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Recession flow analysis as a suitable tool for hydrogeological parameter determination in steep, arid basins

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ABSTRACT

The analysis of baseflow recession of streamflow has been widely used in the evaluation of basin scale parameters because the required data are inexpensive to acquire, and the method is easy to use and generally gives good results. A literature review, however, shows that few studies have examined the applicability of recession methods to arid basins, particularly those set in mountainous landscapes. In this study, we apply a recession method that uses a non-dimensional theoretical curve matching technique to evaluate basin-wide, spatially-averaged hydraulic parameters for several watersheds (Culebrón, Punitaqui, Valle Hermoso, Hurtado, Chalinga, and Camisas), taking as case of study the Coquimbo Region, an arid, mountainous territory with steep topography in North-Central Chile. The studied watersheds range from 200 to 1500 km^2. Results show hydraulic conductivity values in a reasonable range, i.e., 10^{-4} to 10^{-6} m s^{-1}, rather close to those reported in the few existing studies for some of the basins. The method also yields estimates on the order of 10^{-5} for drainable porosity, with no major differences between the basins. The recession flow analysis provides a cost-effective approach to obtaining bulk hydrological parameters in arid and semi-arid steep basins such as those of the Coquimbo Region and elsewhere.

1. Introduction

Arid and semi-arid zones, i.e., where potential evapotranspiration surpasses rainfall, cover more than 30% of the earth's surface. These areas are typically found between latitudes 15–35°, both north and south of the Equator (Simmers, 2003). Water is, by definition, scarce in these areas, where an increased demand on this critical resource exists or is expected to occur worldwide in the coming years. This is due to factors such as population growth and the increasing development of water-demanding activities such as agriculture and mining. Moreover, likely water shortages due to climate variability or climate change (CONAMA, 2006; Souvignet et al., 2010) will add further stressful conditions with respect to water use and water management, a situation that is currently problematic in several basins in the North-Central portion of Chile. This is particularly true in the Coquimbo Region of Chile, the study area for the present research. Indeed, as recently studied by Nuñez et al. (2013), low frequency climate variability has already had important consequences on the hydrological regime of the area and, at the time of this work, the region has experienced nearly seven years of severe drought conditions.

Modern integrated water resource management strategies will be required to cope with the problems of water scarcity in arid zones, and the successful implementation of these strategies requires knowledge of properties and the components of the hydrologic cycle that apply to a given area. As stated in Thomas et al. (2013), “increases in projected water demands require improvements in our ability to characterize low flow behavior of rivers for conjunctive water use management, maintenance of water quality

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and ecosystem services". However, the characterization of the groundwater components of remote or larger study areas is especially difficult, because of the costs associated with such projects. In spite of the fact that groundwater forms the only permanent water source in many arid zones, and a key controlling factor determining streamflow in dry periods, the cost and complexity of basin-scale investigations for hydrologic parameters means that few studies of this type are done, particularly in rural areas with low population densities (Van Camp et al., 2013). For example, although there are a few hydrogeological studies of the Coquimbo Region of North-Central Chile (DGA, 2007; Espinoza, 2005; SERPLAC-DGA-ONU-CORFO, 1979), these studies have typically focused on the irrigated zones and lower valley areas, i.e., narrow floodplains and recent alluvial deposits of the main rivers and tributaries. As a result, there is a general lack of reliable information about the more extended hillside areas. Also, the rather limited information available is normally derived from a small number of aquifer pump tests and is therefore site-specific; extrapolation to larger areas, especially to sloped terrains with shallow soils and fractured bedrock, is problematic.

What is required is a simple and cost-effective approach to establishing a range of hydrogeological characteristics at the basin scale, e.g., aquifer thickness, hydraulic conductivity, and drainable porosity, which is applicable to arid and semi-arid landscapes. Besides the inherent interest and importance of having basic hydrogeological data in arid zones, information such as hydraulic conductivity and water storage conditions is a basic requirement for the implementation of regional scale hydrological models as well as for the analysis of ungauged basins and the assessment of complex hydrological processes such as mountain block recharge and mountain block groundwater circulation (Ajami et al., 2011; Krakauer and Temimi, 2011; Manning and Solomon, 2005; Vannier et al., 2013).

