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A simple approach for the analysis of the structural-geologic control of groundwater in an arid rural, mid-mountain, granitic and volcanic-sedimentary terrain: The case of the Coquimbo Region, North-Central Chile

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ABSTRACT

A practical approach for the assessment of surface water and groundwater resources in rain-fed mid-mountain domains of arid to semi-arid zones is much needed, especially in rural areas for which groundwater is the only reliable and permanent water supply source. This is the case in the Coquimbo region (29°15′- 32°10′ S latitude) of north-central Chile, where groundwater is needed for human consumption but also for agricultural and mining activities at a small to medium scale. This paper examines the usefulness of community knowledge, as encoded in the historical record, for identifying water resources. The existing record of wells and springs in the Coquimbo region is used as a guide to the identification and characterization of structural patterns that may influence the distribution of water resources. The proposed approach combines simple graphical, statistical and geostatistical methods to identify patterns, likely related to local and regional structural controls that influence the distribution of groundwater resources. In the Coquimbo area, these influences tend to align in NW and NE orientations that approximately coincide with regional geological trends. The methodology presented has the potential to form a first step in the search for additional water resources in the Coquimbo region, and may be useful for targeting detailed field studies on the basis of community and historical knowledge in many arid and semi-arid rural areas.

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Arid and semi-arid zones, i.e. regions where annual potential evapotranspiration exceeds annual precipitation, cover more than 30% of the earth's surface (Scanlon et al., 2006). Water resources in these areas are by definition scarce, and factors such as climate variability or climate change can be additional elements of water stress (Núñez et al., 2013; Drake et al., 2015). This is the prevailing situation in many Chilean basins, especially in the arid to semi-arid north-central area of the country (Oyarzún et al., 2014).

Along with the worldwide abundance of arid and semi-arid zones, mountainous zones, i.e. areas with an altitude greater than 1000 masl, or located between 200 and 1000 masl with slopes greater than 20‰, comprise more than 39% of the world continental surface, excluding Antarctica and Greenland (Viviroli et al., 2007). These areas have global economic significance, in addition to their environmental and social importance.

A good understanding of hydrological processes is critical in mountainous arid and semi-arid regions. Furthermore, knowledge of the distribution of water resources in these regions is essential for developing sustainable and integrated water management

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strategies needed to cope with water scarcity. However, obtaining the necessary information is difficult, especially in large and/or remote areas. The cost and complexity of research at the basin or regional level mean that few hydrogeological studies are carried out at this scale. This is particularly true in rural areas with low population densities (Oyarzún et al., 2014; Sternberg and Paillou, 2015) such as the Chilean rainfed mid-mountain zones, i.e. areas below 2000 masl, with moderate or steep slopes, that depend largely or solely on precipitation as a water source. The lack of regional-level studies and inadequate characterization of groundwater resources disproportionately impact rural communities, where the majority of people rely on these typically low-yield sources of water for their subsistence activities.

Unlike the more common "traditional" approach to evaluating groundwater resources, in which a likely distribution of groundwater is determined on the basis of factors such as geology, topography and vegetation (e.g., Mahmood and Vivoni, 2008; Mallast et al., 2011; Tessema et al., 2012), the current work presents an "inverse" approach. In this alternative method, we propose using the locations of known groundwater sources, and analyzing their distribution to infer geohydrological relationships. In particular, our aim is to identify correlations, likely traceable to structural controls, that can be deduced from the distribution of known water sources. In this way, we seek to improve knowledge of the groundwater distribution in middle-mountain dry-land areas of the Coquimbo region, north-central Chile, and similar areas worldwide.

