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ASSESSMENT OF WATER RESOURCES IN A MOUNTAIN ENVIRONMENT WITH A SEMI-DISTRIBUTED HYDROLOGICAL MODEL: SERRA DA ESTRELA CASE, CENTRAL PORTUGAL

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RESUMEN. *Las zonas de montaña son fuentes estratégicas de recursos hídricos. En este trabajo se presenta una evaluación de los recursos hídricos en la cuenca del río Zêzere en la Serra da Estrela, en el centro de Portugal, mediante un modelo hidrológico semidistribuido asociado al código VISUAL BALAN v2.0. Este código realiza balances hídricos diarios en el suelo, la zona no saturada y el acuífero. Un modelo hidrológico agregado no es capaz de reproducir las aportaciones medidas. Los resultados mejoran sustancialmente utilizando un modelo semidistribuido, que tiene en cuenta la variabilidad espacial de la hidrogeomorfología y la dependencia de la precipitación y la temperatura con la altitud.*

El flujo hipodérmico es el componente principal de la escorrentía, siendo de aproximadamente 41% de la precipitación. Este alto valor alto del flujo hipodérmico se debe a las pronunciadas pendientes del terreno y a las características de la zona no saturada, como es la presencia de un suelo de permeabilidad alta sobre capas de granitos de baja permeabilidad, con densa fracturación sub-horizontal a poca profundidad. La recarga media anual al acuífero se ha estimado en un 15% del total de la precipitación.

ABSTRACT. *Mountain areas are the source of strategic water resources. This paper presents an evaluation of water resources in the high-mountain Zêzere river basin in Serra da Estrela, Central Portugal, by means of a semi-distributed hydrological model associated to the VISUAL BALAN v2.0 a code that performs daily water balances in the root zone, the unsaturated zone and the aquifer and requires a small number of parameters. A lumped hydrological model fails to fit measured stream flows. The results significantly improve when a semi-distributed model, which takes into account the spatial variability in hydrogeomorphological variables and the dependence of temperature and precipitation data with elevation, is adopted.*

Interflow is the main component of runoff, reaching 41% of total precipitation. High interflows are due to the steep relief of the basin and to the features of the vadose zone, such as the presence of high-permeability soil overlying fractured low-permeability granitic bedrock with extensive sub-horizontal fracturing at shallow depths. The estimated mean annual groundwater recharge is 15% of total precipitation.

1. INTRODUCTION

The hydrogeological studies carried out at Serra da Estrela Mountain region are ascribed to some of the most essential present-day water-related research issues, such as those mentioned in the UNESCO International Hydrological Programme / IHP (e.g., "High Mountain Hydrology", namely the "High mountains as country's water towers", www.unesco.org/water/ihp; see also Aureli 2002).

This paper presents hydrological modelling for the evaluation of water resources in the high-mountain Zêzere river basin in Serra da Estrela, Central Portugal. Models are solved with VISUAL BALAN v2.0, a code that performs daily water balances in the root zone, the unsaturated zone and the aquifer and requires a small number of parameters.

The study area (Fig. 1, 2) corresponds to the Zêzere river drainage basin upstream of Manteigas village (ZBUM), an area of 28.04 km^2. This area presents specific geomorphologic, climatic and geotectonic characteristics which contribute to control local recharge and flow paths.

Since Serra da Estrela Natural Park, as well as the Zêzere river basin, extends up to the highest elevation zones of the Portuguese mainland (1993 m a.s.l.), they provide unique sites for integrated studies concerning mountain hydrology. In order to assess the interaction between local surface waters (recharge waters) and groundwaters, an integrated multidisciplinary (namely, structural geology, geomorphology, geochemistry, hydrogeology, isotope hydrology, pedology, geophysics and GIS mapping) approach was launched, under the scope of the HIMOCATCH R&D Project "Role of High Mountain Areas in Catchment Water Resources, Central Portugal" (e.g., Espinha Marques *et al.* 2006, 2007).

