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Modeling rock weathering in small watersheds

Fernando A.L. Pacheco [a,*], Cornelis H. Van der Weijden [b,1]

[a] Department of Geology, Chemistry Research Center, Trás-os-Montes and Alto Douro University, Ap 1013, 5000 Vila Real, Portugal
[b] Department of Earth Sciences—Geochemistry, Faculty of Geosciences, Utrecht University, P.O. Box 80.021, 3508 TA Utrecht, The Netherlands

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SUMMARY

Many mountainous watersheds are conceived as aquifer media where multiple groundwater flow systems have developed (Tóth, 1963), and as bimodal landscapes where differential weathering of bare and soil-mantled rock has occurred (Wahrhaftig, 1965). The results of a weathering algorithm (Pacheco and Van der Weijden, 2012a, 2014), which integrates topographic, hydrologic, rock structure and chemical data to calculate weathering rates at the watershed scale, validated the conceptual models in the River Sordo basin, a small watershed located in the Marão cordillera (North of Portugal). The coupling of weathering, groundwater flow and landscape evolution analyses, as accomplished in this study, is innovative and represents a remarkable achievement towards regionalization of rock weathering at the watershed scale. The River Sordo basin occupies an area of approximately 51.2 km^2 and was shaped on granite and metassediment terrains between the altitudes 185–1300 m. The groundwater flow system is composed of recharge areas located at elevations >700 m, identified on the basis of $\delta^{18}O$ data. Discharge cells comprehend terminations of local, intermediate and regional flow systems, identified on the basis of spring density patterns, infiltration depth estimates based on $^{87}Sr/^{86}Sr$ data, and spatial distributions of groundwater pH and natural mineralization. Intermediate and regional flow systems, defined where infiltration depths >125 m, develop solely along the contact zone between granites and metassediments, because fractures in this region are profound and their density is very large. Weathering is accelerated where rocks are covered by thick soils, being five times faster relative to sectors of the basin where rocks are covered by thin soils. Differential weathering of bare and soil-mantled rock is also revealed by the spatial distribution of calculated aquifer hydraulic diffusivities and groundwater travel times.

1. Introduction

The study of rock weathering spans a wide range of disciplines, including petrography and geochemistry, soil science, hydrology and geomorphology (Beig and Lüttge, 2006; Hausrath et al., 2011; Iwashita et al., 2011; Meunier et al., 2007; Middelburg et al., 1988; Ouimet, 2008; Pacheco and Van der Weijden, 2012a,b, 2014; Van der Weijden and Van der Weijden, 1995; Violette et al., 2010; Yoo et al., 2009). This reflects the multiplicity of scales across which weathering processes can be studied: the laboratory scale, the weathering rind and soil profile scales, and the watershed scale (Navarre-Sitchler and Brantley, 2007; Viles, 2001).

This paper is focused on the hydrological modeling of rock weathering at the watershed scale. This topic evolved significantly in the last five decades. Initially, Garrels and Mackenzie (1967) quantified the relation between groundwater chemistry and weathering reactions. Subsequently, modeling studies developed coherent mathematical and computational bases for mass balance calculations of mineral dissolution and precipitation (Bowser and Jones, 2002; Parkhurst, 1997, Parkhurst et al., 1982; Plummer and Back, 1980; Velbel, 1985a,b, 1986). Finally, they incorporated specific contributions in mass balance equations, such as biomass growth or decay (Taylor and Velbel, 1991; Velbel, 1995) or anthropogenic inputs (Pacheco and Van der Weijden, 1996, 2002; Pacheco et al., 1999). With the advent of Geographic Information Systems, weathering models evolved to complex lumped approaches where water–mineral interactions are integrated with watershed data, including morphologic features and hydraulic parameters (Goddéris et al., 2006; Pacheco and Van der Weijden, 2012a; Violette et al., 2010). The main goal of this progress was the calculus of weathering rates at the watershed scale. However, lumped weathering models fail to describe weathering rates in relation to groundwater flow and(or) landscape evolution patterns within the basin. In other words, they could not yet perform a

* Corresponding author. Fax: +351 259 350480.
E-mail addresses: fpacheco@utad.pt (F.A.L. Pacheco), cornelis.h.vanderweijden@gmail.com (C.H. Van der Weijden).
[1] Fax: +31 30 2535302.

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regionalization of rock weathering at the watershed scale. The purpose of this paper is to take this step forward.

2. Study area

2.1. Topography and climate

The River Sordo basin occupies an area of approximately 51.2 km^2, being located in the Vila Real district and Marão cordillera, northern Portugal (Fig. 1). The basin drains to the River Sordo, which is 16.1 km long and debouches into the Corgo River, a tributary of the transnational (Iberian) Douro River. Topography is characterized by a large difference between the altitudes at the source (1300 m.a.s.l.) and mouth of the river (185 m.a.s.l.). Relief is wrinkled and slopes are steep (>30%) in the source areas and easternmost sector of the basin, but the main valley in the central area is wide, smooth and flat (average slope <5%). As a result of differences in elevation, rainfall and temperature gradients are set up across the basin ($1000 \leqslant P \leqslant 1750$ mm; 13 °C $\leqslant T \leqslant$ 15.5 °C).

