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Climate Change Effects on Volcanoes in the Tropics: A review of the deglaciation of Antisana and its effects on subsequent water streams and rivers over 20 years

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CLIMATE CHANGE EFFECTS ON VOLCANOES IN THE TROPICS

A review of the deglaciation of Antisana and its effects on subsequent water streams and rivers over 20 years

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(Haines & Hayoun, 2018)

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Abstract

Located in the Northern end of Ecuador lies the stunning glacier of Antisana which attracts many tourists and whose runoff provides a significant amount of water supply for Quito. Climate change is posing threats to many ecosystems world wide but will have a more substantial impact on the volcanoes in the tropics because they do not have a seasonally altered climate. Small changes in the air temperature can have larger impacts on these areas that are adapted to constant temperatures with seasonal precipitation changes. Climate change, in recent years, had caused an increase in the glacial retreat of the Antisana volcano. This increase in melt and deglaciation has further implications for the Quito's water supply, the surrounding ecosystem of the glacier and subglacial run-off areas, and can impact the quality of water run-off from the Antisana Glacier. This study examines the implications of the melt from the glacier by providing a meta-analysis about the flow of subsequent streams, impacts on water resources for nearby cities, a makeup of environmental impacts from the viewpoint of macroinvertebrate sampling, and a review of the deglaciation from a review of articles and investigation into satellite imagery. The results from this study did not have any significant findings about the retreat of the Antisana glacier in relation to the impact on surrounding ecosystems and water resources for the nearby city of Quito.

Resumen

Situado en el extremo norte de Ecuador se encuentra el glaciar impresionante de Antisana que atrae a muchos turistas y cuya escorrentía proporciona una cantidad significativa de suministro de agua para Quito. El cambio climático está planteando amenazas para muchos ecosistemas en todo el mundo, pero tendrá un impacto más sustancial de los volcanes en los trópicos porque no tienen un clima alterado estacionalmente. Pequeños cambios en la temperatura del aire pueden tener impactos mayores en estas áreas que se adaptan a temperaturas constantes con cambios de precipitación estacionales. El cambio climático, en los últimos años, había causado un aumento en el retiro glaciar del volcán Antisana. Este aumento de la fusión y la desglaciación tiene otras implicaciones para el suministro de agua de Quito, el ecosistema circundante del glaciar y las zonas de escorrentimiento subglaciales, y puede afectar la calidad de la escorrentía de agua del glaciar Antisana. Este estudio examina las implicaciones de la fusión desde el glaciar proporcionando un metaanálisis sobre el flujo de corrientes posteriores, impactos en los recursos hídricos para ciudades cercanas, una composición de los impactos ambientales desde el punto de vista del muestreo de macroinvertebrados, y una revisión de la desglaciación a partir de una revisión de artículos e investigación sobre imágenes satelitales. Los resultados de este estudio no tuvieron hallazgos significativos sobre la retirada del glaciar Antisana en relación con el impacto en los ecosistemas circundantes y los recursos hídricos para la ciudad cercana de Quito.

Acknowledgments

I would like to thank Xavier Silva, Diana Serrano, and Ana-maria Ortega for their guidance with this project and help to prepare me throughout the semester. I would also like to thank Whitman College and SIT for allowing me to participate in this program and giving me access to materials needed to conduct this research. I am thankful for support from my family and friends, especially for helping and guiding me through Google Earth and the collection of satellite imagery. This paper would not have been able to be completed without the hard work of researchers whose studies are cited in this paper. My love and thanks goes out to the Obando family for hosting me while I was in Ecuador.

Introduction

Glaciers in the Adean region of South America

Glaciers contribute to a large portion of Earth's stored water. Evidently, perennial snow and ice make up most of the earth's surface and provide a vital source of drinking water for many countries. Around 68.7% of the world's freshwater is stored in glaciers worldwide (Vandeberg & VanLooy, 2016). South America, more specifically the Andes, hosts 99% of all the tropical glaciers in the world (Rabatel et al., 2013). Besides storing large amounts of freshwater, glaciers also supply a huge source of water used for irrigation of crops, sanitation, and hydroelectric power. Furthermore, some glaciers can represent a cultural symbol or act as a tourist attraction (Bennett & Glasser, 2009; Veettil & Kamp, 2019). However in tropical regions, like South America, the economic and environmental value of glaciers varies on a local or regional basis. Still many Andean communities in South America rely more on glaciers as a water resource for various uses than other communities in the world that live near glaciers (Jomelli et al., 2009).

Other than the importance to local communities, the tropical climate in South America is very different from the mid-latitude environment and has distinct abiotic factors that contribute to the glacial ecosystems (Bennett & Glasser, 2009). Kaser & Georges (1999) suggest that tropic climates feature daily temperature fluctuations that surpass annual temperature fluctuations, a relatively stable climate with two distinct seasons (wet and dry), and has more drastic changes in humidity. Each of these factors lead to more periods of accumulation and ablation of tropical glaciers (Kaser & Georges, 1999). Rising temperatures due to climate change increase the ablation periods of glaciers which decrease the overall glacial mass. Not only are glaciers in general heavily affected by climate change because temperatures will rise more at higher elevations, but tropical glaciers already have unique ecosystems that make them extremely vulnerable to the impacts of climate change (Bradley et al., 2006).

Glaciology and the Impacts of Climate Change

Generally, glaciers have a glacial terminus that is constantly changing, either in an accumulation or an ablation period. Accumulation is the gaining of ice and ablation is the loss of ice. In zones of accumulation, the net mass gain is greater than loss, and zones of ablation, the net loss is greater (Ritter, 2012). Zones of ablation occur due to sublimation, a changing from a solid state (ice) to a vapour (air moisture), wind erosion, melting, and evaporation(Davies, 2020). Zones of accumulation are associated with colder temperatures and more precipitation (Davies, 2020). Climate change can have greater impacts on this process. In the tropic's ablating or receding glaciers expose more rock, dirt or snow, throughout the year, unlike in higher latitudes where ablation occurs seasonally(Favier et al., 2004). Since ablation occurs year-round in the tropics, climate change will decrease the glacier's mass balance, the difference between accumulation and ablation, so more ablation will occur.

The trends with recent weather patterns due to climate change are felt all around the world but are having larger impacts on glaciers that are slowly disappearing due to higher rates of melt which may not be recoverable (Arenas & Ramírez Cadena, 2010). Also, as described before, tropical glaciers tend to melt and accumulate and have specific surroundings that will cause more melting to occur than the annual rate (Rabatel et al., 2013) . Furthermore, the inner tropic ablation periods that affect glacial mass are more specifically regulated by air temperature surrounding glaciers, leaving glaciers in Ecuador,, very sensitive to climate change (Jomelli et al., 2009). A study on the impacts of climate change on the glacial retreat in the tropical Andes identified that the climatic conditions are causing winters to be stronger and more humid, and summers are arider and have more intense periods of heat (Espinosa, 2015). Since tropical glaciers already have a wet and dry season and experience continual ablation periods, this amplification of seasons will have more adverse effects on the glacial melt. Another study by Arenas & Ramírez Cadena (2010) suggests that, along with these factors, glacial loss becomes a positive feedback loop because the decrease in ice sheets will reduce the albedo, which is a measure of how well a surface reflects UV radiation. A lower albedo means the surface absorbs light and does not reflect the radiation very well. This will in turn heat up the surface, and thus the melting process of glaciers is amplified by this process (Arenas & Ramírez Cadena, 2010). As discussed, climate change poses major threats to the state of glaciers, especially in tropical regions. Antisana, an ice-capped volcano in Ecuador,. has recently been receding and is of great importance because of its location.

