for at least a century and, in
some instances, may be of pre-colonial origin (Duke 2010). By Ecuadorian law, water is
the property of the state, with the national water management authority, Secretaría
Nacional del Agua (SENAGUA) granting 10-year usage concessions to user associations.
Las Abras’ longstanding concession is for 60% of Rio Mocha discharge at Boca Toma,
which is formally quantified as 909 L s⁻¹. However, because the water volume entering
the system under normal conditions has been significantly lower than this for several
years, the allocation schedule averages 377 L s⁻¹ and never exceeds 440 L s⁻¹.

The Las Abras user association, Juntas de Riego Las Abras, is comprised of
representatives elected on two-year terms from four sub-districts within the Las Abras
system. The association is responsible for administering the canal and setting the
allocation schedule, though individual users are responsible for opening and closing their
headgates at the appointed times. The schedule is based on the amount of land each user
irrigates, with each hectare of land allocated approximately one hour of water every
seven days. In exchange for this water, users must pay an annual fee of $10 ha⁻¹,
participate in *mingas* (communal maintenance days), attend association meetings and be willing to serve in management capacities if nominated. The US$11,000 yr\(^{-1}\) administration and maintenance budget is derived solely from the annual fee. Nearly all current users have acquired their shares through inheritance or marriage.

The Las Abras system consists of a network of unlined dirt canals that connect segments of natural stream channel that are usually dry. Thus, while the canal may gain water due to short-duration runoff events during periods of extended and/or heavy rains, a significant proportion of in-channel flow (up to 50% by the estimate of one water engineer) is lost due to leakage and in-channel infiltration (Figure 5.4). In addition, all Las Abras users employ flood (aka gravity) irrigation techniques, a highly inefficient way

Figure 5.4. Unlined section of the Las Abras Canal above Basacón. The green vegetation evident along the canal margin is nourished by water lost via infiltration in the canal bed.
of applying water to furrowed crops (Cisneros and others 1999). In 2008, the Korean International Cooperation Agency (KOICA), the development agency of the South Korean government, invested $2.5 million to rebuild the diversion structure at Boca Toma and replace the upper 11.9 km of the canal (as far as the community of Tintatacto) with a concrete channel. The project was originally scheduled to be completed in 2010, however bad engineering and shoddy construction required up to 80% of the new canal to be rebuilt. The first 5.0 km of the new canal became operational in 2011; the remaining 6.9 km of construction were expected to be completed in late 2013. As of early 2014, KOICA and the provincial government were in discussions to proceed with a second phase, which includes improvement of the canal another 9.8 km (to Basacón) as well as construction of two small reservoirs.

Data and Methods

Meteorological Data

An Onset Hobo Micro Station Data Logger (Model # H21-002) with temperature/humidity (Model # S-THB-M008) wind speed/direction (Model # S-WSET-A), and incoming solar radiation (Model # S-LIB-M003) sensors and a tipping bucket rain gauge (Model # S-RGB-M002) was established at 4515 m.a.s.l. on a debris-covered section of the Reschreiter Glacier (450 m above the tongue) on May 13, 2012. Instruments were mounted on a 2 m steel mast secured with guy wires. Data were collected at 10 minute intervals between May 13 and November 8, 2012 (when the data logger batteries failed). Temperature readings were not recorded after September 8 due to an animal chewing through that sensor’s data cable. I used simple linear regressions to
investigate relationships between each meteorological parameter and measured discharge at both Boca Toma and Gavilán Muchim gauging stations. I used 24-hour cumulative rainfall and solar insolation to account for cause/effect lags affecting overland runoff and glacier ablation, respectively. For the same reason, I employed a 6-hour lag between air temperature and measured discharge. This weather station was previously located at the Portal Andino Refuge (4280 m.a.s.l.), ~1 km south of the Gavilán Muchim watershed, and precipitation data collected between October 26, 2011 and May 12, 2012 are from this site.

*Stream and Canal Discharge*

Discharge gauging stations were established at three locations (Figure 5.2): at the Rio Mocha where it enters the Boca Toma diversion structure (130 m below the confluence of Quebrada Gavilán Muchim) at Gavilán Muchim 1.1 km above the Rio Mocha confluence, and on the Las Abras Canal near the community of Basacón (18.6 km below Boca Toma). Each station was equipped with a Solinst Levelogger Junior pressure transducer that measures water depth at 10-minute intervals. I made atmospheric pressure corrections using synchronous measurements collected by Solinst Barologger Gold sensors installed at Boca Toma gauge (also used to correct Gavilán Muchim data) and at the Las Abras Canal. I converted water depth to discharge volume using rating curves developed using standard USGS techniques (Rantz 1982a; 1982b).

The Boca Toma rating curve is based on three measurements ($r^2 = .99$) made between April and June 2012 using a Gurley pygmy current meter. The Gavilán Muchim rating curve is based on six measurements ($r^2 = .97$) made between December 2011 and
June 2012 using a Global Water FP101 current meter (the stream is too shallow for pygmy current meters to be effective). The Las Abras Canal rating curve is based on three measurements made in June and July 2012 ($r^2 = .99$) using the Gurley pygmy current meter. While the limited number of rating curve measurements at Boca Toma and the Las Abras Canal are not ideal, measurements at both were made in rectangular, concrete-line channels, which eliminates one common source of discharge measurement uncertainty. Measured discharge ranges relative to the mean and standard deviations of the entire transducer-derived data set suggest that extrapolation uncertainty is relatively low for Gavilán Muchim [-1.6σ to +1.2σ] and somewhat greater for Boca Toma [-0.6σ to +2.0σ]. The more limited range for Las Abras measurements [-0.9σ to -0.2σ] indicate a greater level of uncertainty in this data set. To determine the amount of water entering the canal, I multiplied discharge as measured by the Boca Toma gauge by 0.63, the mean proportion of Rio Mocha discharge entering the canal as measured on three occasions in June and July, 2012.

*Proportional Contribution of Glacier Melt Runoff*

Waters of varied provenance are exposed to different hydrological, geological and biological processes as they transit the hydrological cycle, often resulting in distinct hydrochemical signatures (Drever 1997; Hooper and Shoemaker 1986; Kendall and McDonnell 1998). These signatures provide natural tracers that can be analyzed using hydrological mixing models that can estimate the proportional contribution of each component to total discharge (Christophersen and Hooper 1992). This hydrograph separation technique has been successfully used in a growing number of watersheds to
better understand the role of glaciers in local and regional hydrology (La Frenierre and Mark 2014), including in the tropical Andes (Baraer and others 2009; Mark and McKenzie 2007; Mark and others 2005; Mark and Seltzer 2003).

Discharge from the upper Rio Mocha watershed is a mixture of waters derived from glacier meltwater runoff, groundwater and, intermittently, precipitation runoff. To quantify the proportional contribution of the glacier meltwater end member entering the Las Abras system, I employed the Hydrochemical Basin Characterization Model (HBCM), a mixing model developed explicitly for use in glacierized tropical watersheds with minimal hydrological monitoring infrastructure (Baraer and others 2009). HBCM uses a multi-component mass balance approach to estimate the relative contribution of different water sources at specific points in a watershed. As with all hydrochemical mixing models, HBCM is based on three fundamental assumptions (Christophersen and others 1990; Soulsby and others 2003): 1) the chemical signatures of each end member are distinct and spatially homogenous throughout the watershed; 2) tracers are conservative, meaning that the chemical signature of mixed water is solely a function of the mixing of inputs and not any post-mixing chemical reactions; and 3) mixing is both instantaneous and complete. HBCM analyzes multiple tracers simultaneously and can utilize any conservative chemical constituent as a natural tracer, including stable isotopes and major solutes. Working downstream from the glacier tongue (where the stream is assumed to be 100% glacier meltwater), HBCM quantifies the proportional input of tributaries at each confluence as well as the proportional input of groundwater within each intervening stream reach. By treating each confluence/reach as a unique cell, HBCM
ultimately provides the data necessary to calculate the amount by which the glacier meltwater end member is diluted at some downstream point of interest. Figure 5.5 illustrates the conceptualization of Gavilán Muchim for HBCM.

Water samples were collected from the Gavilán Muchim sub-catchment during both January and July 2012 to describe any hydrological variation between the short and long dry seasons. I used a synoptic water sampling approach, whereby all samples are collected over a short period of time to capture the hydrological conditions at that moment (Baraer and others 2009; Mark and McKenzie 2007). For the January analysis, samples were collected between the 1st and the 8th, while July samples were collected on the 7th and the 9th. Three samples were taken at each of four confluences located between Boca Toma and the tongue of the Reschreiter Glacier (Figure 5.6): one on each tributary immediately upstream of the confluence and one no less than 50 m downstream of the confluence (to allow for adequate mixing of the two tributary waters). Samples of glacier meltwater were taken at the glacier tongue while groundwater was sampled at two springs, one on the side tributary ~100 m upstream of Confluence B (GW1) and the other on the side tributary ~1 km upstream of Confluence A (GW2). Because these two groundwaters are chemically distinct, HBCM was used to determine that GW2 is most representative of the groundwater that comprises the side tributary of Confluence A, while GW1 is most representative of all other groundwater in the sub-catchment. A precipitation sample was also collected from an evaporation-proof totalizing rain gauge installed at 4350 m.a.s.l. in the upper Rio Mocha catchment (thus aggregating rainfall occurring over the previous 30 days). Ideally, precipitation runoff would have been
Figure 5.5. Schematic representation of the upper Rio Mocha watershed for analysis using HBCM.
Figure 5.6. Water sampling sites in the upper Rio Mocha watershed, including the dominant water type in different sub-basins above the intake of the Las Abras Canal. Because all meltwater runoff generated by the Hans Meyer Glacier is diverted into the Rasourco Pipeline, the entire sub-basin above the confluence of Q. Gavilán Muchim (Confluence D) is considered to be non-glacial water.

eliminated as a discharge component by collecting stream samples only during extended dry periods, however these are rare – even during the dry seasons – in the upper Rio Mocha watershed. While no stream samples were collected during rainfall events, 30 mm of rain was recorded at Portal Andino during the period starting 72 hours prior to the first January water sample and ending when the last water sample was collected. In July, 9
mm of rainfall was recorded at the Reschreiter Glacier weather station over the same interval.