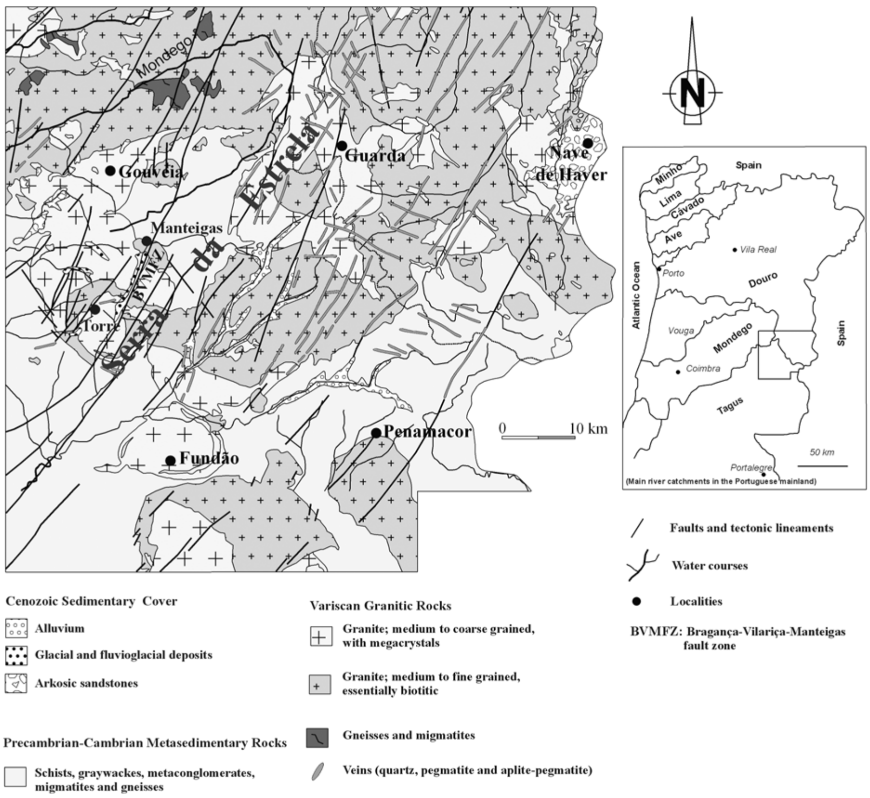

Figure 1. Geological framework of Serra da Estrela region (adapted from Geological Map of Portugal, 1/500.000, 5th Edition; Oliveira *et al.* 1992).

Figure 2. Hypsometric features of the river Zêzere drainage basin upstream Manteigas; vadose zone study sites; hydrogeomorphologic units: Eastern plateau (1); Zêzere valley eastern slopes (2); Lower Zêzere valley floor (3); Nave de Santo António col (4); Upper Zêzere valley floor (5); Zêzere valley western slopes(6); Cântaros slopes (7); Lower western plateau (8); Upper western plateau (9). Taken from Espinha Marques et al. (2007).

2. HYDROGEOLOGICAL FRAMEWORK

The Serra da Estrela (Fig. 1) is the highest mountain in the Portuguese mainland (with an altitude reaching 1993m a.s.l.) and is part of the Cordilheira Central, an ENE-WSW mountain range that crosses the Iberian Peninsula. This region shows distinctive climatic and geomorphologic characteristics that play an important role in the local water cycle. The river Zêzere drainage basin upstream of Manteigas, corresponds to an area of catchment of 28 km^2 with an altitude ranging from 875 m a.s.l., at the streamflow gauge measurement weir of Manteigas, to 1993 m a.s.l., at the Torre summit (Fig. 2).

The relief of the study region consists mainly of two major plateaus, separated by the NNE-SSW valley of the Zêzere river (Vieira 2004). Late Pleistocene glacial landforms and deposits are a distinctive feature of the upper Zêzere basin, since the majority of the plateau area was glaciated during the Last Glacial Maximum (e.g. Daveau et al. 1997, Vieira 2004).

According to Daveau et al. (1997), the Serra da Estrela climate has Mediterranean features, with mean annual precipitation reaching 2500 mm in the most elevated areas. Precipitation seems to be mainly controlled by the slope orientation and the altitude. Mean annual air temperatures are below 7ëC in most of the plateau area and, in the Torre vicinity, they may be as low as 4ëC.

Espinha Marques et. al (2005) proposed 9 hydrogeomorphologic units, based on the spatial distribution of lithological, geomorphological and climatic features (Fig. 2): i) Eastern plateau; ii) Zêzere valley eastern slopes; iii) Lower Zêzere valley floor; iv) Nave de Santo António col; v) Upper Zêzere valley floor; vi) Zêzere valley western slopes; vii) Cântaros slopes; viii) Lower western plateau; ix) Upper western plateau.

