



Thematic focus: Climate change, Ecosystem management, Environmental governance

## Where will the water go? Impacts of accelerated glacier melt in the Tropical Andes

More than 99% of the world's tropical glaciers are located in the Andes Mountains in South America, of which 71% are located in Peru, concentrated on the Cordillera Blanca, and 20% in Bolivia (Kaser, 1999; Rabatel et al., 2013; Bury et al., 2011; IRD et al., 2007). Recent studies have found the glaciers to be melting at an accelerated rate. Though glaciers are melting around the world, in the Tropical Andes the nexus of melting glaciers, dwindling water resources, climate change and a dense population meet (Bradley et al., 2006), creating an urgent need for awareness and management. This bulletin will focus on the impacts of this reported accelerated loss of tropical glaciers to water supplies in Peru as well as broader impacts to the hydrologic cycle, future water supplies and ecosystem status.



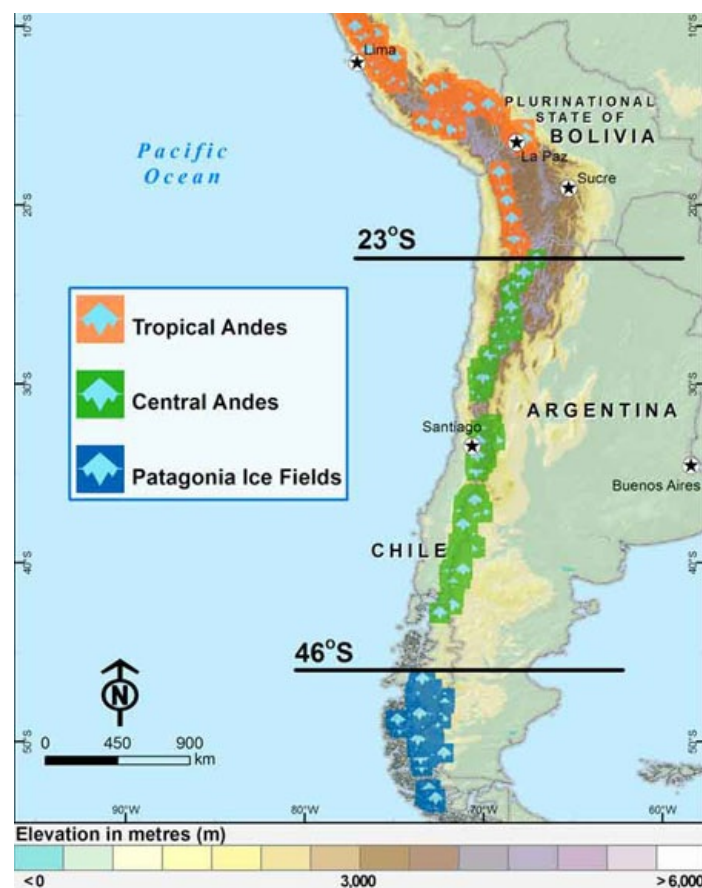
### Why is this issue important?

Glaciers dot the western part of South America and can be divided into three general regions: 1) the Tropical Andes, beginning at the start of the Andes mountain range in western Venezuela and stretching south to 23°S latitude (Vuille and Bradley, 2000); 2) the central Andes in eastern Chile and 3) the Patagonia Ice Fields (North and South) in southernmost Chile and Argentina below 46°S (Glasser et al., 2011) (Figure 1). Glaciers in each region have been reported to be retreating at varying rates and threatened by future climate change (Rabatel et al., 2013; Willis et al., 2012; Nicholson et al., 2009).

More than 80% of freshwater available for downstream populations and ecosystems in the semi-arid tropics and subtropics originates in mountains (Messerli, 2001). Glaciers partly contribute to the water that travels down the western slope of the Andes, supplying coastal regions with water, mostly during the dry season (Chevallier et al., 2011). Where a distinct rainy season occurs only once a year and lasts only a few months, such as in parts of Peru and Bolivia, melting snow and glaciers are a crucial water supply for the dry season (Peduzzi et al., 2010; Kaser, 2001; Rabatel et al., 2013). The dry season generally lasts from May to September (IRD et al., 2007), but may vary slightly according to region and year.