For each sampling site, 60 mL of water was collected and stored in Nalgene bottles. Water destined for major ion analysis was filtered (0.45 μm) in the field, while water destined for stable isotope analysis was not. All bottles were capped, tape-sealed and kept refrigerated until returned to The Ohio State University for analysis. During the January sampling, electrical conductivity, pH and water temperature were measured in the field using a YSI 556 MPS Multi Probe System. Equipment malfunction prohibited these measurements from being made during the July sampling campaign. Major dissolved ions (Li⁺, Na⁺, K⁺, Mg²⁺, Ca²⁺, F⁻, Cl⁻, NO₃⁻, PO₄³⁻ and SO₄²⁻) were measured using a Dionex DX500 Ion Chromatographer at the Water Isotope and Nutrient Laboratory at The Ohio State University School of Earth Sciences. Stable isotopes of water (δ¹⁸O and δ²H) were measured using Piccaro L2130-i CRDS isotope analyzers at the Water Isotope and Nutrient Laboratory and at the Byrd Polar Research Center. Isotope data are reported relative to the Vienna-Standard Mean Ocean Water (VSMOW) standard, with an accuracy of ±0.025‰ for δ¹⁸O and ±1‰ for δ²H. HCO₃⁻ was calculated as the difference in the solution charge balance. The sum of anions and sum of cations are calculated as the sum of the respective milliequivalent values. Total dissolved solids (TDS) were calculated as the sum of all major ions and HCO₃⁻.

Potential tracers were first identified by creating mixing diagrams for various pairwise combinations of solutes as well as δ¹⁸O vs. δ²H. Tracers that are both conservative and distinct will plot along a clear mixing line, with mixed stream samples
bounded by distinct end members (James and Roulet 2006; Mark and Seltzer 2003). Combinations tested include electrical conductivity vs. TDS (January only); Na\(^+\) vs. \(\sum\) cations; K\(^+\) vs. \(\sum\) cations; Mg\(^{2+}\) vs. \(\sum\) cations; Ca\(^{2+}\) vs. \(\sum\) cations; F\(^-\) vs. \(\sum\) anions; Cl\(^-\) vs. \(\sum\) anions; SO\(_4^{2-}\) vs. \(\sum\) anions; \(\sum\) bivalent cations vs. \(\sum\) monovalent cations; H\(^+\) vs. \(\sum\) cations anions (January only); and HCO\(_3^-\) vs. \(\sum\) anions. Because Li\(^+\), NO\(_3^-\), and PO\(_4^{3-}\) were generally below detection limits, they were excluded from consideration. Once potential tracers were identified, cluster analyses were performed to provide visual confirmation that glacier meltwater, groundwater and precipitation are chemically distinct. HBCM then independently tests selected tracers to ensure that they are indeed distinct, and rejects any tracers that do not meet this requirement as each cell is analyzed. Since each cell has two inputs (tributaries or surface flow/groundwater), at least three tracers must be maintained for the model to return a result. Stable isotopes are analyzed at confluence cells; however, they are not analyzed at stream reach cells where groundwater, rather than a surface tributary, is one of two end members. Because the isotopic characteristics of a sample are elevation dependent, a unique groundwater type may present several isotopic signatures (M. Baraer, pers. comm.).

Irrigation Practices and Livelihood Activities in the Las Abras Irrigation System

To understand the irrigation and livelihood practices of Las Abras water users, I conducted four focus groups, one in each of the system’s four sub-districts centered on the communities of Tintatacto (Km 12, 3400 m.a.s.l.), San Pablo (Km 15, 3150 m.a.s.l.), Basacón (Km 20, 3050 m.a.s.l.), and Tapi (Km 29, 2800 m.a.s.l.; see Figure 5.2). Participants were recruited with the assistance of the president of the Las Abras users
association, with representatives from each district first volunteering to participate then
recruiting additional members from within their respective districts. In all, 22 individuals
participated among the four groups, with both men and women present at each.

Discussions were conducted over 60 – 90 minute periods on late weekday afternoons
during May and June, 2012. The Tintatacto, San Pablo and Basacón groups were held in
their respective community centers, while the Tapi focus group was conducted in my
nearby apartment due to the unexpected unavailability of their community center. All
participants were paid a US$5 honorarium to compensate for their time and travel and
were provided snacks and beverages during the activity.

The focus group questionnaire consisted of eight specific questions that were
augmented extemporaneously based on the flow of conversation (see Appendix B). The
questions covered topics including irrigation system performance, recent climate change
and its impact on agricultural productivity, the importance of irrigation for agrarian
livelihoods, strategies for adapting to water shortages, concerns about the allocation of
water within the system, and the major challenges facing Las Abras irrigators. The
questionnaire was approved by the Institutional Review Board at The Ohio State
University and was presented in Spanish (with assistance from a translator). Each group
was digitally recorded and transcribed by either a fluent (Tapi and San Pablo) or native
(Tintatacto and Basacón) Spanish speaker. I translated each transcript with occasional
assistance from a native Spanish speaker.

As part of a larger 59-household survey within San Andres Parroquia, the
township-level administrative district located in the upper half of the Rio Guano
watershed (see chapter 4 and Appendix A), I also conducted nine semi-structured interviews with Las Abras irrigators. The survey extracted both quantitative and qualitative livelihood information about household demographics, economic activities, social support resources, agricultural activities, and irrigation practices and performance. Households were selected using a randomized GIS polygon technique (Bury and others 2011). The survey instrument was also approved by the Institutional Review Board at The Ohio State University and was presented in Spanish (with assistance from a translator) during daylight hours on all days of the week.

Results and Discussion

Supply vs. Demand in the Las Abras Irrigation System

The average volume of water entering the Las Abras system between June 11, 2012 and January 30, 2013 was only 340 L s⁻¹. Thus, despite having already reduced their maximum hourly allocation to 440 L s⁻¹ (from their legal allocation of 909 L s⁻¹), the volume of water entering the system was, on average, only 91% of the amount that had been allocated for that period of time (Figure 5.7). Overall, supply entering the canal at Boca Toma was lower than allocated demand during 80% of the irrigation hours on the system’s schedule. The situation below Basacón was even more dire. Here, water supply only averaged 54% of demand, and scheduled allocations were unsatisfied 90% of the time. In fact, because supply exceeds demand only during those brief periods immediately following significant precipitation events in the upper Rio Mocha watershed, it is evident that baseflow conditions no longer provide enough water to meet the system’s already restricted allocation schedule. The sharp reduction in the
Figure 5.7. Water flow entering the Las Abras Canal as a proportion of actual downstream irrigation allocation at Boca Toma (Km 0.0; blue line) and Basacón (Km 18.7; orange line) between June 11, 2012 and January 30, 2013. Data gaps in the Basacón time series are due to maintenance-related service interruptions. Values below the red line indicate unsatisfied demand.

The supply/demand ratio between Boca Toma and Basacón illustrates the severity of water loss in the upper half of the canal due to infiltration, leakage and, possibly, some users irrigating out of turn. Focus group participants from all four sub-districts, as well all nine of the household survey participants, report that they do not always receive their full allocation. Irrigators living in the Basacón and Tapi districts also report that they sometimes don’t receive any water when it is their turn to irrigate. When this occurs, they have no recourse but to wait until the following week and hope that there will be sufficient water when it is their turn once again.
Results for the January hydrochemical analysis are presented in Table 5.1; July results are presented in Table 5.2. Based on this analysis, electrical conductivity, \( \text{Mg}^{2+} \), \( \text{Ca}^{2+} \), \( \text{HCO}_3^- \), and \( \sum \) monovalent cations were the tracers selected for the January HBCM analysis while \( \text{Mg}^{2+} \), \( \text{Ca}^{2+} \), \( \text{HCO}_3^- \), \( \sum \) monovalent cations and \( \delta^{18} \)O were selected for the July HBCM analysis. Mixing diagrams for the selected tracers are presented in Figure 5.8 (January) and Figure 5.9 (July). These diagrams indicate a consistent mixing line, and clear a distinction between end members. The groundwater tributary that is consistently outside the two groundwater end members on the mixing line is the Rio Mocha at the confluence of Gavilán Muchim (Trib. D), which indicates that this stream is derived from groundwater that is chemically different from that present in the Gavilán Muchim watershed. The slight influence of precipitation in the January sample is also evident in that one of the mixed Gavilán Muchim samples (A-In) is consistently located between the precipitation and glacier meltwater end members along the mixing line. Figure 5.10 shows the results of the cluster analysis used to visually-confirm that each end member is chemically distinct. The consistent similarity among glacier meltwater, the main-stem tributaries and outputs at confluences A, B, and C as well as the similarities among all non-glacial inputs and outputs throughout the system indicates that both tracer sets are acceptable for use in HBCM.

The results of the HBCM analysis indicate that the upper Rio Mocha watershed is a groundwater-dominated system despite its relatively high proportion of glacierized area and that this varies little over the course of the hydrological year (Table 5.3). In January
Table 5.1. Results of hydrochemical analysis for major ions and isotopes in January 2012. Li⁺, NO₃⁻ and PO₄³⁻ were also analyzed, but were undetected in most samples. Because δ²H is not independent from δ¹⁸O, it was not incorporated in this analysis. Tracers used to independently test the validity of the data set for use in HBCM are in bold.

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<th>A-Trib</th>
<th>A-Out</th>
<th>B-In</th>
<th>B-Trib</th>
<th>B-Out</th>
<th>C-In</th>
<th>C-Trib</th>
<th>C-Out</th>
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<th>D-Trib</th>
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<th>GW1</th>
<th>GW2</th>
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<td>0.235</td>
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<td>0.850</td>
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<td>0.775</td>
<td>0.874</td>
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<tr>
<td>∑ cations²⁻ / ∑ cations¹</td>
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<td>2.228</td>
<td>2.880</td>
<td>2.121</td>
<td>2.306</td>
<td>1.779</td>
<td>1.827</td>
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<td>1.800</td>
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<td>2.086</td>
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<td>1.805</td>
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<td>Cond./TDS</td>
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<td>0.772</td>
<td>0.730</td>
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Table 5.2. Results of hydrochemical analysis for major ions and isotopes in July 2012. Li⁺, NO₃⁻ and PO₄³⁻ were also analyzed, but were undetected in most samples. Because δ²H is not independent from δ¹⁸O, it was not incorporated in this analysis. Conductivity and pH could not be measured in the field and are not included here. Tracers used to independently test the validity of the data set for use in HBCM are in bold.