The Serra da Estrela Mountain is located in the so-called Central-Iberian Zone of the Iberian Massif (Ribeiro et al. 1990). The main regional hydrogeological units (Fig. 1) correspond to i) sedimentary cover; ii) metasedimentary rocks; and iii) granitic rocks. The geological and tectonic conditions outline some of the major hydrogeologic features and processes, such as infiltration, aquifer recharge, type of flow medium (porous vs. fractured), type of groundwater flow paths, or hydrogeochemistry. Fractured mediums occur in poorly weathered granitic and metasedimentary rocks. Porous mediums are dominant in the alluvium and quaternary glacial deposits as well as in the most weathered granites and metasedimentary rocks.

According to the soil map of Serra da Estrela region (Agroconsultores and Geometral 2004) the following pedologic units occur in this sector: (i) Humic, Leptic and Skeletic Umbrisols; (ii) Lithic and Umbric Leptosols; (iii) Umbric Fluvissols; (iv) Rock outcrops.

Field observations produced further information concerning the pedologic units occurrence, its spatial distribution according to the hydrogeomorphologic framework and its hydrologic classification by means of the Hydrologic Soil Groups system (from low runoff potential soils, group A, to high runoff potential soils, group D) — (e.g. USSCS 1964).

Some of the most distinctive features of the vadose zone in this sector of Serra da Estrela are the wide distribution of: i) granitic rock outcrops and ii) an umbric A horizon — and by consequence Umbrisols and Umbric Leptosols — thus reflecting the high organic matter content in the upper part of the soil profile.

Four types of vadose zone structures were identified in the region :

— Type i) A single granite layer with very thin or absent soil cover; present in granitic outcrop areas of plateaus and slopes. It is a fractured medium and it is included in soil hydrologic group D.

— Type ii) A soil layer typically less than 0.5 m thick overlying a continuous and hard granitic layer; described in sites 6, 8 and 9; present in plateaus, especially above 1600 m a.s.l., and slopes. Coexistence of porous and fractured media. It corresponds to Lithic and Umbric Leptosols (both integrating soil hydrologic group D).

— Type iii) A a soil layer frequently between 0.5 and 1.0 m thick overlying a weathered granite layer and/or a slope deposit; described in sites 6 and 10; it is present in lower altitude slopes and plateaus (where chemical weathering processes are more active) or along tectonised zones. There are both porous and fractured media. It essentially corresponds to Leptic Umbrisols with C horizon composed of weathered granite and/or a slope deposit. These soils are included in hydrologic group C.

— Type iv) A soil layer frequently over 1.0 m thick overlying a glacial deposit; described in sites 1 to 5 and 7; present in base of slope, col and valley floor areas. It is a porous medium. Skeletic and Humic Umbrisols (A, B or C hydrologic groups) and subdominant Umbric Fluvisols (C or D hydrologic groups) prevail.

3. HYDROLOGICAL MODEL OF THE ZBUM AREA

The hydrology of the river Zêzere drainage basin upstream of Manteigas was first modeled with a lumped model based on available field lithology, structural geology, geomorphology, hydrogeochemistry, soil, land cover and climatology features and published data from other nearby mountain areas. Mean daily air temperature and precipitation data for the basin were derived from the meteorological station of Penhas Douradas (Fig. 2) for hydrological years from 1986-87 to 1994-95. This station was selected because its altitude (1380 m) is closer to the mean altitude of ZBUM (1505 m) than that of the alternative station of Manteigas (815 m; see Fig. 2). This model revealed to be unrealistic because: 1) It failed to account for the high spatial variability of basin features and 2) The mean yearly precipitation recorded in Penhas Douradas during the period 1951-1980, 1406 mm, is much smaller than the normal precipitation for such period which according to INMG (1991) is 1799 mm and also smaller than the measured average yearly flow at the river Zêzere gauge station, 1601 mm. On the other hand, the mean yearly precipitation in the Manteigas station is 1570 mm, which is closer to the normal value for the period 1951-1980.

To overcome the limitations of the lumped hydrological model of the ZBUM area several sub-basins based on hydrogeomorphologic units were considered. Hydrogeomorphological units were defined in three stages. First, units in the ZBUM basin were defined based on landforms: plateaux, slopes, valley bottoms and cols. Then, these units were refined to account for the boundaries of granitic rocks and fluvioglacial deposits. Some units were subdivided based on their elevation into upper and lower units. Valley slopes were subdivided according to their orientation into Eastern and Western units. Finally, nine hydrogeomorphologic units were defined (Espinha Marques et. al., 2005; see Fig. 2). The model was also improved by adopting the Manteigas station as the reference station. Then a virtual meteorological station was considered in each sub-basin. Meteorological data were computed by linear extrapolation of the data of the reference station, using the regression lines of temperature and precipitation versus elevation for monthly values. The mean annual precipitation for the entire basin obtained in this way is equal to 2336 mm, similar to values reported by Daveau et al. (1997).

