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Invited review

Classification of debris-covered glaciers and rock glaciers in the Andes of central Chile

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ABSTRACT

In the Dry Andes of Chile (17 to 35° S), debris-covered glaciers and rock glaciers are differentiated from *true* glaciers based on the percentage of surface debris cover, thickness of surface debris, and ice content. Internal ice is preserved by an insulating cover of thick debris, which acts as a storage reservoir to release water during the summer and early fall. These landforms are more numerous than glaciers in the central Andes; however, the existing legislation only recognizes uncovered or semicovered glaciers as a water resource. Glaciers, debris-covered glaciers, and rock glaciers are being altered or removed by mining operations to extract valuable minerals from the mountains. In addition, agricultural expansion and population growth in this region have placed additional demands on water resources. In a warmer climate, as glaciers recede and seasonal water availability becomes condensed over the course of a snowmelt season, rock glaciers and debris-covered glaciers contribute a larger component of base flow to rivers and streams. As a result, identifying and locating these features to implement sustainable regional planning for water resources is important.

The objective of this study is to develop a classification system to identify debris-covered glaciers and rock glaciers based on the interpretation of satellite imagery and aerial photographs. The classification system is linked to field observations and measurements of ice content. Debris-covered glaciers have three subclasses: surface coverage of semi (class 1) and fully covered (class 2) glaciers differentiates the first two forms, whereas debris thickness is critical for class 3 when glaciers become buried with more than 3 m of surface debris. Based on field observations, the amount of ice decreases from more than 85%, to 65–85%, to 45–65% for semi, fully, and buried debris-covered glaciers, respectively. Rock glaciers are characterized by three stages. Class 4 rock glaciers have pronounced transverse ridges and furrows that arch across the surface, which indicates flow produced via ice. Class 5 rock glaciers have ridges and furrows that appear linear in the direction of flow, indicating reduced flow from limited internal ice; and class 6 rock glaciers have subdued surface topography because the movement of the rock glacier has ceased. Ice content decreases from 25–45%, to 10–25%, to < 10% from class 4 to 6, respectively. Examples from digital imagery, aerial photographs, and field photographs are provided for each class. The classification scheme can be used to identify and map debris-covered glaciers and rock glaciers to create an inventory. This will help improve recognition of these landforms as an important water resource in the dry Andes of Chile, which will aid in sustainable planning and development in basins that hold the majority of the population and support a large share of the economic activity in Chile.

Contents

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1. Introduction

1.1. The uneven distribution of water resources

According to conventional standards, an average annual water availability of 1700 m^3/y/person is the threshold for a country to meet all of its hydrological demands. A condition of *water scarcity* occurs when water availability falls below 1000 m^3/y/person; when water availability reaches below 500 m^3/y/person, it is said to represent a condition of *absolute scarcity* (UNDP, 2006). Chile has an impressive per capita annual average of 60,000 m^3 of water availability; however, the geographical distribution of natural water availability is highly uneven (Fig. 1). The population in the northern half of the country lives under conditions of water scarcity, where water availability is <1000 m^3/y/person (Dirección General de Aguas, 1996; Universidad de Chile, 2010). The northern macro-region (17 to 34° S) covers only 50% of the total area of the country, but it contains about 74% of the total population (17 million people) and 85% of the Gross Domestic Product (GDP). In addition, the northern region is arid, yet contains the most important and most water-dependent economic activities, such as agriculture, mining, and industry (Universidad de Chile, 2010). With a population of 6 million people (about 36% of the total population of Chile), Santiago has an average water availability of 820 m^3/y/person.

Since the 1990s, sustained economic growth in Chile has been based on mining and agricultural exports, which has placed increased pressure on natural resources (Universidad de Chile, 2010). Freshwater has been impacted by the rising demand of a growing economy. About 70% of 17 million inhabitants obtain their water supply from the high Andean basins; economic activities are dependent on the same basins (Universidad de Chile, 2010). Recent mining expansion in the Andes has also placed an additional pressure on water resources and communities by increasing competition for this critical resource (Oyarzún and Oyarzún, 2011; Valdés-Pineda et al., 2014). The arid northern and semiarid central regions of the country have also been experiencing water scarcity because of higher demand and prolonged droughts (Programa Chile Sustentable, 2004). The climate of the semiarid zone has a large annual variability of precipitation (>48%), and it is prone to one drought per decade, lasting between 3 and 6 years. Precipitation during the twentieth century decreased between 40 and 50%, while agriculture and mining have expanded substantially (Ferrando, 2002). Only about 66% of domestic wastewater is treated, whereas the rest is discharged into rivers and the ocean. About 20% of the industries treat their residual waters (Universidad de Chile, 2006). In the northern region, consumptive water use and nonconsumptive water use currently exceed the available natural surface flow; therefore, the unmet demand is satisfied by the overexploitation of aquifers. Available supplies cannot meet the increasing demand, which has resulted in water scarcity and water conflicts (Larraín and Poo, 2010). This problem will become more important in the future because of global climate change: average temperatures are expected to increase, whereas available water is expected to decrease (Universidad de Chile, 2006). Between 1933 and 1992, warming rates at 33° S have been about 2 °C/decade (Rosenblüth et al., 1997). In the northern region, climate models show a projected temperature increase of 1 to 3.0 °C and a decrease in total precipitation of 10 to 25% in the next 90 years (Universidad de Chile, 2006). In central Chile, this would likely result in an increase in future runoff generation from increased melting of snow and glaciers; in the long-term, this will lead to water scarcity and decreased runoff during the summer months (Corripio et al., 2008). Accelerated water use for economic development and a growing population as well as depleted and contaminated water resources associated with climate change are important challenges for water policy in Chile.

1.2. Historical study of glaciers in the Dry Andes

The Andes are an important component of the geography of Chile; however, glaciers have only recently been systematically investigated. The majority of glaciological studies have been performed on clean-ice glaciers, often referred to as *true* glaciers, whereas less is known about debris-covered glaciers and rock glaciers. In the 1950s, Louis Lliboutry (1956) published the first comprehensive glaciological study of the central and Patagonian Andes, which provided a conceptual framework to help establish the discipline in Chile. Lliboutry (1961, 1986) mentioned the widespread existence of valley glaciers in the central Andes that had a top debris cover and discussed the evolution into rock glaciers.

During the 1960s and 1970s, Borde (1966) and Paskoff (1970) noted an abundance of rock glaciers in the western Andes, describing them as a manifestation of permafrost in the high mountain terrain. Paskoff (1970) found that solar insolation played a significant role in the distribution, with rock glaciers occurring more frequently on southern exposures. During this time, Corte (1976a,b) made the same inference for the