<table>
<thead>
<tr>
<th>Date</th>
<th>Glacier Melt</th>
<th>A-In</th>
<th>A-Trib</th>
<th>A-Out</th>
<th>B-In</th>
<th>B-Trib</th>
<th>B-Out</th>
<th>C-In</th>
<th>C-Trib</th>
<th>C-Out</th>
<th>D-In</th>
<th>D-Trib</th>
<th>D-Out</th>
<th>GW1</th>
<th>GW2</th>
<th>Precip</th>
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<td>4245</td>
<td>4475</td>
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<tr>
<td>Na⁺ (μM)</td>
<td>0.066</td>
<td>0.069</td>
<td>0.088</td>
<td>0.067</td>
<td>0.072</td>
<td>0.199</td>
<td>0.074</td>
<td>0.076</td>
<td>0.243</td>
<td>0.078</td>
<td>0.168</td>
<td>0.301</td>
<td>0.290</td>
<td>0.267</td>
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<tr>
<td>K⁺ (μM)</td>
<td>0.012</td>
<td>0.012</td>
<td>0.023</td>
<td>0.012</td>
<td>0.013</td>
<td>0.033</td>
<td>0.014</td>
<td>0.014</td>
<td>0.064</td>
<td>0.014</td>
<td>0.037</td>
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<td>0.051</td>
<td>0.048</td>
<td>0.035</td>
<td>0.014</td>
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<tr>
<td>Mg²⁺ (μM)</td>
<td>0.052</td>
<td>0.052</td>
<td>0.243</td>
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<td>0.056</td>
<td>0.201</td>
<td>0.059</td>
<td>0.064</td>
<td>0.299</td>
<td>0.072</td>
<td>0.252</td>
<td>0.371</td>
<td>0.353</td>
<td>0.222</td>
<td>0.326</td>
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<td>Ca²⁺ (μM)</td>
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<td>0.194</td>
<td>0.097</td>
<td>0.100</td>
<td>0.100</td>
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<td>0.107</td>
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<td>0.262</td>
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<td>F⁻ (μM)</td>
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<td>0.012</td>
<td>0.015</td>
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<td>0.010</td>
<td>0.011</td>
<td>0.010</td>
<td>0.011</td>
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<td>0.011</td>
<td>0.006</td>
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<td>0.010</td>
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<td>0.030</td>
<td>0.036</td>
<td>0.028</td>
<td>0.030</td>
<td>0.052</td>
<td>0.031</td>
<td>0.029</td>
<td>0.063</td>
<td>0.032</td>
<td>0.041</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.043</td>
<td>0.076</td>
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<tr>
<td>SO₄²⁻ (μM)</td>
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<td>0.041</td>
<td>0.014</td>
<td>0.040</td>
<td>0.042</td>
<td>0.023</td>
<td>0.042</td>
<td>0.039</td>
<td>0.023</td>
<td>0.038</td>
<td>0.028</td>
<td>0.185</td>
<td>0.176</td>
<td>0.033</td>
<td>0.006</td>
<td>0.047</td>
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<td>0.381</td>
<td>0.397</td>
<td>1.023</td>
<td>0.409</td>
<td>0.424</td>
<td>1.329</td>
<td>0.450</td>
<td>0.960</td>
<td>1.758</td>
<td>1.677</td>
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<td>0.249</td>
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<tr>
<td>∑ anions meq/L</td>
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<td>0.083</td>
<td>0.119</td>
<td>0.124</td>
<td>0.110</td>
<td>0.124</td>
<td>0.119</td>
<td>0.121</td>
<td>0.120</td>
<td>0.103</td>
<td>0.440</td>
<td>0.421</td>
<td>0.149</td>
<td>0.065</td>
<td>0.188</td>
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<tr>
<td>HCO₃⁻ (μM)</td>
<td>0.245</td>
<td>0.252</td>
<td>0.903</td>
<td>0.261</td>
<td>0.273</td>
<td>0.913</td>
<td>0.285</td>
<td>0.306</td>
<td>1.208</td>
<td>0.329</td>
<td>0.856</td>
<td>1.318</td>
<td>1.257</td>
<td>1.135</td>
<td>0.935</td>
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<tr>
<td>TDS (mg/L)</td>
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<td>74.8</td>
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<td>29.5</td>
<td>78.6</td>
<td>30.5</td>
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<td>102.2</td>
<td>33.5</td>
<td>73.0</td>
<td>131.8</td>
<td>125.0</td>
<td>98.0</td>
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<td>δ¹⁸O (%)</td>
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<td>-12.3</td>
<td>-13.3</td>
<td>-13.4</td>
<td>-13.4</td>
<td>-13.4</td>
<td>-13.4</td>
<td>-13.4</td>
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<td>-12.8</td>
<td>-8.9</td>
<td></td>
</tr>
<tr>
<td>Na⁺/∑ cations</td>
<td>0.173</td>
<td>0.182</td>
<td>0.090</td>
<td>0.177</td>
<td>0.182</td>
<td>0.194</td>
<td>0.181</td>
<td>0.179</td>
<td>0.183</td>
<td>0.173</td>
<td>0.176</td>
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<td>0.173</td>
<td>0.208</td>
<td>0.114</td>
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<td>K⁺/∑ cations</td>
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<td>0.031</td>
<td>0.023</td>
<td>0.032</td>
<td>0.033</td>
<td>0.033</td>
<td>0.033</td>
<td>0.048</td>
<td>0.032</td>
<td>0.038</td>
<td>0.030</td>
<td>0.030</td>
<td>0.037</td>
<td>0.035</td>
<td>0.057</td>
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</tr>
<tr>
<td>Mg²⁺/∑ cations</td>
<td>0.137</td>
<td>0.138</td>
<td>0.247</td>
<td>0.141</td>
<td>0.142</td>
<td>0.197</td>
<td>0.144</td>
<td>0.152</td>
<td>0.225</td>
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<td>0.263</td>
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<td>0.210</td>
<td>0.173</td>
<td>0.326</td>
<td>0.000</td>
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<tr>
<td>Cl⁻/∑ anions</td>
<td>0.208</td>
<td>0.239</td>
<td>0.430</td>
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<td>0.243</td>
<td>0.474</td>
<td>0.246</td>
<td>0.248</td>
<td>0.521</td>
<td>0.269</td>
<td>0.397</td>
<td>0.137</td>
<td>0.142</td>
<td>0.400</td>
<td>0.664</td>
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<tr>
<td>∑ cations²+/∑ cations¹⁺</td>
<td>1.955</td>
<td>1.841</td>
<td>3.917</td>
<td>1.906</td>
<td>1.844</td>
<td>1.703</td>
<td>1.827</td>
<td>1.862</td>
<td>1.663</td>
<td>1.935</td>
<td>1.839</td>
<td>1.979</td>
<td>1.953</td>
<td>1.536</td>
<td>2.841</td>
<td>3.099</td>
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</table>
Figure 5.8. Mixing diagrams of tracers selected for January 2012 HBCM analysis.
Figure 5.9. Mixing diagrams of tracers selected for July 2012 HBCM analysis.
Figure 5.10. Cluster analysis dendrogram for tracers used to calculate the proportional contribution of glacier meltwater runoff in January 2012 (a) and July 2012 (b). While the January dendrogram is difficult to see given the Y-axis scale, the grouping of samples along the X-axis indicates that end-members are distinct while mixed samples are appropriately located between end members.

2012, glacier meltwater contributed 2.8 – 4.9% of total discharge entering the Las Abras system while in July 2012, the contribution was 3.0 – 5.7%. The robustness of these results can be evaluated by comparing the HBCM-calculated proportional contribution of Gavilán Muchim to total Rio Mocha discharge (Confluence D) with the contemporaneous but independent discharge measurements made by the Gavilán Muchim and Boca Toma discharge stations. HBCM calculated that Gavilán Muchim contributed 11.9 – 15.3% when waters were sampled at 09:00 on January 1, 2012, while the discharge gauges indicate that Gavilán Muchim contributed 7.3% at that hour. At 09:30 on July 7, 2012, HBCM calculated an 8.5 – 13.4% contribution from Gavilán Muchim while the discharge gauges indicated a 10.6% contribution. Because the Gavilán Muchim gauge is located 1 km above the confluence, it is likely that additional groundwater discharge augments the
Table 5.3. Estimated proportional contribution of glacier meltwater runoff to total watershed discharge at points between the Reschreiter Glacier and the intake of the LasAbras canal in January and July, 2012.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Location</th>
<th>HBCM Cell</th>
<th>Area (km²)</th>
<th>Glacier Area %</th>
<th>Min Melt %</th>
<th>Max Melt %</th>
<th>Mean Melt %</th>
<th>Min Melt %</th>
<th>Max Melt %</th>
<th>Mean Melt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gavilán Muchim</td>
<td>Glacier Tongue</td>
<td>1</td>
<td>3.4</td>
<td>74.9</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Gavilán Muchim</td>
<td>Confluence A - In</td>
<td>1</td>
<td>3.6</td>
<td>71.7</td>
<td>95.5</td>
<td>100</td>
<td>97.7</td>
<td>99.1</td>
<td>99.1</td>
<td>99.1</td>
</tr>
<tr>
<td>Gavilán Muchim</td>
<td>Confluence A - Out</td>
<td>2</td>
<td>3.8</td>
<td>67.6</td>
<td>83.4</td>
<td>95.2</td>
<td>89.3</td>
<td>98.3</td>
<td>98.3</td>
<td>98.3</td>
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<tr>
<td>Gavilán Muchim</td>
<td>Confluence B - In</td>
<td>3</td>
<td>3.9</td>
<td>65.3</td>
<td>79.5</td>
<td>92.9</td>
<td>86.2</td>
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<td>96.5</td>
<td>96.5</td>
</tr>
<tr>
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<td>Confluence B - Out</td>
<td>4</td>
<td>4.0</td>
<td>63.4</td>
<td>76.6</td>
<td>89.6</td>
<td>83.1</td>
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<td>94.7</td>
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<tr>
<td>Gavilán Muchim</td>
<td>Confluence C - In</td>
<td>5</td>
<td>4.2</td>
<td>61.0</td>
<td>72.9</td>
<td>87.1</td>
<td>80.0</td>
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<td>Gavilán Muchim</td>
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<td>6</td>
<td>5.7</td>
<td>44.7</td>
<td>70.7</td>
<td>84.8</td>
<td>77.8</td>
<td>88.6</td>
<td>89.2</td>
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<tr>
<td>Gavilán Muchim</td>
<td>Confluence D - In</td>
<td>7</td>
<td>7.5</td>
<td>33.9</td>
<td>23.1</td>
<td>32.4</td>
<td>27.8</td>
<td>35.5</td>
<td>42.4</td>
<td>38.9</td>
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<tr>
<td>Rio Mocha</td>
<td>Confluence D - Out (LasAbras Intake)</td>
<td>8</td>
<td>26.0</td>
<td>9.8</td>
<td>2.8</td>
<td>4.9</td>
<td>3.8</td>
<td>3.0</td>
<td>5.7</td>
<td>4.3</td>
</tr>
</tbody>
</table>