Daily water balances were computed using VISUAL BALAN v2 (Samper et al., 2007). The model was calibrated by eye-fitting measured stream flows. Model parameters were adjusted by trial and error to fit measured monthly stream flows, while ensuring a global coherence of the mean annual values of actual and potential evapotranspiration and groundwater recharge with reported values for this study area (e.g., Carvalho et al. 2000; Mendes and Bettencourt 1980). The fit between measured and computed flows achieved in this calibration is very good (see Fig. 3).

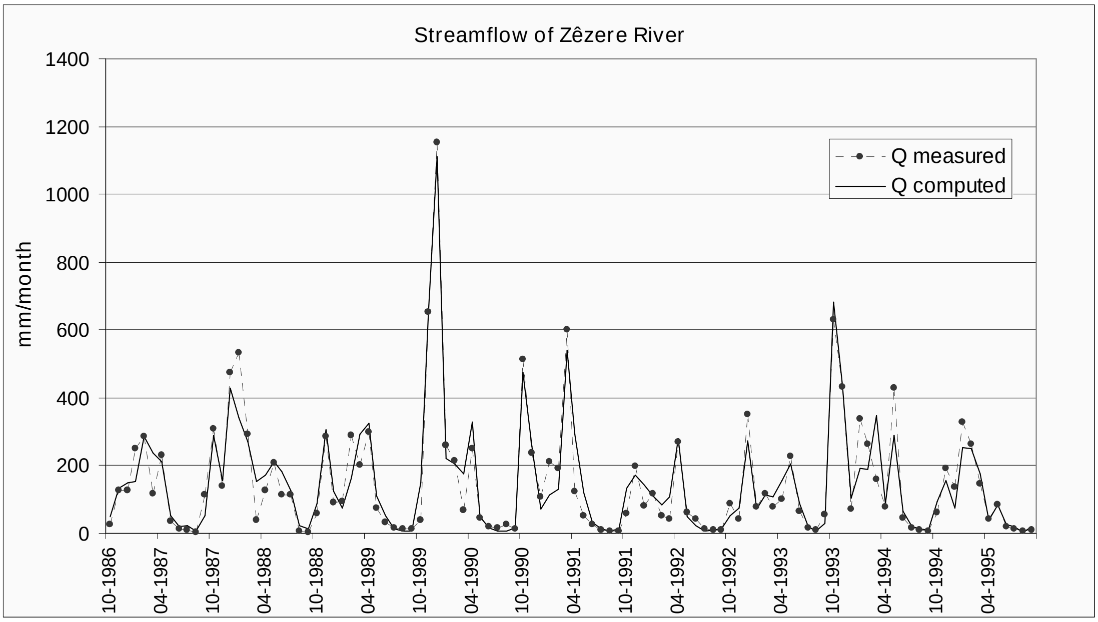

Figure 3. Measured and computed monthly streamflows at Zêzere river gauge station.

Model results show that interflow is the most important fraction of precipitation, reaching 41%. The flow in the unsaturated zone has been solved considering that the water can flow horizontally and discharge to the surface water as interflow or percolate vertically downwards to the aquifer (providing for recharge or percolation). In the unsaturated zone balance, there is one inflow, the potential recharge, and two outflows, the interflow and the recharge. The latter is computed using a formulation of Darcy's law. Interflow and recharge are calculated with the following expressions:

$$I = {}_i V \quad (1)$$

$$R = K_v + {}_r V \quad (2)$$

where I is the interflow [LT^{-1}], $_i$ is recession coefficient for the interflow [T^{-1}], V is water content [L], R is the recharge [LT^{-1}], K_v is the vertical hydraulic conductivity [LT^{-1}], and $_r$ is the recession coefficient for the recharge [T^{-1}].

Model results are discussed in the next section.