The Antisana Glacier and Surrounding Ecosystem

In Ecuador, the Reserva Ecológica Antisana (REA) is a protected area spanning 131,000 hectares of Andean páramo that hosts huge biodiversity due to its unique ecosystem (Williams et al., 2001). Paramo grasslands are crucial ecological areas as they are an important source of water that contain large organic carbon stores, have a huge amount of endemic and threatened species, and are regarded as a hotspot for vegetation diversity (García et al., 2019;Madriñán et al., 2013).

The effects of retreating glaciers surpass economic devastations and can have detrimental impacts on this ecosystem. Studies have shown that the decrease in glacial mass has adverse effects on the biodiversity of flora and fauna found in the paramo ecosystem (Jacobsen et al., 2012). In accordance, recent studies by Brighenti (2019) have discussed the possibility that, after the initial water flow due to glacial loss, there will be reduced amounts of organic carbon, phosphorus and nitrogen and the analogous increase in organic matter can cause a compositional change of bacterial communities and have larger effects on the downstream ecosystems and nutrient cycling. Also, the aquatic biome may adjust to this influx in nutrients and then become more heavily affected when such nutrients as carbon are no longer as readily available (Brighenti et al., 2019).

Additionally, although they seem like uninhabitable environments, glaciers and ice sheets have their own ecosystems known as the supraglacial and subglacial ecosystems. They are considered autotrophic biomes that host viruses, bacteria, and various algae (Brighenti et al., 2019). Beyond the ecosystem impacts, the increase in runoff from the glacier releases stored organic carbon and can change the supraglacial flows that will have detrimental effects on the water quality of glacial-fed streams and rivers.

Local Impacts of Glacial Melt

As well as impacting the aquatic biome and the surrounding ecosystem, glacial retreat will also impact the amount of drinking water supplied to nearby cities. According to a recent study by Bradley (2006), areas relying heavily on glaciers as a source of freshwater will begin to face issues in terms of expenses and difficulties finding alternative water supplies. Quito, the capital of Ecuador and a neighboring city to the ecological reserve of Antisana, currently receives a majority of its municipal and industrial water from the glacial runoff on the Antisana volcano (Williams, n.d.). About 98% of Quito's water sources come from surface water and, almost half of that water comes from the interbasin transfer; the local watershed that supplies drinking water from the high alpine grasslands of the Páramo, which includes drainages from Antisana (Urban Water Blueprint—Quito, n.d.). Thus, changes in climate will directly affect surrounding cities, specifically Quito, that rely on the glacial run-off of the Antisana volcano.

Studies on Glacial Retreatment and Effects on Water Quality

Recent studies have shown that Glaciers in Ecuador are showing higher levels of ablation in response to regional climate change. Small and yearound increases in temperature are having a significant impact on the tropical glaciers (Giné et al., 2018). Previous studies show that between 1979-2007 the Antisana glacier has lost 37% of its glacial mass, others represent similar numbers around 30-35% and from 1997-2006, an even shorter time period, showing a 18.68% reduction, that, if calculated over the same time frame, has an accelerated rate of retreat (Baraer et al., 2012). Preliminary analyses on this phenomenon suggest that climate change, along with increasing regional temperatures, has increased the sea surface temperature that likely contributes to the increase in the melt, as well as local eruptions of Reventador (most recent 2009-ongoing) to Tungurahua (most recent 2016).The ash from these eruptions could affect the speed up glacial ablation due to an increasing albedo (Cáceres, 2009). Climate change can also cause El Niño-Southern Oscillation (ENSO) patterns to be more intense, increasing the melt of the glaciers (Francou, 2004). ENSO involves changes in the temperature of the water in the pacific ocean that can affect rainfall and weather patterns in the tropics. El niño years are associated with above normal temperatures and above normal precipitation. La niña years are associated with below normal temperatures and below normal precipitation (El Nino/Southern Oscillation (ENSO) Technical Discussion, n.d.). Other studies point to the melting of glaciers reducing the flow of rivers which affects the water supply to nearby cities and can harm the surrounding ecosystems due to changes in the makeup of the streams (Williams et al., 2001; Brown et al., 2010). Although the response of ecosystems to an increase in glacial retreat is not thoroughly studied, one article by jknkn who examined global effects of glacial retreat discusses that the retreat will have impacts on the trophodynamics and nutrient cycling of the ecosystem (Fountain et al., 2012). Other studies talk about the future decrease of streamflow changing the benthic (bottom zone of rivers) biota composition (Cauvy-Fraunié et al., 2016). Over recent years Antisana, like all other glacier-covered volcanoes in Ecuador, is receding and giving off more meltwater each year which can have further implications on surrounding communities and ecosystems.

Objectives and Research Question

This study will analyze the rate of glacial retreatment and the impacts on the aquatic and biotic ecosystems. The research question of this investigation is two-part. (1) From 2000-Present, what percent of the Antisana glacier has receded in terms of glacial mass, and what is the average annual percent retreat? (2) How does the increase in loss of the Antisana Glacier impact the subsequent quality of alpine streams and the health of aquatic biomes? In order to answer these questions research needs to be further broadened on how to assess the quality of alpine streams and the health of aquatic biomes.

The objective of this investigation would be first to analyze the Antisana glacier in terms of size, location, and water flow rates. This data would be compared over a 20 year time period to determine how much the glacier has melted and what is the size comparison between data in 2020 compared to 2000. After the data are collected, it will then be compared to meta-data from various sources on the water quality of the glacial runoff to see the impacts the deglaciation has on the water quality on the catchments of that glacier. The analysis of water quality will not be concrete, as it will come from meta-analysis of researchers using various methods to test this. This study will analyze the impacts on subglacial streams and their subsequent tributaries and see if there is a positive or negative correlation to the diminishing size of glacial ice and increased run-off.

It is anticipated that the Antisana glacier will be melting at a higher rate throughout recent years (2000-2020) than the standard seasonal melt. It is expected that the receding of the subglacial cap of Antisana will cause stress on the subglacial streams and the surrounding ecosystems. This is predicted to decrease the quality of the water and pose threats for the aquatic biome.

Methods and Materials

Area of study

Situated in the western side of the Cordillera Real del Ecuador, about 50 km southeast of Quito lies the Antisana volcano at the following geographic coordinates: 0°28 ′30”S y 78°08 ′55”W (Yánez, 2010) (Figure 1). Antisana is a stratovolcano, which is a volcano usually built of alternating layers of lava flows, tephra, and a pyroclastic flow that form steep, conical volcanoes (*U*SGS: Volcano Hazards Program Glossary - Stratovolcano, n.d.). The Antisana volcano is covered in a glacial ice cap and, since the last eruption in 1802, is still possibly active (*Global Cryosphere Watch - Station Information*, 2017). It is approximately 5758 MASL and 13 km in diameter (*Antisana* n.d., 2020). The water from the Antisana glacier contributes to part of the larger amazon basin watershed and also flows into the Antisana La Mica station (Cannon et al., 2010). A subsequent amount of water from the Mica lake and the Papallacta river is distributed to Quito and other run-off contributes mainly to the amazon basin, specifically into Coca through Río Quijos. As above mentioned, the Antisana glacier is a valuable water resource for the surrounding areas and its meltwater is sourced to the nearby cities.

