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Seasonal glacial meltwater contributions to surface water in the Bolivian Andes: A case study using environmental tracers

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ABSTRACT

Study region: The Cordoriri watershed and vicinity in the Cordillera Real, Bolivia, South America
Study focus: Recent warming has contributed to substantial reductions in glaciers in many regions around the globe. Melting of these glaciers alters the timing and magnitude of streamflows and diminishes water resources accumulated in past climates. These changes are especially acute in regions with small glaciers and problematic for populations relying on surface water. In Bolivia, most glaciers are less than 0.5 km^2 and about 2 million people draw water in part from glacier-fed watersheds. Sparse monitoring, however, has limited estimates of glacial meltwater contributions. The use of environmental tracers is one approach that can quantify the contributions of glaciers. We present isotopic and anion data for streams, reservoirs, arroyos, precipitation, and glaciers for the wet and dry seasons in 2010, 2011, and 2012.
New hydrological insights for the region: Glacier meltwater data shows distinct seasonal isotopic values, presenting opportunities for end-member mixing analyses. From isotopes, we estimate 31–65% of the water measured in high altitude streams and reservoirs during the 2011 wet season originated from melting of ice and recent snow, while glacier ice contributed 39–71% of the water in reservoirs in the 2012 dry season. This study demonstrates that more comprehensive sampling in the region could quantify the contributions of glacial meltwater and nonglacial sources to surface water supplies.

1. Introduction

Warming temperatures in recent decades have contributed to substantial decreases in the size of glaciers in many mountain regions, including in the South American Andes (Bradley et al., 2006; Vuille et al., 2008; WGMS, 2009; Rabatel et al., 2013). For instance, glacier area declined by 27% between the 1960s and 2000s in Peru's Cordillera Blanca (Rabatel et al., 2013), while glacier volume decreased by about 43% between 1963 and 2006 in Bolivia's Cordillera Real (Soruco et al., 2009). These glacial changes are altering the timing and magnitude of seasonal streamflows (Mark and Seltzer, 2003), which have implications for tourism, agriculture, hydroelectric power generation, and water supply (Vergara et al., 2007).

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In the Andes, large regional populations obtain water from glacier-fed sources, underscoring the importance of glacial meltwater to surface water supplies. It was estimated that more than half of the Peruvian population may be affected by future changes in glacial meltwater (Magrin et al., 2007). Similarly, major Bolivian cities are vulnerable to changes in glacial meltwater. More than 80% of the municipal water for the city of El Alto originates from reservoirs within glaciated watersheds and the adjacent city of La Paz also obtains a large fraction of their water from these reservoirs (Painter, 2007). Consequently, around 2 million people living in these cities are at least partially dependent on a vulnerable water resource.

To quantify the vulnerability of Bolivian waters supplies to changes in glaciers, two recent studies estimated glacier meltwater contributions. Kinouchi et al. (2013) assessed a small watershed using a temperature index model. They concluded glacial meltwater contributes 24% to total annual discharge. Soruco et al. (2015) estimated seasonal glacier runoff using a water balance model for four major watersheds in the region. They concluded that glaciers contributed 15% of the water resources at an annual timescale, while contributions during the wet and dry season were, on average, 14% and 27%, respectively. These recent studies represent an important step forward. However, these approaches are limited by requirements for meteorological data and discharge data in order to calibrate and verify models, data that is often lacking in remote areas and in developing nations.

Environmental tracers such as stable isotopes have been widely used to estimate water balance components (e.g. He et al., 2001; Mark and Seltzer 2003; Mark et al., 2005; Mark and McKenzie 2007; Liu et al., 2008; Baraer et al., 2009; Burns et al., 2011; Cable et al., 2011; Kong and Pang 2012; Frenierre and Mark 2014). An advantage of environmental tracers is they enable quantifying water source contributions in mixing analyses that do not rely on other detailed meteorological measurements. While there can be challenges to generating realistic mixing model results (e.g. Rice and Hornberger 1998; Liu et al., 2004; Barthold et al., 2011), this approach is suited for remote and inadequately monitored regions, like Bolivia.