One family of techniques that has considerable promise for the assessment of basin scale hydrogeological characteristics is low-flow or baseflow analysis, also known as recession flow analysis. These methods focus on "the part of surface flow that comes from groundwater or other delayed sources" (Tallaksen, 1995). There are generally two basic approaches in this type of analysis; the first is based on basin hydrograph analysis, and has been used extensively in hydrological studies (i.e., rainfall-runoff modeling) as well as in the planning and management of water resources (Sujono et al., 2004). This approach requires suitable information about starting time of flow recession, which could be somewhat difficult to properly establish (Tallaksen, 1995; Zhang et al., 2009). Thus, a second approach that is independent of time was initially presented by Brutsaert and Nieber (1977), whom derived a recession flow analysis based on the Boussinesq equation that described the drainage process from an ideal aquifer. In their analysis, the recession flow discharge (Q) is related to the temporal change in discharge ($\mathrm{d}Q/\mathrm{d}t$), eliminating the problem of identifying a unique start time as a reference point for a recession curve. Recent literature shows the application of this technique yields acceptable results in humid basins with moderate topography, i.e., slowly draining catchments (Malvicini et al., 2005; Stoelzle et al., 2012; Zhang et al., 2009). Unfortunately, the need for simple, low-cost techniques to evaluate hydraulic properties is greatest in arid regions, mountainous regions, and steeply-sloping catchments with thin alluvial cover. A review of recent literature on the subject found only one study in which the Brutsaert and Nieber (1977) methodology was applied to a basin not in a humid region; that study, by Mendoza et al. (2003), focused on a semi-arid basin near Oaxaca, Mexico, with an annual precipitation of more than 650 mm yr^{-1}. In addition to the steep, mountainous terrain characterized by thin alluvial aquifers, the basins investigated in the present study receive 300 mm yr^{-1} of precipitation or less, as well as being subject to very high potential evapotranspiration (PET), which qualifies them as "arid" under the UNEP aridity index (UNEP, 2006). Although the simplicity of the Brutsaert and Nieber (1977) method is attractive, more effort is required to establish its applicability to a broader range of conditions (i.e., sloping aquifers, arid settings). The main objective of the present contribution is therefore to analyze the suitability of this method for catchment-scale hydrogeological properties assessment in several arid basins with steep, complex topography and fractured bedrock, taking as example the Coquimbo Region of North-Central Chile.

The manuscript is structured as follows: first, the theory of recession flow analysis is described. This is followed by a description of the study area, an explanation of data sources, and the methods used in data processing for this study. The final sections discuss the results obtained in the present study and the likelihood that the methods used here may be applied to other arid basins.

2. Theoretical background

Brutsaert and Nieber (1977) presented a recession flow analysis technique, derived from the Boussinesq equation that allows the indirect estimation of basin-scale aquifer characteristics (Mendoza et al., 2003; Szilagyi, 2004; Tallaksen, 1995). This approach assumes that river discharge behavior in a recession stage (i.e., baseflow) is a function of the hydrogeological characteristics of the system (Mwakalila et al., 2002; Rupp and Selker, 2006; Zhang et al., 2009).

The Boussinesq equation describes the drainage of water from an ideal aquifer; that is, a non-confined, rectangular prism with a characteristic breadth B. The aquifer is assumed to be initially saturated, limited below by an underlying impermeable layer, and to be drained by a fully incised stream (Szilagyi et al., 1998; Tague and Grant, 2004). Thus, the theoretical relationship of the temporal behavior (i.e., the variation) of the surface discharge, as fed by the aquifer, will follow an expression of the form (Brutsaert and Lopez, 1998):

$$-\mathrm{d}Q/\mathrm{d}t = aQ^b \tag{1}$$

where Q is the surface discharge [$\mathrm{L}^3\ \mathrm{T}^{-1}$], t is the time [T], a is the intercept and relates to hydraulic and geomorphic characteristics of a basin and b is the recession slope (Ajami et al., 2011). In this conceptualization, all flow in the main stream draining the basin is divided into two components: an initial surface runoff component that operates on a relatively short time between a rainfall event and the arrival of the water to the channel, i.e., the short transit-time regime (hereafter short time), and a component that infiltrates to the aquifer and discharges more slowly; i.e., the long transit-time regime (hereafter short time), or baseflow. Each of these components of discharge are characterized by their own a and b constants.

In order to apply the Brutsaert and Lopez (1998) approach to an actual basin, some method is required to evaluate the characteristic constants, a and b, for both the short and long time flow regimes. Since it may be difficult to properly assess the transition between the short and long time flow regimes, Parlange et al. (2001) presented an alternative, analytical formulation. The method is based on the non-dimensional definitions for discharge, Q^*, and time, t^*, derived from a solution for the short time flow which is also applicable for long time conditions. The method uses a plot of log Q vs. $\log(\mathrm{d}Q/\mathrm{d}t)$; on the basis of least-squares optimization, the investigators found the transition point between the two flow regimes to be located at $\log Q^* = -0.1965$ and $\log(|\mathrm{d}Q^*/dt|) = 0.0918$. To estimate basin scale hydraulic parameters for a specific dataset, the horizontal and vertical displacements, H and V, respectively, between the theoretical values ($\log Q^*$, $\log(|\mathrm{d}Q^*/\mathrm{d}t|)$) and those