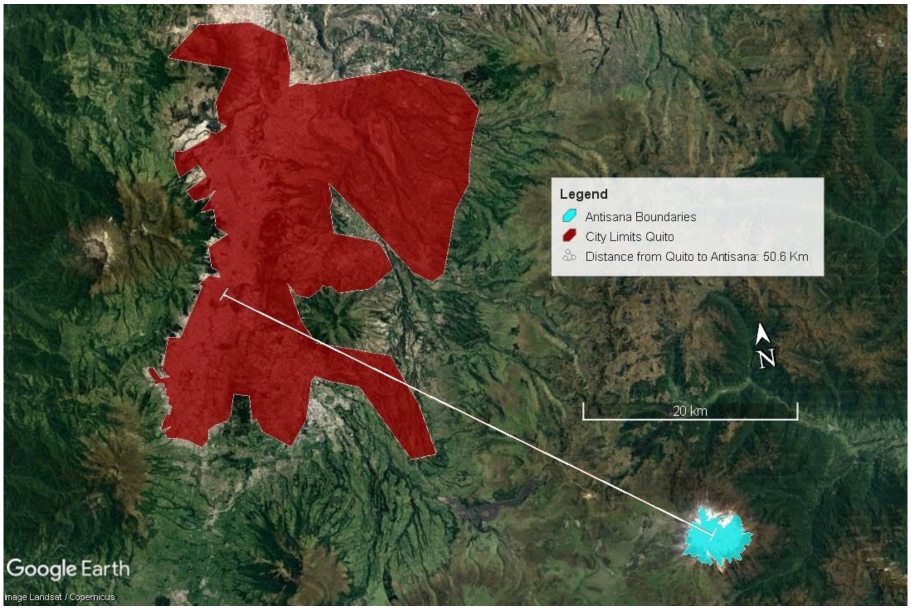

Figure 1. Location of the Antisana Volcano in relation to Quito, Ecuador. Taken from Google Earth Pro satellite imagery, outlined, and mapped.

The glacier is divided into 17 different tongues that all are included in the larger Antisana glacier, that on average loses 610 mm of water annually (see Appendix D)(*Global Cryosphere Watch - Station Information*, 2017). The climate that surrounds the volcano is very complex and even variable depending on the aspect of the volcano. The eastern side climate is a product of the airflow from the amazon, these winds are blown in from the Atlantic ocean, collide with the eastern mountain range, ascend and then cooling causes precipitation to occur (Yánez, 2010). From research done by Favier (2004), the western aspect is vastly different where it contacts seasons of climate, a dry and rainy season (dry season usually June-September). Tropical temperature, similar to what surrounds the Antisana glacier does not have significant changes throughout the year, however, it still can fluctuate annually (Favier, 2004). The wind is the main factor that affects the seasonality of this area but it is also heavily influenced by ENOS, which is the variable oscillations that are sustained by the central pacific atmospheric ocean, creating patterns of warm or cold air (Favier et al., 2004).

Meta-data and analysis

Meta-data was collected from various sources and comparable information was collected. Any outlier in the information, incorrect or not reputable, was disregarded and the average was taken from the rest.

Meta-data will be collected from primary sources, literature-reviewed articles, theses and reports about the impacts of deglaciation on run-off streams. A meta-analysis was conducted to include other research papers discussing the subglacial streams of the Antisana Volcano. Research was pulled from online databases that include ScienceDirect, Research gate, Google Scholar, ScienceOnline, and JSTOR. Many of these articles were accessed through Whitman College or SIT. Due to the manner of this investigative project a specific stream site cannot be determined and will have to include a more extensive location of any water run-off from the Antisana glacier. However, there are two main rivers that this investigation will focus more on, which are Papallacta and Río Quijos. Also, there are currently two hydrological stations, Los Crespos and Humboldt, that are monitored and included in various articles.

Because communities in Quito and surrounding areas rely more on the water from Antisana the focus was mainly on these regions. Specific data was collected from 7 articles about the impacts of Antisana on the water resources in Quito. Assessing water quality of these streams, as well as the health of surrounding aquatic ecosystems, was more difficult due to the nature of meta-analysis. To measure water quality, papers were extracted within the time period (2000-2020) that focused on research into macroinvertebrate communities, PH, temperature, and other indicators of the health of a water system. Supplemental papers in previous years were also included to represent water quality. To measure the health of communities and the surrounding ecosystem, again, data will be extracted from primary and other peer-reviewed articles and compiled to get an overall view of the health of the ecosystem. Throughout this research, only articles assessing macroinvertebrates to quantify water quality were collected. The pH and temperature of subglacial flows were not included due to the limited amount of information. It is also important to further identify the increase in river discharge due to the melting of the Antisana glacier so it can be compared to the data collected from the size of the glacier and the health data. The specific analysis was conducted from stream monitoring in three articles in terms of Qgl (the estimated potential flow from glaciological measures). However the data specific to Los Crespos stream sites was not prevalent and thus not included in this study. Because this is not a field-based investigation it will be difficult to outline a specific time chronogram and a description of time management cannot be supplied.

Satellite Imagery

Multiple Landsat (collection of satellite images) images were collected and analyzed from 2000-2020. Since the availability of Landsat imagery in terms of the years was variable, the data was split into two sections. One worked with images collected from Glovis USGS that included data sets from

Aster Level 1T, EO-1 ALI, Sentinel-2, and LANDSAT. The specific dates were separated from 2001-2007 collected at time intervals of three years, 2015-2017 with a separation of two years, and 2017-2020 that were at a one year time interval. These images were collected from various months, therefore, align with different periods of precipitation. The other section was only data collected from Google Earth Pro from 2000-2016 with year gaps including 2002, 2004, and 2007. These images were all taken the same month of December and are not as affected by the wet or dry seasons. It should be noted that the images used were affected by the date the photo was taken, the cloud coverage (%), and the quality/visible surface of the glacier. Also, the Google Earth Pro images showed half of the Landsat satellite imagery of the volcano in great detail and the other half is more blurry. The images collected from Glovis USGS had less than a 30% cloud cover, more clouds were seen in Google Earth Pro.

A model was constructed in Google Earth with two topographic maps obtained from IGM (*Instituto Geográfico Militar - Ecuador*, n.d.). These topographic maps were combined to have a complete map of the Antisana area. The images were overlaid on satellite images in Google Earth Pro. This provided an exact location as well as including the layers of rivers, lakes, and the topographic contours. Data was created by using polygons to outline areas, adding in overlays of images, and uploading tiff and Kml files into Google Earth Pro.

The watersheds that the Antisana glacier contributes to were calculated by selecting the lowest point of water or stream from a lake and then all the water, based on the topographic lines and height measurements, that drains into the selected area was outlined. This also includes streams that are not connected to the Antisana glacier but also drain into the basin.

A rough outline of the Antisana glacier was constructed by roughly including all the water and rivers that drain from the Antisana glacier. This outline was used in correlation with studies about water quality and ecosystem health to show that Papallacta, Rio Quijos, the Humboldt and Los Crespos station are all water drainages that the Antisana glacier contributes to. Glacier coverage was not taken for the streams outlined because this investigation is not conducted on one specific stream but rather any that the meta-data represents, thus it is not needed.