The Bolivian Andes has a large elevation gradient that causes precipitation to have different isotopic values depending on the elevation in which it falls. Additionally, the region has distinct wet and dry periods that enable quantifying the contributions of the different water balance components at the seasonal timescale. While this setting suggests that environmental tracers could be effective at quantifying water balance components, they have not been applied in the region.

We therefore assess the applicability of using environmental tracers in end-member mixing models. We combine published geochemical data from several sources and stable isotopic and major anion data we collected. We report hydrogen and oxygen isotope and major anion chemistry for water samples from within and near the remote and difficult to access Condoriri watershed in the Bolivian Andes. This watershed contains several small glaciers that contribute water to the largest reservoir in the region. We estimated relative seasonal glacial and nonglacial contributions to surface water.

2. Study area and regional context

The Condoriri watershed is located about 30 km north of the adjacent cities La Paz and El Alto near 16.5° S latitude on the western side of the Cordillera Real, Bolivia (Fig. 1). The Cordillera Real is the eastern margin of the Bolivian Altiplano, a large intermountain plateau with an average elevation of about 3800 m above sea level (masl). Numerous mountain peaks in the Bolivian Cordillera Real crest 6000 m, with the highest peak in the Condoriri watershed reaching about 5700 m. At high elevations in and around the Condoriri watershed, streams flow over shallow glacial and fluvial deposits overlying metamorphic and igneous rocks that contain sulfide minerals (Salvarredy-Aranguren et al., 2008). Outside the stream channels, the terrain is steep and rocky, soils are shallow, and vegetation is limited to small shrubs and grasses. Many streams flow into small alpine lakes and/or reservoirs.

There is distinct precipitation seasonality in the Bolivian Andes (Fig. 2). During the wet season between October–March period (austral summer), easterly winds at the surface and aloft transport moisture is transported from the continental lowlands into the Altiplano (Vuille et al., 1998). In contrast, during the dry season between the April–September period (austral winter), the easterly winds are restricted to north of 10° S latitude and westerly flow dominates to the South (Vuille, 1999). Consequently, about 83% of the annual precipitation measured in La Paz falls during the wet season, an amount that is similar to other areas on the Altiplano (Garreaud et al., 2003). During this time, rain occurs in the Condoriri watershed up to altitudes occupied the glacier, depending on the freezing line elevation of the storm. Rain can occur in the region during the dry season, usually in July and August, although these events are rare (Vuille, 1999).

Approximately 20% of the world's tropical alpine glaciers are located in Bolivia (Kaser, 1999), and about 80% of these have an areal extent of less than 0.5 km^2 (Francou et al., 2000). An assessment of a clear sky ASTER satellite image from June 2004 shows 9 separate glaciers in the Condoriri Watershed with the largest approximately 1.7 km^2 (Fig. 1). Bolivian glaciers experience year-round ablation, with wet season melting markedly higher than during the dry season (Kaser and Georges 1999; Wagnon et al., 1999; Sicart et al., 2005). In the early stages of the wet season (November–December), elevated solar radiation and low glacial albedo (which can persist from the dry season if precipitation is low) can cause high glacier melt (Ribstein et al., 1995; Wagnon et al., 2001; Sicart et al., 2011). As the wet season progresses, snow accumulation increases albedo, but long-wave radiation emitted from clouds helps maintain melt (e.g. Sicart et al., 2005). During the dry season, melt is reduced mainly because of a deficit in long-wave radiation as a result of low emissivity of the thin, cloudless atmosphere at high altitudes (Rabatel et al., 2013).

Bolivian glaciers have been retreating in recent decades and have experienced accelerated recession most notably since 1980 (Ramirez et al., 2001; Rabatel et al., 2006; Rabatel et al., 2013). Soruco et al. (2009) estimated the total volume of 376 glaciers in the Cordillera Real declined by 43% between 1963 and 2006.