flow and that gauge measurements will always slightly underestimate the actual volume of water exiting the stream. The inherent uncertainty associated with making direct discharge measurements must also be noted (La Frenierre and Mark 2014). The increased uncertainty evident in the January data is likely due to the slight influence of precipitation runoff, which wasn’t treated as an end member in HBCM but is evident in the A-In sample in the January mixing diagrams (Figure 5.8).

Though groundwater dominates the upper Rio Mocha hydrological system, comparison of relationships between various meteorological parameters and discharge variation between Gavilán Muchim and the upper Rio Mocha watershed as a whole indicates that Chimborazo’s glaciers do have a measurable influence on stream behavior (Table 5.4). Air temperature correlates with Gavilán Muchim discharge variation much more that it does for the full upper Rio Mocha whereas precipitation is more strongly correlated with discharge variation for the Rio Mocha than for Gavilán Muchim (see also
Table 5.4. Correlations between precipitation, air temperature and solar insolation and discharge variation in the Gavilán Muchim sub-catchment and entire upper Rio Mocha watershed. All correlations are significant at the 0.01 level. The 6-hour lag in the air temperature was selected based on correlation analysis using the Gavilán Muchim discharge data. No lag effect was evident in the Rio Mocha discharge data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gavilán Muchim Q Variation (r)</th>
<th>Rio Mocha Q Variation (r)</th>
<th>Proportional Contribution of Gavilán Muchim to Rio Mocha (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature (6-hour lag)</td>
<td>.452</td>
<td>-.056</td>
<td>.411</td>
</tr>
<tr>
<td>Precipitation (24-hour cumulative)</td>
<td>.217</td>
<td>.521</td>
<td>-.207</td>
</tr>
<tr>
<td>Solar Insolation (24-hour cumulative)</td>
<td>-.252</td>
<td>-.298</td>
<td>.444</td>
</tr>
</tbody>
</table>

Figure 5.11). Insolation doesn’t correlate with discharge variation in Gavilán Muchim any better than it does in the entire upper Rio Mocha since rainfall is not independent of insolation (see also Figure 5.12). These data are consistent with the expected behavior of glacial watersheds and they demonstrate that the glacier compensation effect does influence water supply in the Las Abras system. A greater proportion of precipitation runoff is delayed (as accumulating snow) in Gavilán Muchim than in the upper Rio Mocha, where most precipitation falls as rain and runs off more quickly. Conversely, enhanced ablation resulting from elevated solar radiation and warming temperatures on sunny days increases Gavilán Muchim discharge while streamflow in the groundwater-dominated upper Rio Mocha is not enhanced under these conditions. Given these behaviors, it is evident that, despite the modest contribution of glacier meltwater runoff, the loss of long-term water storage capacity as a result of continuing glacier shrinkage will result in some negative impact on downstream water supply.

The majority of water entering the Las Abras system thus originates from the
Figure 5.11. Measured discharge for the Rio Mocha at Boca Toma (dark blue) and Gavilán Muchim (light blue) between January 1, 2012 and January 30, 2013. The red line indicates 24-hour cumulative rainfall measured at the tongue of the Reschreiter Glacier.

Figure 5.12. Proportional contribution of discharge from Gavilán Muchim (light blue) to the Rio Mocha between January 1, 2012 and January 30, 2013. The yellow line indicates 24-hour cumulative solar radiation measured at the tongue of the Reschreiter Glacier.
springs and *bofadas* along the main branch of the Rio Mocha upstream of Gavilán Muchim. However, even within the Gavilán Muchim sub-catchment, the proportional contribution of glacier meltwater diminishes rapidly with distance from the glacier (see Table 5.3). At its confluence with the Rio Mocha, only 3.5 km below the glacier tongue, the stream is ~55-75% groundwater (67.6 – 76.9% in January 2012; 57.6 – 64.5% in July 2012) despite the 34% watershed glacierization. Furthermore, Gavilán Muchim’s mean daily specific discharge between January 1, 2012 and January 30, 2013 was less than half that of the non-glacierized portion of the upper Rio Mocha watershed (Table 5.5), which contradicts the expected hydrological behavior of a glacierized watershed (Baraer and others 2009; Mark and Seltzer 2003). In fact, despite containing 29% of the total watershed area above its confluence with the Rio Mocha (again, excluding those areas that where drainage is captured by the Rasourco irrigation system), Gavilán Muchim contributed only 14% of total measured discharge at Boca Toma over those 13 months.

Comparison of the dry-season relationship between glacierized area and groundwater contribution to total discharge in Gavilán Muchim and in highly glacierized watersheds in the Cordillera Blanca, Peru, further indicate the unique hydrological

### Table 5.5. Mean daily specific discharge in the Upper Rio Mocha watershed. Watershed areas and glacierized percentages exclude terrain that drains into the Rasourco irrigation system.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Watershed Area (km²)</th>
<th>Glacierized Area (%)</th>
<th>Mean Discharge (m³ s⁻¹)</th>
<th>Mean Daily Specific Discharge (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gavilán Muchim</td>
<td>7.5</td>
<td>33.9</td>
<td>0.09</td>
<td>1.0</td>
</tr>
<tr>
<td>Upper Rio Mocha (above Gavilán Muchim)</td>
<td>18.4</td>
<td>0</td>
<td>0.54</td>
<td>2.5</td>
</tr>
<tr>
<td>Upper Rio Mocha (Total)</td>
<td>26.0</td>
<td>9.8</td>
<td>0.63</td>
<td>2.1</td>
</tr>
</tbody>
</table>
behavior here. In the Cordillera Blanca, an apparent exponential relationship exists
whereby small increases in glacierized area result in a sharp decrease in the proportional
contribution of groundwater (Baraer and others in review). In these watersheds, a simple
dilution model predicts that groundwater contribution exceeds glacier meltwater
contribution only once glacierized area is less than 8%. In Gavilán Muchim, by contrast,
a linear relationship is evident whereby groundwater contribution is predicted to exceed
that of glacier meltwater when glacierized area is ~40%. Because the region’s 2012
weather was not considered abnormally wet or cold, this behavior suggests that a
considerable amount of glacial meltwater may be infiltrating into local aquifer systems,
perhaps even at the glacier bed. The lack of any surface glacier meltwater runoff below
most of Chimborazo’s other glaciers and the presence of large springs at lower points
elevations in the mountain’s watersheds also provide further evidence that this may be
the case. Similar behavior has been observed at Antisana, another glacierized Ecuadorian
volcano (Favier and others 2008), which indicates that the hydrological importance of
glacier meltwater at Chimborazo may be greater than has been quantified here.

*Explaining Decreasing Water Supply in the Las Abras Irrigation System*

Though long-term glacier shrinkage such as has been evident at Chimborazo
results in decreased watershed yield, the lack of heritage discharge data make it
impossible to know if the upper Rio Mocha has experienced the ‘peak water’
phenomenon that has been described in other Andean watersheds (Baraer and others
2012). However, the modest present-day contribution of glacier meltwater in the upper
Rio Mocha watershed suggests that glacier change is not primarily responsible for the
dramatic reduction in water supply to the Las Abras system in the past few decades. While acknowledging the uncertainty concerning the relationship between glacier melt and groundwater discharge, shifting precipitation and water usage patterns on the mountain appear to be the main drivers of the increased water stress that irrigators are experiencing. Instrumental precipitation data do not indicate a decrease in the amount of precipitation falling in the region, however the near unanimity on the part of area residents – irrigators and non-irrigators alike, and at all elevations – that rainfall is less frequent and increasingly unpredictable suggests that discernible changes have occurred (see Chapter 3).

Las Abras users are also well aware that there have been multiple new pipelines built within the past decade to transport potable water from springs above the Boca Toma to communities south of the mountain. Indeed, many benefit from these developments. At the time of this study, eight pipelines transferred water out of the upper Rio Mocha watershed (seven domestic as well as the Rasourco irrigation system; an eighth domestic system began diverting water from a five-spring complex in 2013). Combined, these eight diversions have been granted concessions from SENAGUA totaling 55 L s\(^{-1}\). While this is significantly less than the 500+ L s\(^{-1}\) reduction in supply that Las Abras has experienced, actual water flow into these systems may be greater since discharge is not measured and is regulated only by the size of the water pipes (50 – 110 mm in diameter). One of the fundamental water management problems here is the fact that SENAGUA and its administrative predecessors have granted concessions without benefit of a formal water resources inventory (the first such province-wide study was only initiated in 2012).
As one Las Abras irrigator explains, “one four-inch pipe isn’t a lot of water, but four communities each with four-inch pipes accounts for a lot of water, and that will reduce our supply” (Tintatacto Focus Group, 9 June 2012).