4. RESULTS AND DISCUSSION

Model results are within the range of expected values for a high-mountain area in crystalline and metasedimentary rocks. Most of the hydrological components have mean yearly values which agree with those obtained in previous studies of other aquifer systems of the Central-Iberian range. Mean annual potential evapotranspiration (605 mm/y) is close to the value calculated by Mendes and Bettencourt (1980) for the meteorological station of Penhas da Saúde (558 mm/y), located near the SE limit of ZBUM (1510 m a.s.l.). However, the mean annual actual evapotranspiration computed with VISUAL BALAN (325 mm/y) is significantly smaller than that reported by Mendes and Bettencourt (1980), 479 mm/y. The main reason for such difference is that these authors selected an unrealistic value of available water content in the soil (100 mm). In fact, soil data from the ZBUM area suggest that this parameter has a strong spatial variability. Available water content in our model is equal to 100 mm in sub-basins 3 and 4 while in the rest it varies from 30 mm to 50 mm.

Interflow is the most important fraction of precipitation, reaching 41%. The vadose zone features in ZBUM are particularly favourable to interflow. Most of the basin area is characterized by the presence of highly permeable soil overlying fractured and much less permeable granitic bedrock (Fig. 4). Interflow in ZBUM is also favored by the wide presence of a layer of weathered granitic rock showing intense subhorizontal discontinuities and/or low-angle fissure network zones (Fig. 4).

Our estimate of annual groundwater recharge is 15% of mean annual precipitation. This value is consistent with those obtained in the last decades in Northern and Central Portugal with a wide variety of techniques. Recharge estimates range from 2% (Henriques 1985) to over 30% of mean annual precipitation (Lima and Silva 2000, Oliveira 2006). Carvalho et al. (2000) reported recharge values in hard rock mountain basins from 6% to 18% and Carvalho (2001, 2006) reported a recharge of 10% in the Corgas Largas aquifer system situated in the Western part of the Serra da Estrela massif.

Model calibration revealed that results are especially sensitive to: 1) The soil thickness or the available soil storage (difference between field capacity and permanent wilting point) and 2) The interflow recession coefficient. A sensitivity analysis was performed to analyse these these relations. Regarding the total runoff, only the available soil storage is important: a decrease of 20% in soil storage causes an increase of approximately 23% in annual runoff. Interflow is very sensitive to both the available soil storage and the interflow recession coefficient, while aquifer recharge is sensitive to the recession coefficients for interflow and recharge. Indeed, a change of 20% in the interflow recession coefficient ($_i$) causes a change of -16% and +23% in recharge respectively. The average of the calibrated $_i$ and $_r$ for the whole basin are 0.15 d^{-1} and 0.06 d^{-1} respectively. As a consequence of this analysis, and regarding the unsaturated zone, we have reasonable confidence on the calibrated values of $_i$ and $_r$, but less confidence in the the vertical hydraulic conductivity K_v. Of course, this fact is strongly related with the equations applied to solve the unsaturated flow.

Figure 4. Illustration of the low-permeability bedrock with sub-horizontal fractures.

Considering the importance of the interflow in the water balance, it seems very important to deepen the knowledge on the phenomena involved in the generation of interflow in these type of mountain areas.

5. CONCLUDING REMARKS

The water resources in the high-mountain Zêzere river basin in Serra da Estrela, Central Portugal, have been evaluated by means of a semi-distributed hydrological model associated to the VISUAL BALAN v2.0 code.

VISUAL BALAN calculates daily water balances in the root zone, the unsaturated zone and the aquifer and requires a small number of parameters. Model results and the fit to measured streamflows improve when spatial variations in hydrogeomorphological variables and changes in rainfall and air temperature with elevation are taken into account by defining nine sub-basins. Daily temperature and precipitation data from Manteigas meteorological station are extrapolated to each sub-basin by using known vertical gradients of temperature and precipitation. Model parameters have been calibrated by fitting stream flow measurements in the Zêzere river.

Uncertainties in model parameters and groundwater recharge have been evaluated by sensitivity analyses. Computed streamflows are very sensitive to soil thickness. On the other hand, they are much less sensitive to the rest of the parameters. Computed groundwater recharge is most sensitive to the interflow and percolation recession coefficients. As frequently found in a high-mountain aquifer system, interflow is the main component of runoff, reaching 41% of total precipitation. High interflows are due to the mountainous relief of the ZBUM area which shortens the water path in the unsaturated zone, to the presence of a high-permeability soil overlying the fractured low-permeability granitic bedrock and to extensive sub-horizontal fracturing at shallow depths.

The annual groundwater recharge is 15% of mean annual precipitation. This value is consistent with other results from previous studies from hard-rock basins in the Central-Iberian Zone of the Iberian Massif.

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