The study area (Coquimbo region) is part of a N-S tectonic segment that extends between latitudes 28° and 33°S, characterized by the lack of the central tectonic depression present in the rest of the Chilean territory, which is a consequence of W-E tectonic compression (Parada et al., 2007). W-E relief in this area includes a narrow coastal plain (10–20 km width), a middle mountain area 50–60 km wide (ca. 200–2000 masl; the westernmost part is known as the Coastal Cordillera), and the Andean mountain belt, 40–60 km in breadth and attaining heights of 5000 masl. The limit between the Coastal and the Andean belts is rather sharp and controlled by thrust faulting. The majority of the region comprises volcanic-sedimentary formations of primarily Cretaceous age, and Upper Paleozoic to Tertiary granitoids. In general terms, Paleozoic to Jurassic strata crop out in both the western and eastern belts. Neogene sediments are rather scarce, except in the Coastal Belt between 29° and 30°. Also scarce are permeable clastic sedimentary rocks and limestone. In consequence, groundwater resources are limited to the narrow alluvial plains, and to crystalline rocks possessing secondary permeability. The volcanic-sedimentary rocks that account for a major part of the outcrops present remarkable lithological uniformity from the Upper Paleozoic to the Tertiary, a consequence of the rather invariable plate tectonic conditions controlling the segment geological evolution. However, magma compositions do oscillate between basaltic-andesitic and andesitic-dacitic. The former were mainly erupted as lava flows, while the latter produced pyroclastics interbedded with clastic sediments having a similar volcanic composition. These formations generally strike N-S and are gently folded. In hydrological terms these rocks possess very low primary permeability; however, groundwater circulates along gently-dipping contacts between different rock types, and through fracture openings. Fracturing, enhanced by the presence of dikes, is the source of a fair amount of secondary permeability in the abundant granodioritic outcrops of the region (Luengo, 2004). In summary, the geology of the study area may be pictured as gently folded volcanic and sedimentary strata, age-ordered but vertically displaced by mainly N-S normal faults and separated by large N-S elongated batholitic outcrops that have not affected their structural patterns (Rivano and Sepúlveda, 1991; Emparán and Pineda, 1999, 2006).

The information used in this study comes from a public database of water use rights granted by the DGA (Chilean Water Resources Agency) in the Coquimbo region (http://www.dga.cl/productosyservicios/derechos_historicos/Paginas/default.aspx). The DGA database comprises records of 5972 water rights associated with wells and 57 corresponding to springs. In addition, this database was supplemented with a list of 271 wells, built under the framework of an INDAP (National Institute for Agriculture Development) photovoltaic pumping system program for small farmers of rain-fed areas (http://www.minagri.gob.cl/wp-content/uploads/2013/08/5.-Apoyo-de-INDAP-a-ERNC.pdf). The ground elevation for the location of each well or spring (information not originally available in the cited databases) was obtained from http://www.gpsvisualizer.com/elevation. From the original list of wells and springs, we removed all records with suspect location coordinates or missing discharge data, as well as those wells and springs located below and above 200 and 2000 masl, respectively. Also, and given the objective of this work, wells located in alluvial fill zones, clearly related to main rivers and stream flows, or located in irrigated areas, were removed from the database.

The final database included 3822 water sources (mostly wells), 2928 of which had (nominal) discharges up to 1 l/s, 792 with discharges between 1 and 10 l/s, and 102 with discharge greater than 10 l/s. Their spatial distribution is shown in Fig. 1. A notable feature is the abundance of groundwater sources in the zone of the Punitaqui Creek sub-basin in the Limarí Province. The Punitaqui Creek sub-basin is characterized by extensive granitic bedrock with negligible primary permeability, but with permeability developed on structural and weathering-related zones of high secondary porosity related to NW oriented joints and dikes (Luengo, 2004). The fact that the majority of water sources have low discharge rates (<1 l/s) is not unexpected, due to the nature of the system under study and the locations of the sources, i.e. their presence in semi-arid to arid, rain fed mid-mountain zones with shallow soils and underlying bedrock of low primary porosity. Although not viable for higher-demand activities, these low-yield wells and springs nonetheless provide a critical resource for small rural settlements, especially for micro- and small family farms and rural communities that exist with marginal water resources, as well as for small-scale mining activities.

The analysis presented here was based on a visual identification of linear alignments in the spatial distribution of water supply locations (wells and springs). The assumption underlying this analysis is that the apparent distribution of linear traits associated with groundwater sources is an expression of structural features and geological discontinuities that control the occurrence of higher permeability zones (and therefore the availability of water). The result is shown in Fig. 2A. In total, 116 linear alignments were identified for the Coquimbo region. Although there is some scatter in the feature orientations, two main clusters can be identified, with orientations distributed around 45° and 135° (angles measured clockwise from north), as shown in Fig. 2B. For comparison purposes, Fig. 2C presents the main orientations of faults extracted from the 1:1.000.000 geological map for Chile (Sernageomin, 2003). Although a dominant N-S orientation of the principal faults is apparent, the alignments of wells and springs are rather preferentially oriented in NW and NE directions. It is likely that structures other than the principal N-S faults are controlling the water source alignments. In the current W-E compressive tectonic regime, the permeability of major N-S faults may be reduced or limited by their orientation normal to the direction of maximum compressive stress, while minor NW or NE striking faults may provide more conductive pathways for groundwater flow. It is also possible that major N-S high angle faults could host deeper

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