A total of 21 satellite images (from 2000-2020) were analyzed in this study to quantify glacial retreat. The images collected from Glovis were imported as tiff files and would be calibrated to the latitude and longitude of Google Earth Pro. The images satellite images from Glovis were overlaid into Google Earth Pro and a polygon of the glacial was taken for each image. Some of this data was more of a rough estimation if the image was unclear, lighting was off, or the difference between the snowline and glacier line could not be differentiated. The measurement was taken for each for the surface area of the glacier (m^2). A comparison and a chart were made between the 9 years (2001-2020) of data collected. Percent retreat was calculated between each period: 2001-2007 (3 years apart), 2015-2017 (2 years apart), and 2017-2020 (1 year apart). This same method was conducted for the Landsat satellite images collected from Google Earth Pro. A comparison and a chart were made between 2000-2016 on a yearly basis excluding 2002, 2004, and 2007. Percent of the glacial retreat was calculated between each period and then compared across the years and different months.

The percent glacial retreat calculated from Glovis and Google Earth Pro were also compared to ENSO patterns throughout the same time periods. The data was also compared to precipitation but there was no relation to precipitation patterns and this data is not included in the study.

Ethics

Due to the structure of a meta-analysis, this investigation had no direct contact with local communities in the Ecological Reserve of Antisana and did not have any direct impact on the environment. Since there was no contact there is no need for approval from the institutional board approval. The ethics of other articles were reviewed to ensure that, if they interacted with people or the environment, were also in accordance with ethical principles. One article cited that it was conducted on private land but permission was granted from the owner and no endangered or protected species were affected (Cauvy-Fraunié et al., 2015).

Results

1. Landsat Satellite Imagery

1.1 Outline of the watersheds in the Antisana study area

Five Different watersheds were outlined in Google Earth Pro (Figure 2). Two of the catchment areas flow into major rivers Papallacta (outlined in light purple) and Rio Quijos (included in the yellow outline) that contribute to larger water flows to Coca and Quito (n=red, n=yellow). One of the watersheds flows into Laguna de Mica, a huge part of where Quito receives its water supply.

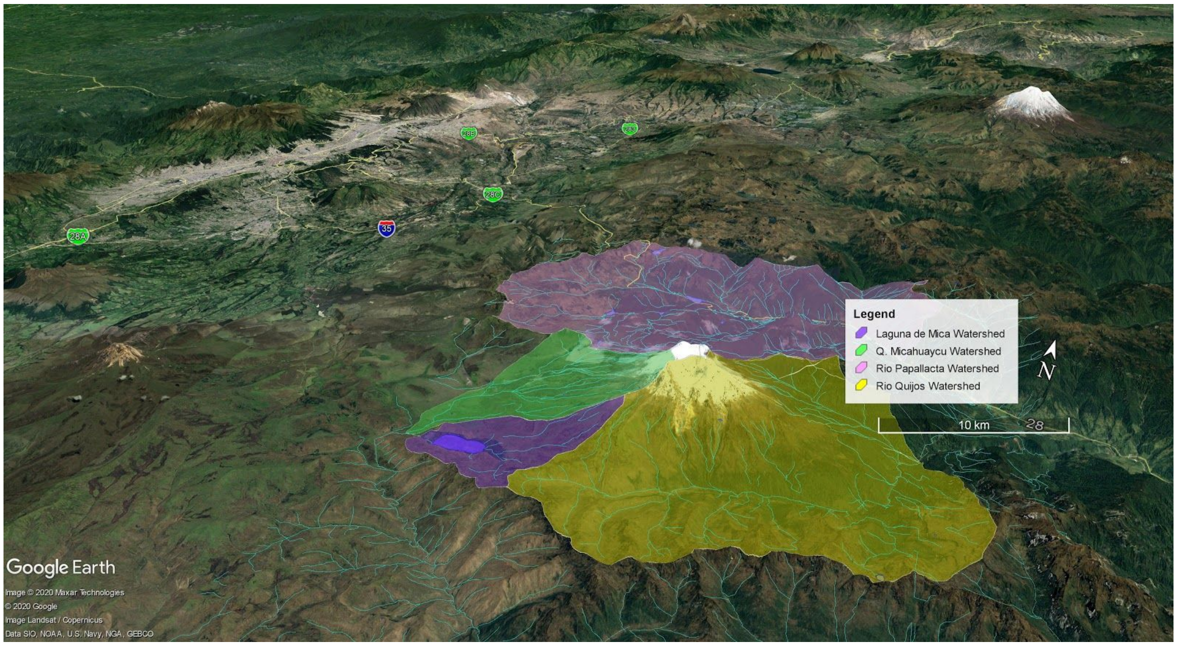

Figure 2. An outline of the Watersheds that the Antisana glacier melt contributes to.

1.2 Landsat imagery taken from Glovis USGS from the period 2001-2020

An example of the outline of the Antisana glacier using a glovis overlay is seen in Figure 3, reference Appendix A and C for all of the glovis overlay Landsat mapping. This image was collected from August 15, 2017. The outline of the glacier is highlighted in black that gives the measurement of the glacier. Surface area is 15,341,466 for this specific date collected.

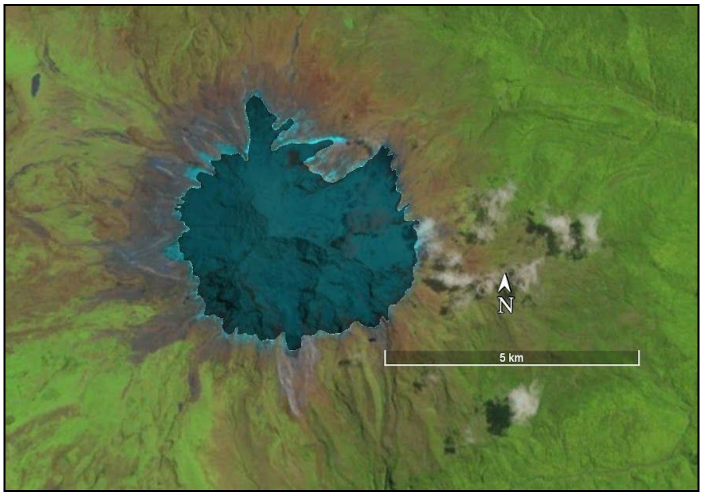

Figure 3. A representation of the data collection from Google Earth Pro using an overlay of Glovis USGS. This image used the data set WHAT from August 15, 2017. The other 9 images and the outlines of the glacier are included in Appendix A.

Data was taken from 8 years of various data sets using glovis USGS (*Figure 4)*. In 2001 the glacial surface area (g.s.a) of Antisana was 21,271,676 and in 2020 the glacial surface of Antisana was 11,801,585. No R^2 value is given because all of the different lines of best fit were below 0.5. Data was seen from 2004 (g.s.a= 12,900,336) and 2007 (g.s.a= 12,043,070) that did not fit with the trend. Also there was a large increase from the data collected in 2019 (g.s.a=19,122,777)**.**