It is essential to recognize, however, that water system development is not independent of changing climatic conditions. While there has been considerable population growth in the province (1.4% annual growth rate 2001 - 2010; INEC 2010), the greater problem is that nearly all water sources on Chimborazo’s southern slopes are becoming increasingly unreliable. It may appear unreasonable for SENAGUA to be granting new concessions upstream of the Las Abras system, however potable water supplies are given the highest legal priority according to Ecuadorian water law. In effect, then, Las Abras is not only suffering from changing hydrological conditions within its source watershed, but also changing conditions at a more regional scale.

Consequences of Insufficient Water Supply in the Las Abras Irrigation System

Among the agrarian communities served by the Las Abras system, the perception that water scarcity and other socio-environmental stressors are driving a serious reduction in agricultural productivity is ubiquitous, and exists independent of the household’s irrigation status, environmental attributes, or livelihood activity (see Chapter 4). In the higher elevation areas where moisture is more abundant and soils are of better quality, people report that many households have converted their fields from higher-value but more water-dependent crops such as wheat, barley, and carrots to lower-value but more drought-tolerant products such as alfalfa and other pasturage and that investment in lower-risk livestock production has greatly increased in recent years. At lower elevation
areas, especially below Basacón, a considerable amount of previously productive agricultural land has been abandoned as households seek external employment in Riobamba or emigrate from the area entirely.

Throughout the Las Abras system, irrigators report that they have thus far been spared the worst of the livelihood disruptions that their non-irrigating neighbors have experienced. Impacts are nonetheless accumulating among irrigators, and they are accumulating most rapidly in the lower elevation areas where environmental conditions are less favorable and irrigation supply is less reliable. In Tintatacto and San Pablo, for example, adaptive strategies such as limiting dry season production, adjusting crop selection and seeking external employment remain hypothetical responses to an imagined life without irrigation. In Basacón and, especially, Tapi, irrigators are already being forced to make exactly these types of changes. “A carrot, if not watered, will die and then you’ll lose everything”, one irrigator explained. “This is why we’ve adopted alfalfa - it will endure for a month without water” (Tapi Focus Group, 4 June 2012). Another commented, “Almost all of us have taken jobs, rightly or wrongly, so that we can afford our families. Here it’s mostly construction and I say this is now a construction worker’s neighborhood. The beautiful fields are being abandoned” (Basacón Focus Group, 1 June 2012). Such statements suggest that the livelihood stability long afforded by irrigation is being eroded on the lower reaches of the canal, and that resilience against drought is weakening as water scarcity becomes more acute.

One consequence of the spatial disparity of water scarcity impacts is that conflict between users within the Las Abras system is becoming more common. While conflict
among irrigation users in the Chimborazo region is nothing new (Duke 2010), Las Abras users report that, “people are now a little more aggressive,” (Tintatacto), “there’s no longer fair dealing.” (Basacón), and that conflict is, “steadily getting worse” (Tapi). Much of this conflict revolves around the perception that upstream irrigators are taking water out of schedule. As one Tapi irrigator complained, “It should be that during the dry season, everyone lowers their allocation, but [upstream] users do not. Maybe instead of reducing their water flow, they open their headgate more and sometimes no one below will get water. They take everything.” This concern is evident even in the higher reaches of Tintatacto: “If I don’t have the opportunity to keep watch, my water may be stolen.” As one person in Basacón explained, “most everyone, at least 90%, respect the [irrigation] schedule. Regrettably, there are people above us who do not.” One of the drivers of conflict is the decision by association leadership to parse reduced allocations equally among all users, without differentiating between the needs of higher and lower elevation users. This has led to an increased sense of injustice on the part of those living near the bottom of the canal. As one Tapi irrigator commented, “those at the top of the canal have more water everyday … but it is those of us at the bottom who are the most affected [by water scarcity].”

The differential experiences of upstream and downstream farmers – irrigators or otherwise – also illustrate a ‘space-for-time’ dynamic that is evident in the region. In upstream areas surrounding San Pablo and Tintatacto non-irrigators are being forced to adjust their modes of agricultural production and are pursuing supplemental off-farm employment while irrigators generally continue to enjoy the level of productivity once
common throughout the region. In downstream areas near Tapi, irrigators are having to make these same adaptations while most non-irrigators have already abandoned agricultural livelihoods completely (see Chapter 4). As warming and drying conditions creep upward in elevation with future climate change, farmers in the higher districts can expect to face the same impacts and upheavals as their downstream neighbors are now experiencing. For irrigators in Tintactato, the agricultural realities faced by non-irrigators in Tapi may seem like a distant problem. For irrigators in Basacón, those realities appear increasingly inevitable: “Right now, of my family that was born here, three have emigrated and two remain. What will happen in twenty years if we continue like this? All five of us will have emigrated and no one will be left since we can’t live if we don’t have water. This land will be a desert.”

Addressing Increasing Water Stress in the Las Abras Irrigation System

Las Abras users identify a range of potential mitigation strategies for addressing the persistent water stress they are now enduring, and engineering solutions such as upgrading canal infrastructure, developing storage systems, and converting from flood to sprinkler irrigation are dominant in current discourse. There are, however, considerable obstacles to these types of approaches, not least of which is the system’s lack of financial resources and technical capacity for undertaking large projects. The KOICA initiative to replace the upper third of the canal with a concrete channel should have been a significant first step; however, the need to redo the majority of the project has, rightly or wrongly, left users distrustful of KOICA’s technical capacity and motivations. The project also highlights the tremendous disparity between Las Abras’ $11,000 annual
budget and the US$2.5 million price tag for this first phase of development. Even if the project’s proposed second phase comes to fruition, it is clear that considerable outside intervention will still be required if the entire system is to be upgraded. Establishing storage capacity within the system would help alleviate shortages, however hydrological data indicate that this alone will not be sufficient. In 2012, Las Abras’ 60% share of total upper Rio Mocha watershed yield – including excess storm runoff – amounted to only 98% of the volume currently allocated to users. While seemingly close to matching demand, the reality is that capturing and storing all storm runoff, especially in glacial system with high sediment loads, is extremely difficult without large scale, highly technical, and very expensive structures. A transition from highly inefficient flood irrigation to sprinkler irrigation is likely the system’s best engineering solution, and several small (non-glacial) irrigation systems in Chimborazo Province have recently implemented this technology. However, the infrastructure obstacles, including the need to build storage tanks to achieve necessary water pressure, are also daunting.

Adjusting water allocation practices, both within the system itself and in the province as a whole, represents another pathway for addressing water shortages. However, there are considerable political obstacles to doing so, especially considering the economic, political, and cultural value ascribed to water in Andean society. Many users identify considerable institutional weakness on the part of both the Las Abras system and Ecuadorian water management institutions. A common refrain is that Las Abras users are too disorganized to effectively compete with the broad collection of other water interests within the province, and the fractiousness apparent at user meetings justifies this
perception. As one user explained, “[we] are too individually-oriented and not very well united. This disorganization results in water not being used as efficiently as possible, it breeds distrust in its management, and it leave us unable to advocate for ourselves with regards to other users and the Ecuadorian government” (Tapi). Many users also see SENAGUA as an ineffective bureaucracy that is very difficult to navigate. The agency undoubtedly has a challenging mandate given the turbulent history of water management in the country (e.g. Boelens and Doornbos 2001), however examples of administrative obstacles such as the need for user associations to retain legal counsel in order to submit basic petitions illustrate the structural barriers that continue to limit access by those groups who are economically and politically disadvantaged. The other key challenge facing Las Abras is that more and more water from the upper Rio Mocha is likely to be reallocated for potable supplies as populations continue to grow and other water sources become less reliable. As one Tapi irrigator explained, “SENAGUA is already converting water concessions for domestic use and the preference will continue to shift from irrigation to domestic use. Our sector will be urbanized, but everyone – not only us – will have water shortages. There are already multiple lawsuits, but you cannot deny domestic use”.

Conclusion

Volcán Chimborazo dominates its surrounding landscape and its glaciers are viewed by many people as both symbolic of local environmental conditions and a source of dependable water supply. The rapid recession of these glaciers in recent decades has raised considerable alarm in the agrarian communities that lie at the foot of the mountain,
and as local irrigators confront shifting rainfall patterns, withering water sources and declining agricultural productivity, many openly wonder about their ability maintain viable livelihoods in the face of such unprecedented change. In this research, I have taken a uniquely integrative approach in order to develop a better understanding of both the hydrological processes operating in Chimborazo’s glacierized watersheds as well as the social conditions that determine how these changes might impact the livelihoods of irrigators here.

The Las Abras irrigation system is the largest and most glacially-dependent irrigation system in the Chimborazo region. Water scarcity has become a serious problem and the situation appears to be worsening. During the 7.5 month period in which canal discharge was analyzed, the volume of water entering the system was insufficient to meet the system’s allocation schedule 80% of the time. Below the canal midway point, supply was unable to meet demand 90% of the time, which indicates that water loss within the canal itself is further exacerbating water stress on the part of downstream users. Because the upper Rio Mocha watershed yield was only sufficient to satisfy the system’s already sharply reduced irrigation schedule immediately following significant precipitation events, it is evident that normal baseflow conditions in the watershed are no longer able to meet the needs of the Las Abras system.

Despite the presence of large glaciers in it headwaters, the upper Rio Mocha is a groundwater dominated hydrological system, and the proportion of water entering the Las Abras system directly derived from glacier melt is typically only ~5%. While this suggests that glacier loss in and of itself is not likely to result in a significant further
reduction in water supply, there is evidence that a glacier compensation effect operates in the watershed and that the loss of glaciers would result in a somewhat more variable water supply. The unexpected fact that specific discharge in the glacierized Gavilán Muchim sub-catchment is only half that of the non-glacierized portion of the watershed also suggests that there may be a strong relationship between glacier meltwater and groundwater discharge, and that the hydrological importance of Chimborazo’s glaciers may be greater than is immediately apparent. This is a question that demands further research attention.