A recent overview of the findings of many studies conducted in recent decades (Rabatel et al., 2013) reports that glacier loss in the Tropical Andes has accelerated over the past three decades and now is occurring at an unprecedented rate. This loss has already had some ecological and social effects and could lead to the disappearance of some glaciers, especially those in lower elevations (Bradley et al., 2006; Urrutia and Vuille, 2009).





**Figure 1:** Glaciers of South America. Source: Glacier location data from WGMS, 2012; Rabatel et al., 2013; Digital Elevation Model (DEM) from: USGS-EROS, 1996; visualisation by UNEP/GRID-Sioux Falls

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## What are the findings?

### Current trends

Each country in the Tropical Andes has experienced significant decreases in glacier area and mass balance (See Box 1). Locations of features mentioned are shown in Figure 2.

- Venezuela has the smallest area of glacier coverage of any country in the Tropical Andes. In 1952, glaciers covered an area of 3 km<sup>2</sup>, spanning four peaks, but by 2003 only one peak, Humboldt, had glacier cover remaining (about 1 km<sup>2</sup>) (Azancot, 2010).
- Between the 1950s and the mid-2000s, 51% of glacier coverage in Colombia was lost, with the greatest loss occurring between the late 1990s and mid-2000s. In just the five years from 2002 to 2007, the total amount of glacier area shrunk from 60 km<sup>2</sup> to less than 45 km<sup>2</sup>, with some regional differences in pace and magnitude of retreat (Poveda and Pineda, 2009). Approximately 30% of glacier surface area on Nevado del Huila was lost in just two years due to volcanic eruptions in 2007 and 2008 (Rabatel et al., 2013). Four of Colombia's six remaining glaciers are on volcanoes, which can increase the pace of glacier loss (Rabatel et al., 2013; Poveda and Pineda, 2009). Poveda and Pineda (2009) project that all Colombian glaciers will disappear within the 2010-2020 decade.
- Some glaciers in Ecuador are also located on volcanoes. The Antisana glaciers (12 and 15) experienced a period of rapid retreat between 1995 and 1999, followed by a short period of advance from 1999 to 2001 (Vuille et al., 2008) and another year of advance, in which a few metres were gained, in 2008 (Rabatel et al., 2013), but since then, Antisana glaciers have begun to retreat again (Vuille et al., 2008).
- Most of the world's tropical glaciers are concentrated along the Cordillera Blanca in Peru (Bury et al., 2011). The Cordillera Blanca alone lost about 200 km<sup>2</sup> in glacier surface area from 1980 to 2006, going from 742.8 km<sup>2</sup> to a little more than 500 km<sup>2</sup> (Ordoñez et al., 2010). The glacier on Nevado Coropuna, south of the Cordillera Blanca, has decreased at least 60% in surface area since 1955. If it continues to decline at the current rate, it may disappear before 2045, although continued studies on ice thickness and volume are needed (Peduzzi et al., 2010). Across all glaciers on the Andes in Peru, the rate of glacier mass balance loss between 1964 and 1975 was 0.2 m water equivalent per year (w.e./yr) and between 1976 and 2010, the rate accelerated to a loss of 0.76 m w.e./yr (Rabatel et al., 2013).
- There was a 48% decline in surface area of 376 glaciers investigated in the Cordillera Real in Bolivia from 1975 to 2006 (Soruco et al., 2009); the glacier Chacaltaya completely disappeared in 2009

(WGMS, 2011).



**Figure 2:** Locations of physical features prominent in the discussion of glaciers in the Tropical Andes. Source: Glacier location data from WGMS, 2012; Rabatel et al., 2013; DEM from: USGS-EROS, 1996; visualisation by UNEP/GRID-Sioux Falls.