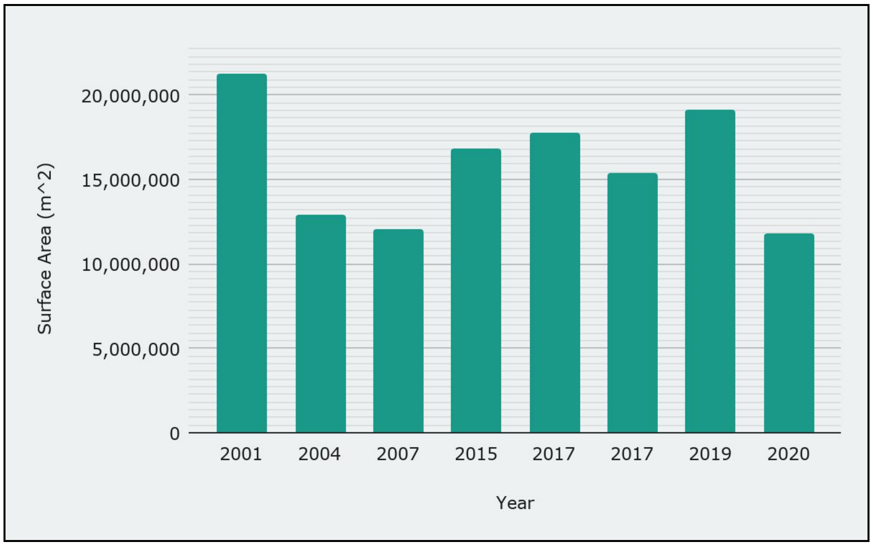

Figure 4. Graph of the glacial retreat in terms of surface area (m^2) from Glovis overlay on Google Earth Pro. From the glovis data there was no actual trendline of the two layers. The table that included this data and the glacier percent coverage is in Appendix E.

Data from the Glovis Landsat collection of glacial surface area and El Niño-Southern Oscillation (ENSO) weather patterns were compared to investigate the effect of ENSO events on glacial retreat

(Figure 5). A graph comparing ENSO weather patterns to the surface area identified gives no correlation between a warm weather period to an increased ablation of the Antisana glacier. There was one year that was associated with an El Niño weather pattern in 2015 (Figure 5).

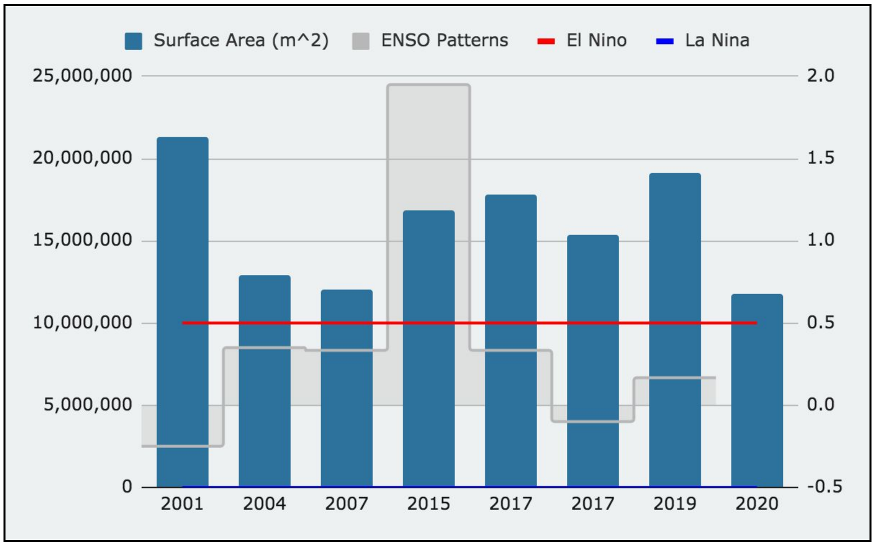

Figure 5. Graph of the glacial retreat (2001-2020) in comparison to the ENSO weather patterns. Based on the national weather service (NOAA's Climate Prediction Center, n.d.) the warm (red) and cold (blue) periods have a threshold of +/- 0.5 °C, therefore the anywhere above the red line or below the blue line are significant El Niño or La Niña years, respectively.

1.3 Data collection of Landsat imagery taken from Google Earth Pro from the period 2000-2016

An example of the outline of the Antisana glacier using a Google Earth Pro is seen in Figure 6, reference Appendix A and C for all of the glovis overlay Landsat mapping. This image was collected from August 15, 2017. The outline of the glacier is highlighted in black that gives the measurement of the glacier. Surface area is 15,341,466 for this specific date collected.

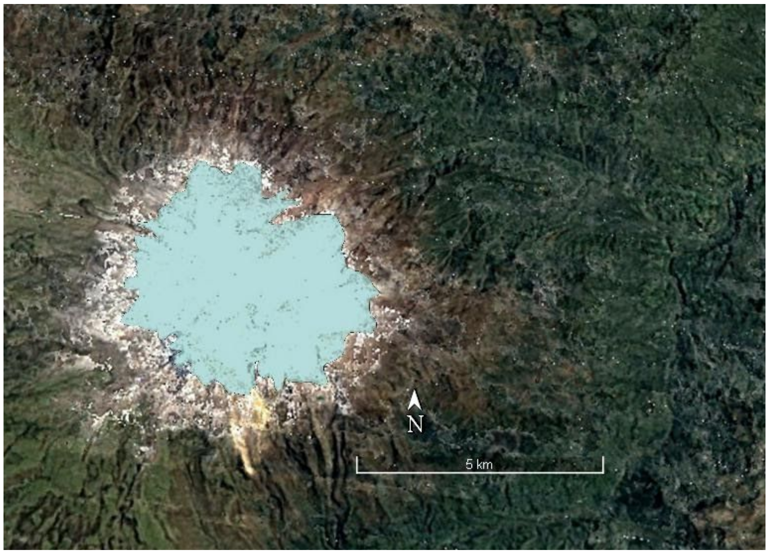

Figure 6. A representation of the data collection from Google Earth Pro. The image represented here is from December 2008.

The surface area of the antisana glacier was measured between the years 2001-2016 (Figure 7). The glacial surface area (g.s.a) in 2001 was 19,985,988 m^2 and in 2016 the g.s.a was 15,707,558 m^2. The R^2 value of 0.82 was found using a polynomial best line of fit. There were no outliers found in this study using Google Earth Pro landsat images. Every satellite image used to collect this data was taken in the month of december.

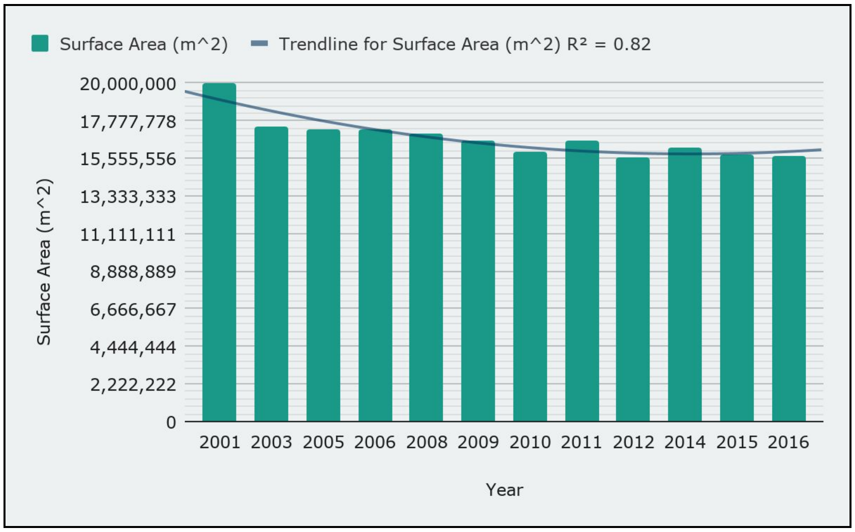

Figure 7. Graph representing glacial retreat in terms of surface area (m^2) and glacial percent coverage. Data was taken from 2001-2016 all in the month of december. Trendline is shown on the graph. The table that included this data is in Appendix E.