Irrigators up and down the canal report persistent water shortages and note that conflict within the system is increasing. People living in downstream districts are experiencing the most serious impacts, since their natural environmental conditions – a drier climate and less productive soils – enhance their vulnerability to water stress. Here, some irrigators report that they have already been forced to transition from high-value but water intensive crops to lower-value, drought-tolerant pasturage, and, in some cases, even augment their incomes with off-farm employment. In a place where access to irrigation has traditionally represented sufficient insurance against normal hydrological variability, these sorts of adaptations on the part irrigators suggest that the climate change thus far manifested here already exceeds the bounds of many peoples’ coping capacity. Engineered mitigation approaches could provide some relief, however technical and financial obstacles to their implementation are significant and require major outside intervention while internal and external institutional limitations also frustrate efforts at both mitigation and adaptation. Ultimately, without significant changes, the impacts
presently faced by downstream irrigators will become increasingly severe and widespread. The ‘space-for-time’ dynamic evident in the system means that many Las Abras users will have to learn from the experiences of their downstream neighbors.

The challenges confronting the Las Abras system are emblematic of the impact of climate change on local institutions in much of the developing world. Due to forces both local and global, irrigators here are facing increasing water stress at levels that threaten their ability to effectively adapt without significant economic and social disruption. As impacts continue to intensify, the type of integrative, local-scale assessment modeled in this research will become increasingly important. Integrative, because climate change is perhaps the ultimate coupled-systems problem, and the tightness with which climate links human and natural systems makes it impossible to understand the behavior of one without understanding the influence of the other. Local, because the highly differentiated impacts of climate change make adaptation a highly localized problem, and a matched scale of analysis is necessary if truly actionable knowledge is to be produced.
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My primary objective in undertaking this research has been to provide concrete information to Chimborazo’s water users so that they will be better positioned to understand the implications of climate change for their water supplies. Water is essential for sustainable livelihoods in these semi-arid agrarian communities. Because their crops live and die as a result of the providence of the year’s rainy seasons, their socioeconomic
well-being is directly impacted when hydrological variability brings unexpected conditions. Irrigation provides insurance against such variability and has long meant enhanced economic stability for those fortunate enough to have water rights, however, the region’s largest irrigation system rises at the base of Chimborazo’s largest glaciers. As the ice retreats farther up the mountain, the security provided by irrigation could become more tenuous. Climate change-induced disruptions to the hydrological system thus represent a potentially serious threat, compounding other socioeconomic challenges that people here already face. With these concerns in mind, I developed a set of three specific questions that, once answered, should improve the capacity of people here to anticipate the impact of climate change on their water supply and, ultimately, their lives.

Here, I summarize the key findings of this research.

**Summary of Key Findings**

1) *At what rate have Volcán Chimborazo’s glaciers been shrinking in recent decades, and how much ice remains?*

   Between 1986 and 2013, Volcán Chimborazo lost 21% ± 9% of its glacier area, and at present, the mountain has seventeen glaciers that, in total, comprise 11.1 km² ± 3% of ice. The overall average annual rate of change since 1986 has been -0.8% yr⁻¹, though this rate has increased to -1.2% yr⁻¹ since 2000. The proportion of debris-covered ice has increased from ~17% to 27% since 1986, and the mean minimum elevation of clean ice has increased 180 m to 5320 m.a.s.l. Since 1986, the tongues of four glaciers have detached from their accumulation zones. Overall, eight of the mountain’s glaciers now
feature detached tongues and five of these are fully debris-covered and apparently stagnant.

Though the absence of detailed mass balance records at Chimborazo somewhat limits the conclusions that can be drawn, the coherence of climate records and glacier behavior at Chimborazo with that documented elsewhere in the tropical Andes provides strong evidence that glacier shrinkage at Chimborazo is being driven by global climate change. Though not statistically-significant, the apparent local warming trend of 0.11°C decade⁻¹ (0.26°C total since 1986) is in close agreement with rates estimated elsewhere in the region. While available instrumental records do not indicate a shift in the amount of precipitation, farmers living south and east of the mountain are in near unanimous agreement that rainfall is now less frequent and more unpredictable than in decades past and that local springs, streams and ponds are drying up. While the atmospheric warming evident since 1986 can account for a ~50 m increase in freezing level height, the four-fold greater increase in the mean minimum clean ice elevation of Chimborazo’s glaciers indicates that atmospheric warming alone cannot account for glacier change. Instead, given the compelling anecdotal evidence for decreased precipitation, it is plausible that this factor, which reduces mass input while enhancing melt through the preservation low ice-surface albedo conditions, has also been an important driver of recent glacier change.

2) What is the hydrological role of Chimborazo’s glaciers and how does glacier shrinkage impact regional water supply?

Although tropical glaciers experience ablation on a year-round basis, surface meltwater runoff is not constant in most of Chimborazo’s watersheds. Only four of the
mountain’s seventeen glaciers produce year-round surface discharge, nearly all of which drains via the Rio Mocha. Meltwater from a small lobe of the one glacier does provide a small quantity of year-round discharge in the Rio Colorado watershed on the mountain’s northwest flank, though this will cease to be the case within a few decades if present rates of ice loss persist. Another glacier in the Rio Colorado watershed, along with two in the Rio Chimborazo watershed on the mountain’s southwest flank, generate meltwater when warm, sunny conditions persist for several days, though such conditions may only happen a handful of times per month even in the dry season. All remaining glaciers, including those located within the intensively-farmed Rio Guano watershed on the mountain’s southeast flank rarely generate any surface meltwater runoff.

Because it generates the greatest and most reliable water supply on Chimborazo, the Rio Mocha watershed is the most heavily-exploited for both domestic and irrigation water. The Las Abras irrigation system, which diverts 60% of the Rio Mocha into San Andres Parroquia – the township-level administrative district in the upper Rio Guano watershed – is the largest originating on the mountain, and the one most reliant on glacier meltwater runoff. However, despite the presence of Chimborazo’s two largest glaciers within its headwaters, the upper Rio Mocha is a groundwater dominated hydrological system. The proportion of water entering the Las Abras system that is directly derived from glacier melt is typically only ~5%, and this varies little between the short (December – January) and long (June – September) dry seasons. While this suggests that glacier loss alone is not likely to result in a significant further reduction in water supply, there is evidence that a glacier compensation effect operates in the watershed and that the
loss of glaciers would result in a more variable water supply. The unexpected fact that the specific discharge in the glacierized Gavilán Muchim sub-catchment is only half that of the non-glacierized portion of the watershed also suggests that there may be a strong relationship between glacier meltwater and groundwater discharge, and that the hydrological importance of Chimborazo’s glaciers may be greater than is immediately apparent.

3) **How do residents of the agrarian communities that surround Chimborazo perceive their vulnerability to climate change, how are their livelihoods impacted by shifting hydroclimatic conditions, and what adaptation strategies are realistic given the range of social and environmental stressors they presently face?**

Agrarian households in San Andres Parroquia face a range of socioeconomic and environmental stressors that, together, are enhancing the perception that livelihood vulnerability is increasing. While factors such as degrading soil productivity, increased pests and land scarcity are problems, evolving hydroclimatic conditions and increased water stress are the most prominent factors that people identify as drivers of reduced socio-economic well-being. These factors affect nearly all households to some extent, though the severity is differentiated between households and is highly spatially heterogeneous. Non-irrigators, especially those farming below 3100 m.a.s.l., where the climate is drier and soils are less productive, have already been forced to make dramatic livelihood adaptations. Here, nearly all households rely on off-farm employment and a considerable quantity of formerly productive agricultural land is now abandoned. In higher elevation areas, non-irrigators are adapting by shifting from producing only water-
intensive vegetable crops to a mixed portfolio that is increasingly livestock – especially dairy – oriented. These households are also increasingly reliant on off-farm income, and there is a strong sense that community cohesion is being compromised as more and more people, including the majority of young men, seek work in Riobamba or beyond.

Irrigators are not immune to the accumulating impacts of climate change, and in the Las Abras system, water shortages have become a significant problem. Despite having already reduced their maximum aggregated allocation from the 909 L s\(^{-1}\) specified in their water concession to 440 L s\(^{-1}\), the volume of water entering the system was still insufficient to meet the system’s allocation schedule 80% of the time during the 7.5 month period during which canal discharge was analyzed. Below the canal midway point, supply was unable to meet demand 90% of the time, which indicates that water loss within the canal itself is further exacerbating water stress on the part of downstream users. In lower elevation districts, irrigators are now being forced to make the same adaptations the higher-elevation non-irrigators are making. Considering that access to irrigation has traditionally represented sufficient insurance against normal hydrological variability, these sorts of adaptations on the part of irrigators suggest that the climate change thus far manifested here already exceeds the bounds of many peoples’ coping capacity. This is leading to an increased level of conflict among water users, which further undermines the collective sense of well-being.

For irrigators in the Las Abras system, engineered mitigation efforts to reduce water loss and improve irrigation efficiency dominate the discourse about how to respond to these challenges. However, there are considerable technical, financial, and institutional
(internal and external) obstacles, as the recent Korean-financed project to reconstruct the upper third of the canal well-illustrates. For non-irrigators, the barriers to adaptation are even more onerous. Limited financial capital for obtaining additional land and purchasing animals, limited education, minimal non-agricultural skills, and a dearth of stable employment opportunities are all widespread and persistent. Emigration, though a common adaptation strategy in Andean Ecuador since the 1990s, is highly disruptive and carries considerable social costs at the individual, household and community levels. Obtaining access to irrigation remains an idealized option for many farmers, however, because all reasonably accessible surface water is fully allocated and this is no longer viable option for most households. Indeed, the need to develop replacement potable water sources to counter the dwindling flows of springs on the southern side of the mountain will mean that irrigators such as those in the Las Abras system are likely see their water supplies further diminished beyond that resulting from the hydrological changes occurring in the upper Rio Mocha watershed.

