Characterization of the Groundwater Storage Systems of South-Central Chile: An Approach Based on Recession Flow Analysis

Víctor Parra 1,2,*, José Luis Arumí 1,2,*, Enrique Muñoz 3,4 and Jerónimo Paredes 1

1 Department of Water Resources, Universidad de Concepción, Chillán 3812120, Chile; jarumi@udec.cl (J.L.A.); jparede@udec.cl (J.P.)
2 Centro Fon MAP CRHIAM, Concepción 4070411, Chile
3 Department of Civil Engineering, Universidad Católica de la Santísima Concepción 4090541, Chile; emunozo@ucsc.cl
4 Centro de Investigación en Biodiversidad y Ambientes Sustentables CIBAS, Concepción 4090541, Chile

* Correspondence: vmparra@ing.ucsc.cl; Tel.: +56-41-234-5355

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Abstract: Groundwater storage and discharge are important processes that have not yet been sufficiently studied in some parts of Chile. Additionally, in watersheds without snow cover or glaciers, groundwater storage and release are the main sources of minimum flow generation; therefore, improvements are required to characterize this process. This study aimed to use recession flow analysis to link groundwater storage depletion to the predominant geological characteristics of each watershed in order to improve our understanding of the groundwater storage-release process in 24 watersheds in south-central Chile. The results allowed different groundwater storage behaviors associated with different geological characteristics to be identified, making recession flow analysis a valuable tool for improving the representation and conceptualization of this process in order to advance toward better minimum flow predictions.

Keywords: geology; recession flow analysis; groundwater storage

1. Introduction

Mountain watersheds tend to be dominated by snowmelt or occasionally glacier melt, which are often the main sources of water in adjacent low-lying areas [1]. However, in watersheds without snow cover or glaciers, groundwater storage and release make up the main source of minimum flow (or baseflow) generation, making it an important process in the hydrological system of a watershed [2], and its contribution to river streamflows proves fundamental to meeting the water demands of various economic activities in periods of water scarcity. Therefore, improvements are necessary to characterize the low-flow behavior of rivers for the joint management of water use, water quality management, and ecosystem services [3].

The descending flow of rivers in rainless periods is known as the recession flow. These flows are directly related to the groundwater storage of the watershed; therefore, the groundwater storage and discharge process can be studied through flow measurements during the recession period [4]. Brutsaert and Nieber [5], using recession-period flow data, proposed an analysis method (the recession flow analysis method) to indirectly estimate watershed-scale hydraulic parameters [6] based on the Boussinesq equation, which describes the drainage process of an ideal aquifer. Put simply, the analysis consists of plotting the average recession flow discharge (Q) as a function of the rate of change in discharge (dQ/dt) in log-log space. This allows different recession events to be identified,
producing a data cloud that permits different recession regimes to be identified in order to indirectly obtain the hydraulic parameters of the aquifer [6]. However, recent literature has shown that the method can be applied more broadly [7]. For example, Brutsaert [8] showed that flow records can be used to characterize groundwater storage and release processes in a watershed. The author developed a methodology to quantify the variability of long-term groundwater storage using recession flows. Kirchner [9], using the recession flow method, developed a methodology to quantify dynamic groundwater storage, with which the watershed can be represented as a simple dynamic system. The methodology described by the author allows estimates of the dynamic storage of the basin and recession times to be obtained. Ajami et al. [10] used recession flow analysis in the Sabino Creek catchment (United States), which has a fractured rock influence, to derive groundwater storage-release relationships in order to estimate changes in storage to quantify mountain block recharge (MBR) rates. Shaw and Riha [7] applied the recession analysis approach of [5] considering individual events in seven basins in the United States. The authors suggest that individual analysis of recession events can be a valuable tool to obtain information on watershed-scale hydrological processes and can justify alternatives to current low-flow models. According to the literature cited, recession flow data contain information on the dynamic behavior of groundwater storage and release [8–10]; thus, these data can represent the rate at which the groundwater storage is depleting (groundwater storage behaviors) and in turn different storage structures. Therefore, the behavior of recession flow data can be associated with the predominant geological characteristics of watersheds to provide a better understanding of hydrological processes in order to improve the structure of hydrological models.

There are various mountain watersheds in Chile with fractured geology (e.g., the watershed system associated with the Chillán volcanic complex), [11–13], as well as mountain watersheds with mixed geology [14]. In addition, due to the formation of the country, the Central Valley presents a higher proportion of geological sequences of sedimentary origin [14]; therefore, the watersheds located in this area and mountain watersheds should present different storage behaviors. Thus, the objective of this study is to identify and characterize the behavior of groundwater storage systems in watersheds with different geological characteristics using recession flow analysis to improve our understanding of the groundwater storage-release process.

2. Methods

To study the groundwater storage behavior in the watersheds the recession flow analysis method described in Brutsaert and Nieber [5] was used. Then, to complement the analysis the identified behaviors were linked to the geological characteristics of each watershed.

2.1. Study Area and Hydrometeorological Data

The study area comprises of 24 watersheds located in south-central Chile between latitudes 35° and 41° S (Figure 1), 16 of which are located in the Andes Mountains (AM), 6 in the Central Valley (CV), and 2 in the Coastal Range (CR). The watershed areas range between 123 and 5688 km² (see Table 1). Watersheds without anthropogenic alterations or with minimal alterations were selected in order to discard anthropogenic effects on the analysis.

In general, the selected watersheds in the central zone present a Mediterranean climate (latitudes ~35–36° S), while those farther south (latitudes ~37–41° S) present a wet climate [15]. In addition, they present a hydrological regime dominated by precipitation in winter and high precipitation variability, with annual averages from 700 to 4000 mm [13,15,16]. Table 1 provides a summary of the geological formations present in each watershed. In accord with the classification carried out by SERNAGEOMIN [14], the geological formations are classified as sedimentary sequences (SS), volcano-sedimentary sequences (SVS), volcanic sequences (VS) and, to a lesser extent, formations associated with intrusive (IF) and metamorphic rocks (MF). These formations consist mainly of alluvial, colluvial, and mass removal deposits, moraine, fluvio-glacial, and glaciolacustrine deposits (SS), basaltic to dacitic lavas, epiclastic and pyroclastic rocks (SVS), pyroclastic deposits, mainly rhyolitic, associated