Data was compared from the Google Earth Pro Landsat Imagery of glacial surface area to El Niño-Southern Oscillation (ENSO) weather patterns (Figure 8). As stated above, ENSO affects the temperature of the pacific ocean and causes warm (El Niño) and cold (La Niña) periods. El niño years are associated with above normal temperatures and above normal precipitation. La niña years are associated with below normal temperatures and below normal precipitation (*El Nino/Southern Oscillation (ENSO) Technical Discussion*, n.d.). In this comparison there are no correlations between El Niño or La Niña periods. There is also no outlier in this data.

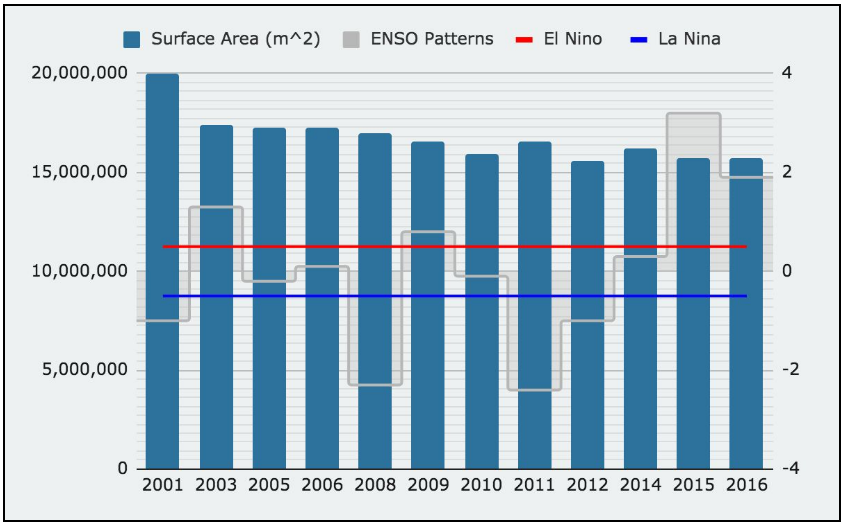

Figure 8. Graph of the glacial retreat (2001-2016) in comparison to the ENSO weather patterns. Based on the national weather service (NOAA's Climate Prediction Center, n.d.) the warm (red) and cold (blue) periods have a threshold of +/- 0.5 °C, therefore the anywhere above the red line or below the blue line are significant El Niñoor la nina years, respectively.

2. Glacial retreat based on various studies on the Antisana glacier in addition to Landsat imagery

2.1 Data from six studies representing the glacial changes of the Antisana glacier

Meta-data from six studies examining the glacier mass balance of Antisana through glaciological and hydrological measuring are included in the Table 1. All six of the studies reported a negative net balance of the Antisana glacier (S=2,3,4,5,6 reported on the Antisana glacier 15). The five studies reported the Equilibrium line altitude to be between 5050 and 5245 m, this spanned between the years 1950-2007 (S=2,3,4,5,6). Five studies reported that there was a decrease in glacier coverage over the time period of their study (S=1,2,4,5,6). All of the articles analyzed either concluded or hypothesized that the current state of climate change will lead to a retreat of the equilibrium line and the net mass balance to be negative.

Study # (S)	**Article**	**Date**	**Measurement Type**	**Glacier**	**Equilibrium Line**	**Balance**	**% Glacier Coverage**
1	(Maisincho et al., 2006)	1950-2020	Evolution of Ice masses (literature analysis)	Antisana and others in the Cordillera Blanca	---	Negative Net Balance	40-50% loss
2	(Caceres et al., 2006)	1995-2005	Measure the evolution of the Glacier	Antisana Glacier 15 a	Average ELA of 5115 (1950-2005)	Negative Average Balance (1995-2005)	Decreased

3	(Favier et al., 2008)	1995-2005	Glaciological Balance	Antisana Glacier 15	5050 (the measurement used in this study)	Negative average Net balance (1995-2005)	---
4	(Maisincho et al., 2007)	1956-2007	Mass balance and glacier retreat Antisana.	Glacier 15 a and B Antisana	2007 @ 5170m	2007 Negative	Decreased
5	(Bontron et al., 1998)	1956-1998	Glaciological, hydrological, meteorological, and topographic data	Glacier 15 a and B Antisana	1995-5245 m, 1996-5115 m, 1997-5110 m, 1998-5100 m (glacier 15 a)	negative average net balance (1994-1998)	Decreased
6	(Villacís, 2008)	1995-2005	Mass Balance	Glacier 15 a and Los Crespos Antisana	5150 for Glacier 15a and 5110 for Los Crespos	Negative mass balance	Decreased

Table 1. Studies on the glacial retreat of the Antisana glacier based on glaciological data collection

2.2 Specific studies that include surface area data of the Antisana glacier

3. Ecosystem and environmental impacts of the accelerated glacial retreat

3.1 Streamflow makeup from streams in rivers with glacial influence collected over various years

Meta-data of streamflow was compiled from studies monitoring various discharge sites in the glacial catchment from Antisana, all are included in Table 3. The articles that included information about the flow rates of the streams monitored, about 57% cited that there was an increase. One study conducted by Cauvy-Fraunié et al. (2016) studied two stream sites. One they kept as their control and the other they manipulated to mimic lower streamflow, they found that the low-flow stream had more negative impacts on the macroinvertebrate and biotic makeup of that area.

Study #	**Article**	**Date**	**Measurement Type**	**Location**	**Increase**	**Decrease**
1	(Cauvy-Fraunié et al., 2016)	2009-2013	Streamflow Discharge (l/s)	Two streams in the 'Los Crespos' catchment	0	1
2	(Villacís, 2008)	1995-2005	Station Monitoring	Streamflows from Antisana Glacier 15 @, Glacier 12, and Los Crespos	---	---
3	(Herzog et al., 2011)	2008	Habitat Simulation Models	Papallacta in the Antisana Ecological Reserve	1	0
4	(Chevallier et al., 2011)	2008	Glacial Discharge	Basins of Antisana Glacier	1	0
5	(Cauvy-Fraunié et al., 2013)	2000-2010	Wavelet Signals and Streamflow	15 streams belonging to two-glacial fed catchments	0	1

6	(Maisincho et al., 2007)	1999-2007	Streamflow (m^3/s)	Los Crespos and Humboldt Station	---	---
7	(Caceres et al., 2002)	1997-1998	Streamflow (l/s)	Effluent river from Glacier 15	1	0
8	(Favier et al., 2008)	1997-2002 and 1995-2005	Discharge and Precipitation	Glacier 15 of Antisana	0	1
9	(Minaya et al., 2016)	2014	Isotopic and Hydrochemical Samples	The catchment Los Crespos-Humboldt	1	0

Table 2. Meta-data from studies on streamflow collected on subglacial flows and rivers that are in the Antisana glacier catchment. The data was collected from 9 different articles that monitored or took samples from streams. The articles are cited under the 'article' section.

3.2 Macroinvertebrate sampling in streams located in Antisana Ecological Reserve

Compiled data from macroinvertebrate sampling in various streams are shown in Table 2. Two of the studies found that macroinvertebrates in various streams of the Antisana Ecological Reserve have been environmentally filtered to live in these harsh environments (S=4,5). Four of the studies found that an increase in glacial retreat can change the makeup of macroinvertebrate communities (S=1,2,3,5).
All of the studies found a correlation to flora and fauna makeup in stream to percent of glacial catchment. Two of the studies specifically state negative effects associated with a lower percent of glacial influence on the catchment (S=1,3).