Reflecting the differential climate change impacts thus far being experienced in the Chimborazo region, considerable heterogeneity also appears to exist in the future livelihood vulnerability faced by people here. Irrigating households located at higher elevation areas where moisture is more abundant and soil quality is favorable face relatively low risk of increased livelihood vulnerability. Non-irrigating households in these areas face a moderate risk of increased livelihood vulnerability since their soils and climate are generally favorable, but they lack protection against increased drought. Indeed, households located at the highest habitable elevations (above 3600 m.a.s.l.)
actually view changing climatic conditions to be advantageous, since warming and drying conditions are improving productivity and decreasing the risk of frost-loss. Somewhat counterintuitively, non-irrigating households at lower elevations are also generally only at moderate risk of increased livelihood vulnerability due to climate change. While these areas are already experiencing severe water stress, most of these households have already reduced their exposure to direct impacts by limiting their economic reliance on agricultural production. Instead, the households at greatest risk are those in lower elevation areas that continue to rely on irrigated agriculture as their primary means of income. Though these families have thus far been somewhat insulated from the worst stressors, increasingly unreliable water supplies are putting their economic viability at risk, too. These patterns illustrate the strong ‘space-for-time’ dynamic that exists with regards to climate change impacts in the Chimborazo region. As warming and drying conditions creep upward in elevation with future climate change, farmers in the higher districts can expect to face the same impacts and upheavals as their downstream neighbors are now experiencing.

**Intellectual Merit of this Dissertation**

Climate change is, perhaps, the ultimate coupled-systems problem, and the tightness with which climate links human and natural systems makes it impossible to understand the behavior of one without understanding the influence of the other. Furthermore, the highly differentiated impacts of climate change make adaptation a highly localized process, and a matched scale of analysis is necessary if the most effective responses to such dynamic challenges are to be identified. As climate change
impacts continue to intensify, an approach that effectively integrates physical and social process research conducted at local scales will be increasingly vital for the transformation of scientific research into useful adaptive action. As individual pieces of research, work that improves our knowledge of recent glacier behavior at Chimborazo, the hydrologic behavior of the mountain’s glacierized watersheds, and the water resources vulnerability of people living near the mountain would each prove a useful exercise. However, the integration of this research permits a more complete picture of the relationships among glacier change, hydrological variability and increased water stress to become apparent. This dissertation demonstrates the value of such a holistic approach. As an example of the integrative possibilities of geography, my hope is that this research will help inform other geographers who seek to move past traditional disciplinary divisions in order to perform similarly applied research.

Future Research Directions

To further understand the impacts of climate change on Chimborazo’s water supply, there are several areas where additional research is warranted. Foremost is the need to better understand the hydrogeology of the Chimborazo region, particularly the relationship between glacier meltwater and groundwater recharge. At first inspection, it appears that glacier meltwater is not a significant component of surface runoff. However the lack of surface glacier runoff from Chimborazo, and the fact that the mountain’s most glacierized sub-catchment generates only half the specific discharge of adjacent non-glacierized watersheds, suggests a more complex situation. Given the strong dependence of local people on Volcán Chimborazo’s springs, especially for potable water, the
question of the hydrological consequence of glacier retreat has not yet been fully answered.

Another area warranting further investigation is the discrepancy between the instrumental data and local perceptions of shifting precipitation patterns. The tendency within the scientific community is to trust ‘hard’ data, and while it is common human nature to view past conditions as preferable to those of the present, the ubiquity with which people here report about shifting rains, and the intensity with which this opinion is held, suggests that the instrumental record has not captured climatic reality. Understanding why this may be the case would do much to improve our ability to monitor climate change in Andean Ecuador as well as many other places where technical climatological infrastructure may be limited.

Finally, the research presented in this dissertation is but a snapshot of conditions as they existed in 2012. Climate change is highly dynamic, and the social processes that result in vulnerability to climate (and other modes of socio-environmental change) are highly complex. It would be very beneficial to continue monitoring glacier retreat, hydrological change and shifting patterns of livelihood vulnerability in the Chimborazo region. Doing so would not only provide the information that people need in order to respond to evolving conditions, it would also help improve our intellectual understanding of how coupled systems respond to various agents of change over an extended period of time. Hopefully, this dissertation will serve as a useful baseline from which similar future studies can be undertaken.
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Appendix A: Household Survey – Water Supply, Irrigation, and Livelihoods around Volcán Chimborazo

Date:     Time:
Community:
House Code:
Gender:  M   F   Age:______ Married:  Y   N
Status in Household:  Head   Spouse/Partner   Adult Child   Other Relative
                      Friend   Other

Interviewee Description:

Comments About Survey:

I’d like to ask you some questions about your agricultural activities. Me gustaría preguntarle acerca de su agricultura.

1. How many parcels do you have? Cuénteme acerca de sus terrenos, cuantas parcelas tiene?
2. Where are your parcels? Donde están sus parcelas?
3. In total, how many hectares or quadras are your parcels? En total, de cuantos hectareas o quadras están sus parcelas?
4. What do you cultivate? Que cultiva?
5. In your last harvest, how many sacks did you harvest? De la última cosecha, cuanto quintales vendió?
6. Do you irrigate your parcels? Riega agua sus parcelas?
7. Do you own, rent or borrow your land? Es propietario de su terreno, o lo arrienda, o le prestaron?
   a.  (if not owned) Tell me about your arrangements for (renting/borrowing).
       Dígame bajo qué condiciones es el contrato por (arriendo/préstamo)
8. What do you do to minimize the impact of crop loss due to bad weather or some sort of extreme event? ¿Qué hacer para minimizar el impacto de la pérdida de cultivos debido al mal tiempo o algún tipo de evento extremo?

9. If you lost your most important crop, what would your family do? Si usted perdió su cultivo más importante, cuál sería su familia?

IF IRRIGATOR: Continue to Question 10;
IF NOT IRRIGATOR: Continue to Question 20

Segue: Since you irrigate your crops, I’d like to ask you some specific questions about that. Porque irriga sus cultivos, me gustaría hacerle algunas preguntas acerca esta.

10. Are you a registered user of an irrigation system? Es usted miembro de una junta de usurarios riegos?
   a. (If yes) Which system? Cual sistema?
11. What is your irrigation schedule? Cuál es su horario de irrigación?
12. Do you use irrigation water all year or only in certain months? Utiliza el agua de para irrigar todo el año o solo en algunos meses?
   a. Which months? Que meses usted irriga?
13. Does your irrigation system work well or do you have problems with it? El sistema de irrigación trabaja bien o tiene problemas?
14. What would make your irrigation system better? Que haría para que el sistema de irrigación mejore?
15. Do you always have enough irrigation water to meet your needs or are there regular times during the year when you don’t have enough irrigation water? Siempre tiene suficiente agua para irriar, o hay temporadas en las que no tiene suficiente agua para la irrigación?
16. What do you do when there isn’t enough irrigation water? Qué hace usted cuando no tiene suficiente agua para irrigar?
17. Do you think there is usually enough water for everyone in the area? Usted piensa que hay suficiente agua para todos aquí?
   a. If not, what do you think can be done to solve this problem? Que cree que se puede hacer para solucionar el problema?
18. What is your biggest concern about water? Cuál es su mayor preocupación acerca del agua?
19. What would you do if you didn’t have any irrigation water? Qué haría si no tiene agua para la irrigación?

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20. I notice that you don’t irrigate. Why not? **Me doy cuenta de que Usted no irriga. Porque?**

21. If you had access to permanent irrigation water, what would you do differently? **Si usted tiene agua para irrigación todo el tiempo, que más haría?**

Segue: Let’s talk about your animals. **Hablemos acerca de sus animales**

22. What animals do you own? **Qué animales tiene?**

   a. Since the beginning of 2012, how many have you sold? **Desde comienzos del 2012, cuantos animales ha vendido?**

   b. How much did you sell them for? **En cuanto los ha vendido?**

<table>
<thead>
<tr>
<th>Animal</th>
<th>Number</th>
<th>Number Sold in 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goats</td>
<td></td>
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</tr>
<tr>
<td>Cows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burros</td>
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<td></td>
</tr>
<tr>
<td>Pigs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alpacas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Llamas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuyes</td>
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<td></td>
</tr>
<tr>
<td>Rabbits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chickens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

23. (If dairy livestock) Do you sell milk to a dairy? **Vende la leche a las lecherías/queserías?**

   a. IF YES: How many liters per week? **Cuantos litros de leche vende por semana?**

24. (If egg-producing livestock) Do you sell eggs? **Vende huevos?**

   a. IF YES: How many per week? **Cuantos huevos vende por semana?**

25. We’ve talked about your income from your chakras and from your animals. How else do people in your household earn money? **Hemos hablado de los ingresos de su terreno y de sus animales. De que otra manera gana dinero en su hogar?**

246
26. What are the biggest challenges your family faces in earning enough money? ¿Cuáles son los mayores desafíos que enfrenta su familia en ganar el dinero suficiente?

27. What do you do to overcome these challenges? ¿Qué hacer para superar estos desafíos?

Segue: I’d like to ask you a few questions about changes in the environment you may have noticed since you’ve lived in this community. Ahora, me gustaría hacerle algunas preguntas acerca de los cambios en el medio ambiente, es posible que haya notado cambios desde que has vivido en esta comunidad.

28. How long have you lived in this community? ¿Cuánto tiempo vive en esta comunidad?
   a. (If not entire life) Where did you live before? ¿Dónde vivía anteriormente?
   b. (If married) How long has your spouse lived in this community? Desde cuándo vive su esposo/a en esta comunidad?
      i. Where did your spouse live before? De dónde era su esposo/a antes de vivir aquí?

29. Have you noticed any changes in the local climate, such as more or less rain, changes in seasons, warmer or colder temperatures, fewer or more frequent frosts? Ha notado algún cambio en el clima local, por ejemplo más o menos lluvia, los cambios en las estaciones, las temperaturas más cálidas o más frías, menos heladas o más frecuentes?

30. Have you noticed any changes in the amount of water in springs or streams near your community? Ha notado algún cambio en la cantidad de agua en los manantiales o quebradas cercanos a su comunidad?

31. Have you noticed any changes to Chimborazo’s glaciers? Ha notado algún cambio en los glaciares del Chimborazo?

32. Have any of the changes you’ve described affected your personally or affected your community? Algunos de estos cambios le ha afectado personalmente o ha afectado a la comunidad?