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## Causes of melting

Glaciers located in different regions have varying rates of melt and accumulation due to geographic factors such as latitude and elevation and atmospheric factors such as albedo and climate. Detailed discussion of melting dynamics is outside the scope of this bulletin, but can be found in Mark and Seltzer (2003), Rabatel et al. (2013), and Chevallier et al. (2011) among others. A basic discussion is presented below and definitions of glacier terminology are explained in Box 1.

### Box 1. Glacier terminology

**Accumulation** occurs when snowfall exceeds melting  
**Ablation** occurs when snow or ice is lost through evaporation and/or melting  
**Mass Balance** is the net profit or net loss of snow and ice  
**Equilibrium Line** exists where mass accumulation equals mass loss; it separates the accumulation zone from the ablation zone  
 Source: USGS, 2007

Melt water is produced only during above-freezing temperatures over the lowest glacier point (tongue) and storage increases only when there is precipitation over the accumulation zone (Kaser et al., 2010). Changes in glaciers due to melting can be described in four ways (Rabatel et al., 2013; Mark and McKenzie, 2007; Peduzzi et al., 2010; Huh et al., 2012; IRD et al., 2007):

1. Length, measured by changes in the location of the glacier tongue (where it terminates)
2. Mass balance, expressed through loss or gain in water equivalent (such as mm of w.e./yr)
3. Volume, expressed through cubic measurements, such as km<sup>3</sup>, and measured using remote sensing techniques or snow stakes

#### 4. Surface area, typically measured using remote sensing techniques or aerial photographs

Rabatel et al. (2013) report a trend among glacial melt for selected glaciers between Colombia and Bolivia with extended mass balance time series in the Tropical Andes. They observed that over the past 35 years, glaciers with a maximum elevation of 5,400 m above sea level (a.s.l.) or more have been losing mass balance at a rate of 0.6 m w.e./yr, while those at elevations below 5,400 m have been losing volume at a rate of 1.2 m w.e./yr. This trend may occur because lower elevations are exposed to ablation more than glaciers at higher elevations, which are able to maintain a permanent accumulation zone (Rabatel et al., 2013). Smaller glaciers at low elevations, without a permanent accumulation zone, have also been retreating at a pronounced rate and could soon disappear completely (Rabatel et al., 2013; Vuille et al., 2008).

#### Impacts of continued melting

Mountain glaciers serve as a crucial buffer as they help to provide water (as melt water) when rainfall is minimal or nonexistent (Vuille et al., 2008), such as during the dry season or during drought conditions. This implies that some melting is necessary to fuel the existing hydrologic processes and fulfil consumption needs. However, an accelerated rate of melting will bring a short-term surge in supply that could create an unsustainable dependency (Vuille, 2013), degrade seasonal capacity (Bury et al. 2011), increase risk of hazards such as landslides, massive flood events referred to as glacial lake outburst floods (GLOFs) (see Box 2) and avalanches (Chevallier et al., 2011; Chisolm et al., 2012) and alter ecosystems (Rabatel et al., 2013). Reduction in glacier size can and will affect availability of water downstream (Vuille et al., 2008). For example, glacier retreat in the area surrounding the Shallap, Tararhua and Uruashraju glaciers along the Cordillera Blanca could lead to a 30% decrease in average dry season discharge (Baraer et al., 2012).

Glaciers supply water to the countries of the Tropical Andes in varying quantities, creating an uneven distribution of potential impact and result in an even larger disparity in the distribution of water resources in the region (Chevallier et al., 2011). Currently, the Antisana glaciers (12 and 15) supply approximately 5% of potable water to the capital city of Quito, Ecuador (Moreno, 2010). About 24% of flow source for the Humboldt and Crespo rivers comes from the Antisana 15 glaciers (UNEP, 2011). In Bolivia, glaciers of the southern Cordillera Real supply approximately 15% of potable water for the urban areas of La Paz and El Alto and can increase to approximately 30% during the dry season from May to August (Soruco, 2012). The World Bank (2008) reports that the volume of glaciers that Peru has already experienced is equivalent to about 10 years of water supply for Lima, Peru's capital of more than 9 million people (UN, 2012), an estimated 7 billion m<sup>3</sup> of water. In addition to water supplies for big cities such as Lima and La Paz, glacier melt water also contributes to the water supply for rural settlements (Poveda and Pineda, 2009). For example, melt water from the Coropuna glacier in Peru directly supplies approximately 8,000 people with water and indirectly supports 30,000 people (Peduzzi et al., 2010). Stern (2006) estimates that a 1°C temperature increase could cause smaller glaciers to disappear, affecting the water supply of almost 50 million across the Andes.