Study #	**Article**	**Date**	**Measurement Type**	**Location**	**Glacial Impact on Ecosystem**	**Abundant Species**	**Lost (L) or Fewer (F) Species**	**Percentage of glacial catchment**
1	(Cauvy-Fraunié et al., 2016)	2009-2013	Abiotic and Biotic Monitoring on low flow streams	Two streams in the 'Los Crespos' catchment	-Poorer water quality found -Increase in benthic primary producers	Ceratopogonidae and Empididae	Blephariceridae and Scirtidae (L) Simuliidae (F)	Lower percent= Increase in algae and herbivore mass
2	(Jacobsen et al., 2010)	2008	Sampling benthic macroinvertebrates	9 streams from the 'Crespo' glacier	-Can reduce species turnover (B-diversity) -Reduce species at regional level (y-diversity) -If Tmax exceeds 4 c then stoneflies may be more abundant	Podonominae, most abundant near the glacier. Orthocladiinae abundant all sites	Chironomidae (Diptera) decreased downstream	Taxon richness increased with lower percentage
3	(Jacobsen et al., 2012)	1977, 1986, 1998-1994, 1996-2002, 2004-2007	Collecting macroinvertebrates using Surber nets	49 streams in the Antisana Ecological Reserve	-Leads to extinction on the local and regional scale -Loss of endemic species	---	---	Loss of regional species with lower percentage (<50%)

4	(Jiménez, 2016)	2009-2010	Using biological traits to assess the functional diversity of macroinvertebrates	15 rivers in the Antisana Ecological Reserve	-Found that macroinvertebrates have been environmentally filtered thus adapted to their environment and will be heavily affected by climate change.	Chironomidae	---	-Non-swimming macroinvertebrates have increased with higher glacial influence -Swimming is opposite
5	(Cauvy-Fraunié et al., 2015)	2009-2010	Sampling benthic macroinvertebrates	51 streams in the Ecological Reserve of Antisana	-Glacial melting has an impact on community variation -primary environmental filter	Orthocladiinae	---	Further away (lower percentage) correlates with community variation and specific taxa

Table 3. Meta-data from studies on macroinvertebrates on stream sites in the Antisana Ecological Reserve. There were studies that included streams outside of the glacier catchment but only results were included from streams with glacial influence. This data was collected from articles that are cited under the 'article' section.

4. Water resources for surrounding cities of the Antisana glacier

Meta-data was studied from articles that discussed the water resources of Quito, a nearby city to Antisana, and the impact on increased glacial retreat on the water supply. Seven studies cited the water from Antisana as a large contributor to the fresh-water drinking supply for Quito. Another prevalent use of the water collected from Antisana is for hydropower and irrigation for agriculture. All of the studies examined noted that the retreat of the Antisana glacier will have impacts on the water supply of Quito, each article is specifically stated in Table 4.

Study #	**Article**	**Date**	**Type/Description of Article**	**Activities or Uses Cited**	**Impact**
1	(En El Antisana, Un Glaciar Que Se Derrite En Ecuador, UE Alerta Sobre Cambio Climático, n.d.)	---	News Article	Water resource	-Studies show that the Antisana has an increase in melt that will have significant impacts on the local population of Quito.
2	(Nolivos et al., 2015)	2015	Management of Water Resources	agriculture, industrial mining, and electricity generation	Currently, the usage of water in Quito is not sustainable, especially if the Antisana glacier is retreating
3	(Vuille et al., 2007)	2007	Future climate change and its implications on water resources	Drinking water, water for hydropower production, mining and irrigation	-Glaciers give off more water now but this trend will soon diminish. -The local population may become accustomed to the influx of water. -This will have a large impact on nearby cities, especially since it's mass balance changes year round.

4	(Zambrano-Barragán et al., 2010)	2011	Climate Change Strategy in Quito	Drinking water, hydroelectric power	-The glacier is about 35% of quitos water resource, therefor losing this resource will have larger implications for the water resource for the city of Quito
5	(Herzog et al., 2011)	2011	Climate change in the Tropical Andes	Irrigated agriculture, hydropower, consumption, livestock, energy production, navigation, and fisheries.	-Research shows glacier retreat could alter stream flows and thus threaten local water supply and energy production
6	(Chevallier et al., 2011)	2010	Climate change threats to the Tropical Andes	Water supply and Energy through (Hydropower)	-With climate change temperatures will rise, reducing glaciers area, which alters the flow of glacier fed rivers and impacts water availability for Quito.
7	(Favier et al., 2008)	2008	Hydrological and Glaciological measurements on the Antisana 15 glacier	Hydro-electric production and water supply	-This study states that the Antisana glacier is rapidly diminishing and will eventually have a negative effect on the contribution of glacier melt water to the water resource of Quito.
8	(Villacís, 2008)	2008	Hydrological and Glaciological Monitoring and Measurement of the Antisana 15 and Los Crespos Glacier	Water Resource for the city of Quito	-This study used the A2 scenario to show that there is a huge increase in glacial melt in recent years. -It also noted that this speed of decrease should be taken into account when assessing water resources.

Table 4. Meta-data compiled from 8 studies that discussed glacial retreat of Antisana and its impact on water resources

Analysis

The watershed that was outlined from Landsat imagery in Google Earth Pro clearly shows that there are four main watersheds that the Antisana volcano contributes to (Figure 2). Two major rivers, Papallacta and Rio Quijos, are part of the catchment area of Antisana. This is important because this water flows into larger basins, like the Amazon basin, and the water quality or flow will have further downstream effects. Laguna de Mica also has a large collection of water from Antisana that is channeled to Quito for their storage of water. Precisely about 50% of Quitos water supply is from interbasin transfers from nearby rivers (Urban Water Blueprint—Quito, n.d.).

The data taken from Glovis USGS did not show clear results and had variants within the data. Overall the glacial retreat seemed to represent a trend downwards of overall less glacial coverage in terms of surface area (Figure 7). However there are three outliers in the study. The years between 2001 and 2007 represent a very low glacial coverage compared to the rest of the data collected. In 2002-2004 there were more months that fell into the El Niño seasonand between 2005-2006 the El Niño month still has a higher representation (*NOAA's Climate Prediction Center, n.d.)* .

In order to figure out other factors that could contribute to the difference in surface area measured from 2001-2020 (Glovis overlay) other confounding factors were analyzed. Such as months of imagery taken that coincide with rainy or dry seasons or patterns of ENSO. However, there was no significant correlation between El Niño or the wet season (not included in this dataset because no correlation was found) and the retreat of the Antisana glacier. Since no data from years before 2015 is presented in the graph, the trend of this year has an unclear association with El Niño weather pattern effects on glacial retreat. However, a study conducted by Francou (2004) about the ENSO impact on low-latitude glaciers found that over an 8-year period the mass balance of Antisana was negative during El Niño periods and was around equilibrium during La Niña years.