33. Why do you think these changes are happening? Porque cree que están sucediendo estos cambios?

Segue: Finally, I’d like to ask some questions about the people who live in your house. Finalmente, me gustaría hacerle algunas preguntas acerca de la gente que viven en su casa.
34. How many people live in your household? **Cuantas personas viven en su casa?**

<table>
<thead>
<tr>
<th></th>
<th>Adult (15+)</th>
<th>Child (&lt;15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

35. Does anyone regularly send you money? **Alguien envía regularmente dinero a usted?**

36. How many years of schooling do you have? Your spouse? **Cuántos años de educación escolar tiene usted y tiene su esposo/a?**

37. Where do ____ live? **Donde viven sus:**
   a. Parents? **Padres?**
   b. Siblings? **Hermanos y hermanas?**
   c. Grown children? **Hijos mayores?**

38. I’ve noticed that you own a(n) __________. Do you also have any of the following in your household? **He notado que usted es dueño de un/a __________. Tiene en su casa:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Carro/camioneta</td>
<td></td>
</tr>
<tr>
<td>Motorcycle Moto</td>
<td></td>
</tr>
<tr>
<td><strong>Televisión</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Radio</strong></td>
<td></td>
</tr>
<tr>
<td>Cell phone Teléfono celular</td>
<td></td>
</tr>
<tr>
<td>Refrigerator Refrigerador</td>
<td></td>
</tr>
<tr>
<td>Hot water shower Ducha de agua caliente</td>
<td></td>
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</tbody>
</table>
Appendix B: Las Abras Focus Group Questionnaire

Introduction

Good afternoon. My name is Nellie McLean-Browne and this is Jeff La Frenierre. First of all, we would like to thank each of you for taking the time to be here today. Jeff is a scientist from the United States, doing research to try and find out if changes in Volcán Chimborazo’s glaciers might affect water supply now and in the future. I will be leading the discussion and translating for Jeff.

Les preguntamos a venir hoy porque el sistema de las Abras y uno de los grupos de usuarios más antiguos e importantes en esta área, y depende en parte del agua de los glaciares de Chimborazo. Tenemos ocho preguntas que gustaríamos discutir. Debido a que las opiniones de todos son importantes, quisiéramos estar seguros que cada persona tenga la oportunidad de hablar. Sin embargo, quisiéramos que esto sea menos como una entrevista y más como una discusión...
de grupo. En vez de solo esperar su turno para contestar la preguntas, esperamos que también hable de sus opiniones con los demás. Por favor recuerde, no hay respuestas correctas o incorrectas. De hecho, sabemos que algunos van a tener opiniones diferentes y esperamos que vayan a compartir su opinión aunque sea diferente de lo que otra persona haya dicho.

Please note that we are recording this discussion because we don’t want to miss anything that someone has said. However, we will not be including your names in the final report, so you can be sure that your comments will remain anonymous.

Por favor tenga en cuenta que estemos grabando esta discusión porque no queremos perder nada de lo que alguien haya dicho. Sin embargo, no vamos a incluir sus nombres en el informe final, así que ustedes puedan estar seguros que sus comentarios van a quedar anónimos.

We’ve brought some cookies that Jeff’s wife made from a recipe she uses in the United States. There is also some juice available. Please feel free to have a snack or drink at any time you like. Also, as Jeff described at the user’s meeting last month, each of you will receive $5 for your time and transportation costs. We will give you an envelope with this money at the end of the meeting.

OK, let’s begin.

Questions

1. I’d like everyone to introduce themselves, tell us where you live, and what type of crops or animals you raise with the water you receive from the canal. Me gustaría que todos se presenten, díganos dónde vive y que para que usa el agua del riego?

2. First, I’d like to ask about your opinions on the climate here. Think back to when you were children, or, when you first lived in this area. Is the weather different in
some way? For example, is there more or less rain, is it warmer or colder, or are
the seasons different than they used to be?

Primero, me gustaría preguntarle acerca de sus opiniones sobre el clima de
aquí. Recuerdan cuando eran niños o la primera vez que vivía en esta zona.
Es el tiempo diferente en alguna manera? Por ejemplo, hay más o menos
lluvia, es más cálido o frío, o son las estaciones diferentes de o que solía ser?

3. Now, I’d like to talk about the importance of irrigation to your agricultural
activities. Imagine that you have never had irrigation water. How would life here
be different?

Ahora me gustaría hablar de la importancia del riego en sus actividades
agrícolas. Imagínense que usted nunca ha tenido agua de riego. ¿Cómo sería
la vida diferente?

4. Think back to when you first started using water from the Las Abras system.
Have you noticed any changes in the quantity of water, or the times of year in
which there is more or less water supply?

Recuerdan cuando empezó a usar el agua del sistema de Las Abras. Ha
notado algún cambio en la cantidad de agua, o los tiempos del año cuando
hay más o menos agua?

5. I’d like to find out more about how Las Abras users deal with periods when there
is less water. When there are times where there isn’t enough irrigation water, what
do you do?

Me gustaría saber más sobre como abordan los tiempos cuando hay menos
agua. Cuando no hay suficiente agua de riego, que hace?

6. Do you think that water is being shared fairly between all of the Las Abras users?
(Follow up: If so, what do you think needs to be done to fix these problems?)

Cree que se distribuye el agua en una manera justa entre los usuarios de Las
Abras? (Si es así, que crees que se debe hacer para resolver estos
problemas?)

7. What do you think about the project with the Koreans to rebuild sections of the
Las Abras canal? What will be different about irrigation for Las Abras users once
it is complete?
Que piensa sobre el proyecto con los coreanos para reconstruir las secciones del canal de Las Abras? Que será diferente acerca del riego por los usuarios de Las Abras cuando termine el proyecto?

8. All things considered, what do you think is the biggest challenge facing people who use irrigation water from the Las Abras system?

A fin de cuentas, que piensa es el mayor desafío que enfrentan a las personas que usan el agua del riego de sistemas Las Abras?

Conclusion

Ok, these are all the questions we have. Again, we’d like to thank you very much for your time. Before we finish, is there anything important that you think we missed in this discussion?

Buenos, estas son todas las preguntas que tenemos. Otra vez, nos gustaría darles las gracias por su tiempo. Antes de terminar, hay algo que nos falta en esta discusión?

When Jeff is finished with his report, in about one year, he will return to Ecuador and share his results with the users of the Las Abras system. Until that time, good luck to each of you, and go well.

Cuando Jeff se acabe con su informe, en más o menos un año, va a regresar a Ecuador y compartirá sus resultados con los usuarios del sistema Las Abras. Hasta ese momento, buena suerte a todos y que vayan bien.
Note: All coordinates are in UTM 17S (WGS84). Elevations are in meters.

**Totalizing Rain Gauges**

Monthly precipitation totals were collected at seven locations using hand-built, evaporation-proof totalizing rain gauges.

<table>
<thead>
<tr>
<th>Station</th>
<th>Easting</th>
<th>Northing</th>
<th>Elev.</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
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<td>9845609</td>
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<td>11/11</td>
<td>7/12</td>
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<td>7/12</td>
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<td>7/12</td>
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<td>7/12</td>
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<td>7/12</td>
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<td>3950</td>
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<td>7/12</td>
</tr>
<tr>
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<td>9836419</td>
<td>4857</td>
<td>11/11</td>
<td>7/12</td>
</tr>
</tbody>
</table>

**Automated Weather Stations**

Automated weather stations (Onset Hobo Micro Station Model #H21-002) were installed at three locations. These stations collected data at 10-minute intervals. The Portal Andino station was relocated to the Reschreiter Glacier. Upon completion of field work in August 2012, these stations were turned over to the control of Instituto Nacional de Meteorología e Hidrología (INAMHI). Data collected in 2013 and later may be available from this agency (contact the Glaciology office).

<table>
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<tr>
<th>Station</th>
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<th>Elev.</th>
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<th>End Date</th>
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<tr>
<td>Control Whymper</td>
<td>736458</td>
<td>9834297</td>
<td>4389</td>
<td>11/4/11</td>
<td>1/31/13</td>
<td>(1) Precip; Wind Speed; Gust Speed; Wind Dir; Temp; Relative Humid.</td>
</tr>
<tr>
<td>Portal Andino</td>
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<td>5/12/12</td>
<td>(2) Precip; Wind Speed; Gust Speed; Wind Dir; Temp; Relative Humid.</td>
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<tr>
<td>Reschreiter Glacier</td>
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<td>9839519</td>
<td>4516</td>
<td>5/13/12</td>
<td>11/8/12</td>
<td>(2) Precip; Wind Speed; Gust Speed; Wind Dir; Temp; Relative Humid; Solar Radiation</td>
</tr>
</tbody>
</table>

(1) Temperature and relative humidity sensor failed 8/30/12
(2) Temperature and relative humidity sensor failed 9/10/12
Temperature and Humidity Loggers

Automated loggers (Lascar Electronics EL-USB-2) that collect air temperature, relative humidity, and dew point (at either 30 minute or 1 hour intervals) were installed at multiple locations. Those stations still in operation in January 2013 have been turned over to the control of INAMHI. Sensor reliability was a problem, and significant data gaps exist for most stations.

<table>
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<tr>
<th>Station</th>
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<th>Elev.</th>
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<th>End Date</th>
<th>Data Gaps</th>
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</tr>
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<td>1/30/13</td>
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</tr>
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<td>12/15/10 – 7/24/11, 11/15/11 – 12/6/11</td>
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<tr>
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<td>7/31/12</td>
<td>11/30/11 – 12/6/11, 7/23/12 – 7/31/12</td>
</tr>
<tr>
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<td>7/31/12 – 1/9/13</td>
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</table>

Stream Depth

Automated pressure transducers (Solinst Levelogger Junior) that record stream depth were installed at three locations. Barometric pressure transducers (Solinst Barologger Gold) were also installed to provide atmospheric correction. Data were collected at 10 minute intervals. These stations have been turned over to the control of INAMHI.

<table>
<thead>
<tr>
<th>Station</th>
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Figure C.1. Location of sensors installed for this dissertation research.