Loss of glacier cover and eventual reduction in runoff volume has a significant impact on unique ecosystems such as high-altitude *paramos*, and cloud forests (Bury et al., 2013; Poveda and Pineda, 2009). For many small towns and villages along the Andes, including the Colombian capital of Bogotá, *paramos* provide a source of potable water (Poveda and Pineda, 2009). Wetlands that cannot continue to be sustained risk increasing fragmentation of biodiversity, already observed in the Quilcayhuanca Valley in Peru (Bury et al., 2013). Additionally, survival of regional and endemic species could be at risk if glacier loss altered the hydrologic system. Based on a study of glacier-fed catchments in the Ecuadorian Andes, Jacobsen et al. (2012) estimate that 11% of regional and endemic species could be lost if glaciers were to disappear and there would also be noticeable loss in species richness downstream.

The hydropower industry will also feel the residual effects of melting glaciers such as reduced streamflow, which could result in decreased efficiency and energy output. Since hydropower accounts for approximately 71% of electricity generation in Colombia, 49% in Ecuador, 32% in Bolivia and 56% of energy in Peru (World Bank, 2010), maintaining the integrity of the industry is important for the people of the Tropical Andes. While glacier melt water does not supply all the water needed for hydropower, it does have some impact. Vergara et al. (2007) derived an estimate for the impact of the reduction of glacial melt water on the power generation capacity of the Cañon del Pato hydropower plant on the Rio Santa in Peru. They conclude that a 50% reduction in glacier runoff would result in a decrease in annual power output of approximately 10% (from 1540 GWh (gigawatt hours) to 1250 GWh). Further, if glacier melt water disappeared completely, annual power output would be reduced to 970 GWh. Additional regional impact studies are needed to determine the localised impact and potential for future impact of reduced flow to rivers that are used for hydropower.

Additional research is needed to quantify the impact future glacier loss will have on the environment and human populations more precisely so that appropriate and effective adaptation and water management strategies can be developed. A challenge in the data analysis process is that some glaciers have been closely



monitored for only a few decades, using data with varying degrees of resolution and accuracy, and many missing years of data in between.

### **Agglacier gone: Chacaltaya, Cordillera Real, Bolivia**



A Pacific climate shift from 1976 most likely contributed to the accelerated retreat of Chacaltaya (Francou et al., 2003). Figure 3 shows the decline of Chacaltaya from the Little Ice Age to 2006. In 2005, it was estimated that only 5% of its surface area and 0.6% of its volume remained, as compared with records from 1740 (IRD et al., 2007). Chacaltaya completely disappeared in 2009 (WGMS, 2011), a few years before scientists predicted that it would (Francou et al., 2003; Mark and Seltzer, 2003).