2.2. Drainage network hierarchy and watershed morphometry

The River Sordo basin is oriented in the NW–SE direction (Fig. 2), with hillsides being much longer and wider in the upstream areas than in the downstream region. According to the Strahler (1957) classification, the River Sordo is an order-3 water channel. Given the large basin width in the upstream areas, the river is fed by a number of order-2 and order-1 tributaries in these areas. For the opposite reason, in the downstream region only a few order-1 tributaries drain to the main valley. Sub-basins located upstream of order-1, order-2 and order-3 (Sordo basin) channel outlets are illustrated in Fig. 3. According to Horton (1945), morphometric parameters of the basins, such as area (A, m^2), topographic volume (V, m^3) and length of water channels (L, m), are firmly related to the Strahler order. For the River Sordo basin, these relationships are represented by the following exponential formulas:

$$A = 1.1 \times 10^5 e^{1.99i} \; (R^2 = 0.97) \tag{1a}$$

$$V = 1.0 \times 10^7 e^{2.55i} \; (R^2 = 0.98) \tag{1b}$$

$$L = 1.42 \times 10^4 e^{0.42i} \; (R^2 = 0.96) \tag{1c}$$

where i is the order. In points located away from order-i basin outlets, for example at spring sites (Fig. 2), Eqs. (1a)–(1c) can still calculate A, V and L, providing that i is replaced by an equivalent order (i_{eq}), defined as an average of the orders of the surrounding streams, calculated as follows:

$$i_{eq} = \frac{\sum_{j=1}^{n} L_j \times i}{L} \tag{2}$$

where L_j is the length of channels of order j located inside a square of dimensions $p \times p$ meters containing the point, L is the total length of channels inside that square and n is the highest channel order. The concept of equivalent order was introduced by Pacheco and Van der Weijden (2012a) and the distribution of i_{eq} values within the River Sordo basin is illustrated in Fig. 2.

2.3. Geology

The geology of River Sordo basin is dominated by Paleozoic metassediments. During the Hercynian orogeny, these rocks were intruded by granites and in the Campeã valley were subsequently covered by alluvial deposits (Fig. 4a). The mineralogy of metassediments is characterized by quartz, albite, chlorite and muscovite. The granites are composed of quartz, K-feldspar, plagioclase (albite–oligoclase), biotite and muscovite. The rock massifs are intensely fractured by conjugate sets striking to NE–SW till NNE–SSW and to NW–SE. A less important fracture system strikes to

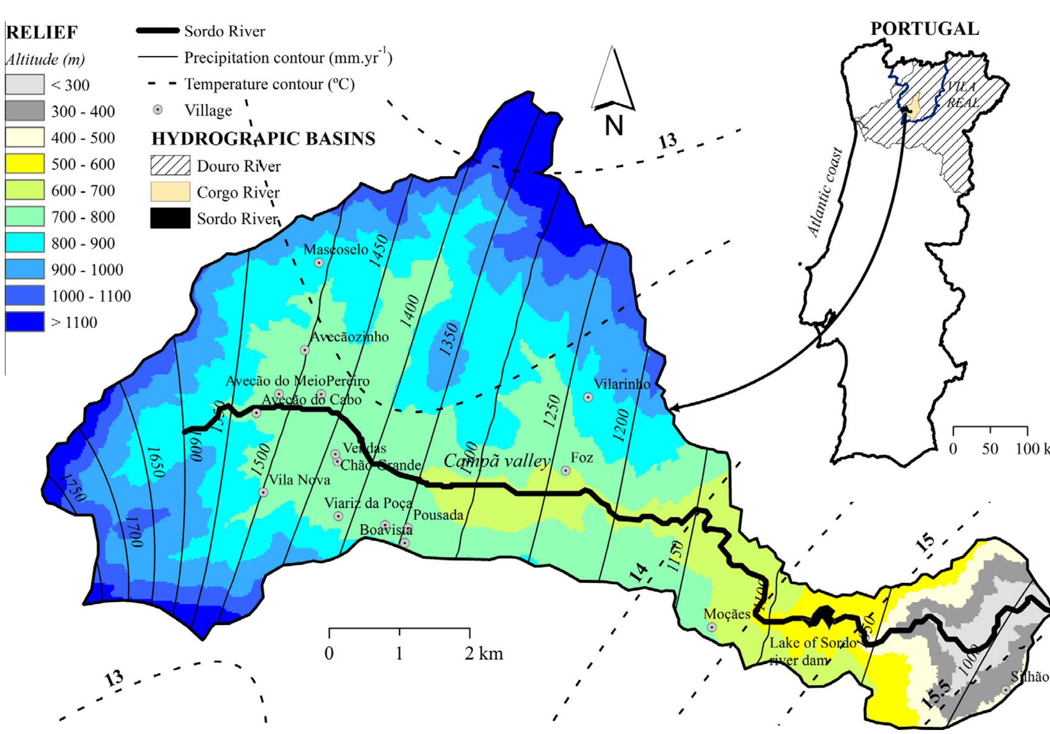

Fig. 1. Location of River Sordo basin in the territory of continental Portugal, and spatial relationship with the Corgo River and Douro River basins. Digital Elevation Model (DEM) with coloured areas representing altitudes above sea level. Spatial distribution of annual precipitation (solid contours) and mean annual temperature (dashed contours).