Other data from Google Earth Pro was also included since each satellite image was taken from the same month of december thus seasonal precipitation patterns would not have an impact on the data collected. The graph had the highest R^2 value of 0.82 when there was a polynomial fit that represents periods of higher rate of ablation or glacial retreat. It can also be noted in around 2010-2015 little variation is seen and the graph is relatively flat. This data more clearly shows that the Antisana glacier has been decreasing over the years and that for these satellite images, taken from 2001-2016, a higher rate of retreat is prevalent. The evidence of glacial retreat of the Antisana glacier is in alignment with other studies that report a decrease in glacier mass balance over recent years (Basantes-Serrano et al., 2016; Rabatel et al., 2013). Since this data did have some small variations, it was also related to ENSO weather patterns to see if that had an impact on any variation. There were significant periods of El Niño and La Niña, however they did not have any correlation with the data presented from Google Earth Pro. Again, this is different from earlier trends seen that the Antisana glacier's mass balance has a higher dependence on ENSO (Francou, 2004).

In addition to the Landsat investigation, meta-data was collected about the mass balance and evolution of the Antisana glacier. There is strong evidence from this meta-data that the Antisana has an average net-balance over the time period 1950-2020. The ELA for the glacier was relatively similar in each study, with a 195 meter difference between the minimum and maximum reported. Also there were a significant amount of studies (83%) reported that there was an overall decrease in glacial coverage.

The meta-data constructed from the streamflow makeup in the Antisana glacier catchment shows insignificant results (Table 2). Many of the articles stated that there will be an increase in streamflow. This is evident from numerous studies that cite an increase in run-off in the future, however once a peak is reached, between the years 2025-2150, the flow will decrease (Chevallier et al., 2011; Favier et al., 2008; Herzog et al., 2011). This could account for the variance in flows and that most glacial tongues are still increasing in discharge. Some glacier tongues like Antisana (15) may also have more of a decrease in streamflow because it extends further than other tongues in the Antisana glacier thus has a different micro-climate that affects the melt (Maisincho et al., 2006).

A majority (80%) of the studies either said that the increased melt from the Antisana glacier on subsequent streams will have an impact on the macroinvertebrate makeup either due to the fact that the species are well adapted to harsh glacial flows, will have more competition, or may not be able to live in the changing water conditions (Table 3). There was a larger impact on the makeup of macroinvertebrates with some studies reporting either and increase or decrease. Usually when there was an increase that included more macroinvertebrates that are adapted to live in less harsh glacial streams (Cauvy-Fraunié et al., 2016). An example of this taxa is Ceratopogonidae and Empididae were seen to increase in one study examined (Table 3). The same study conducted by Cauvy-Fraunié et al. (2016) studied two stream sites.

One they kept as their control and the other they manipulated to mimic lower streamflow, they found that the low-flow stream had more negative impacts on the macroinvertebrate and biotic makeup of that area (Cauvy-Fraunié et al., 2016). This is a good representation of what could happen in the future if all the streams are having an influx in water that will peak and then decrease later on. This study is crucial to our understanding of the impact that an increase run-off will have on the aquatic ecosystem. This is because most studies actually show or say that the glacial melt has increased in the next coming years until it reaches a peak, then it will decrease then cause ramifications for the biota and makeup of streams (Chevallier et al., 2011; Favier et al., 2008; Herzog et al., 2011).

Water resources are vital resources for nearby communities especially Quito that receives some of its water supply from the run-off of Antisana. The meta-data showed that the main use of the water collected is for drinking water, irrigation for agriculture, and a large part for energy created from hydropower (Table 4). The water run-off is said to be increasing which allows the city to become accustomed to a higher level of water to be available. This trend is poor in many ways. One is that this consumption of water is not sustainable because it is expected to decrease drastically in some years (Chevallier et al., 2011). Also, because there is an increase in water, there is less management of the resource, which leads to unsustainable practices (Jean-Christophe et al., 2008). Although it is unknown what the actual implications of having less water available in Quito will be, many studies conclude that the water supply will diminish and it will have negative implications for water resource management for Quito (Table 4).

Conclusion

Summary of Findings

As previously mentioned, other studies that reviewed the Antisana glacier have found an increase in retreat and a higher ELA (Equilibrium Line Altitude). Previous studies show that an increase in air temperature shows that this will cause a huge change in the mass balance and can cause the ELA to increase by 480 to 900 meters (Hernández et al., 2018). However research is still lacking in how glacier retreat is affecting the ecosystem or what negative impacts will occur. Despite being able to conclude anything from this study, there is a strong argument for an increase in glacial melt having negative consequences for the surrounding ecosystem and biota that live in the streams.

There was no direct correlation found in this investigation of precipitation or ENSO weather patterns correlating to the glacial retreat of Antisana. However, there have been other studies that investigated ENSO patterns and have shown that they can have a larger influence on the melting of glaciers (Francou, 2004). Also, various articles mentioned the impact the season wet or dry periods will have on the ablation or accumulation of the Antisana glacier, which leads to variance in surface data collected over the year (Cauvy-Fraunié et al., 2013). Although there may be a lot of evidence of the glacial retreat of Antisana, the data presented in this paper through macroinvertebrate makeup and stream assessments don't come to any conclusions about the effects on the ecosystem.

Limitations to the study

This study was a meta-analysis and an investigation of Landsat satellite imagery. There are some gaps in this study as this meta-analysis does not include a statistical analysis of the results. Although many of the articles may have had similar conclusions about their investigation, it is not known if they are statistically significant to report. Further, there are basic issues with the format of meta-analysis such as publication bias, poor studies could be included, and the compiled data may not be similar. A few of the articles were only written in French and there could be some variation between the article and what was translated.

Landsat imagery was not able to be collected for all the years between 2000-2020. Missing data in imagery is from the year 2002. Also, other issues with Landsat include having blurry and unclear lines of the glacier or lots of cloud coverage. This affected being able to differentiate between the snow and ice and the actual outlines of the glacier. Some Landsat images were on a gray-scale making it more difficult to clearly outline the limits of the glacier. Also, this study, because of its remote sensing format, was only to quantify the surface area of the glacier. The variations in months and days made it more difficult to compare accurately across all of the images collected, however, this was also taken to account in the analysis.

Suggestions for future studies

Future studies should look into the effects that an increase in the glacial retreat will have on subsequent flows. The specific effects they should examine are the flow of streams, turbidity, temperature, and pH and make estimates for what could change. Then they should replicate these changes to see the impact on the ecosystem and environment. Many studies predict that temperatures will increase and the flow of rivers and streams will decrease further into the future (Favier et al., 2008). Another study that was examined also followed a similar procedure and was able to quantify differences between low-flow and normal-flow streams (Cauvy-Fraunié et al., 2016).

It can be strongly suggested that the retreat of the Antisana glacier will have an impact on the water supply for the city of Quito, Ecuador. The Antisana glacier is of high importance due to its location in reference to Quito and is more susceptible to climate change because of the nature of the tropical climate. Heavy monitoring and analysis of the Antisana glacier are crucial in the future for the health of our environment and to help inform policymakers about decisions regarding the water supply in Quito and its reliance on water for the Antisana glacier. One of these issues is more black and white and the other one becomes more complex and globally intertwined. The more simple issue is about the city of Quito and how it needs to think about its water resource and what it can change in the future. On the other hand, the disappearance of Antisana and how it can impact the ecosystem is more difficult because it relies on climate change. Since climate change is a global issue and involves decisions made from people all around the world it is hard to alter this. One article even said that the glacial retreat is non-reversible and it will disappear (*En El Antisana, Un Glaciar Que Se Derrite En Ecuador, UE Alerta Sobre Cambio Climático*, n.d.). If that is the case what then will happen to the unique high Andean paramo or the water supply that Quito so desperately needs?

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[1] Note there is overlap between the two sections.

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