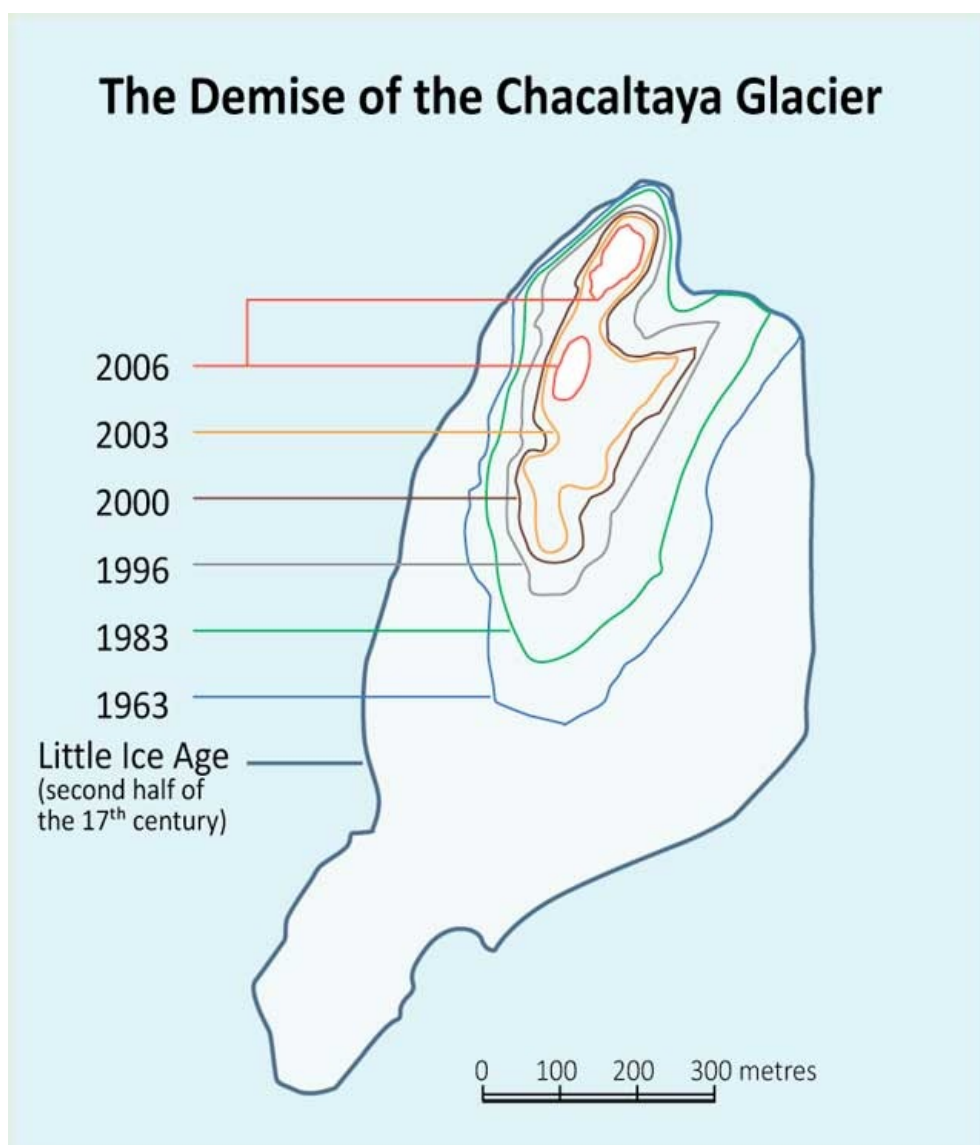


Figure 3: Changes in size of the Chacaltaya Glacier. Source: adapted from UNEP/GRID-Arendal, 2010; IRD, et al., 2007).

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### **Impacts of glacier loss on the watersheds of the Cordillera Blanca, Peru**

*Hazard potential in the Paron watershed*





The Paron watershed, which contains the Artesonraju glacier, has experienced a loss of more than 30% of its glacier surface area since 1930. Glacier coverage in the watershed increased slightly between 1990 and 1997. However, coverage has decreased ever since (Baraer et al., 2012).



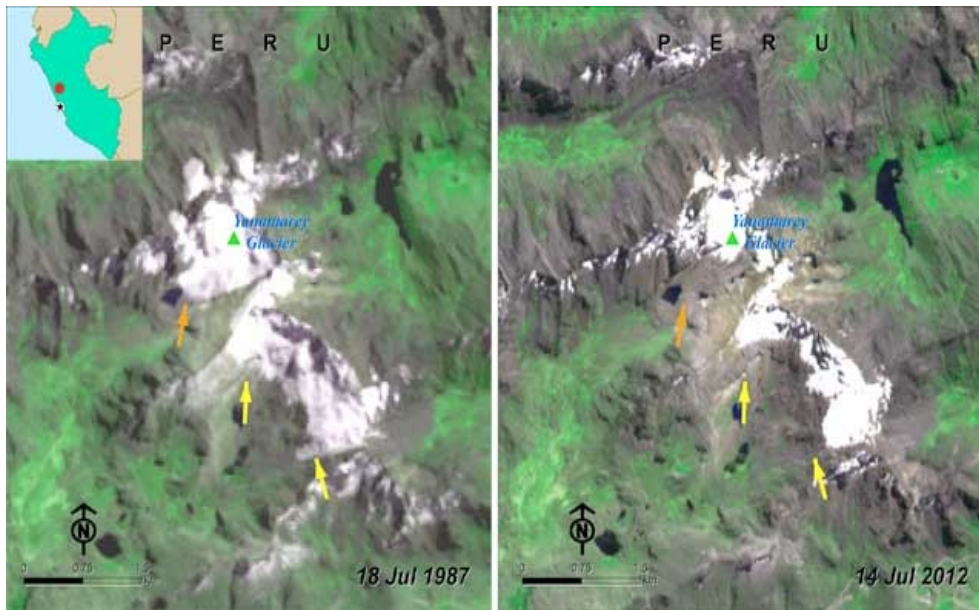
Figure 4: Artesonraju glacier; Source: Landsat, visualisation by UNEP/GRID-Sioux Falls

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The Artesonraju glacier has been losing mass balance at an average of 0.6 m w.e./yr over the past 40 years (Rabatel et al., 2013). Retreat of Artesonraju and the neighboring Artesoncocha glaciers has resulted in the formation of a new highland lake (denoted with a yellow arrow in Figure 4) that is characterised by overhanging ice and loose rocks, making the area vulnerable to landslides. In addition, the new lake sits above two previously formed lakes, including Lake Parón, the largest lake in the Cordillera Blanca. This positioning poses a threat for a catastrophic GLOF event should an avalanche or landslide, triggered by additional melting into the new lake, occur (Chisolm et al., 2012).



Using satellite image analysis, Huh et al. (2012) found that the surface area of Yanamarey decreased 85% between 1962 and 2008. Mark et al. (2010) predict that it will completely disappear by 2020. In addition to retreating, it has also thinned, causing it to lose more than 88% of its volume (Huh et al., 2012) and decreasing its seasonal storage capacity (Bury et al., 2011). Yanamarey lies within the Querococha sub-watershed of the Rio Santa watershed, which has lost more than half of its glacier-covered area since 1948 (Baraer et al., 2012). The orange arrow in Figure 5 indicates where Yanamarey has retreated and yellow arrows point to noticeable changes in snow and ice cover from 1987 to 2012 in smaller surrounding glaciers. Melt water from Yanamarey contributes 100% of the streamflow to its watershed during the dry season (June to September) in its immediate watershed and proportionately less downstream – ~24% to more than 50% depending on year and season (Bury et al., 2011) – so continued loss and eventual disappearance will have a significant impact on the hydrologic scheme of the area as well as the associated ecosystems and human populations.



**Figure 5:** Satellite images showing changes in the Yanamarey glacier. Source: 1987 image: Landsat, 2012 image: ASTER, visualisation by UNEP/GRID-Sioux Falls

[Full Size Image](#)

### What are the implications for policy?

The disappearance of small glaciers is pronounced and happening on a shorter time scale (Rabatel et al., 2013), making it an important issue for water managers, decision- and policy-makers now. It also presents a pressing supply issue. Decreased water supplies caused by the disappearance of smaller glaciers that contribute melt water will also likely result in increased competition for use and governance among hydropower companies, municipalities and agricultural stakeholders, as well as competition for governance and water rights (Vuille et al., 2013; Bury et al., 2013).

### Climate change modelling and policy-making

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