Hydrologic models and Geographic Information Systems for water resources evaluation: Application of GIS-BALAN to Atlantic basins in Spain and Portugal

JAVIER SAMPER[1], MIGUEL ANGEL GARCÍA VERA[2], BRUNO PISANI[1], DIEGO ALVARES[1], JORGE ESPINHA MARQUES[3], ALBERTO VARELA[1] & JOSÉ ANGEL LOSADA[2]

[1] Escuela de Caminos, Universidade da Coruña, Campus Elviña, 15192 Coruña, Spain, e-mail: jsamper@udc.es
[2] Confederación Hidrográfica del Ebro, Ministerio de Medio Ambiente, Spain, e-mail: mgarciave@chebro.es
[3] Dep. de Geologia (CGUP), Universidade do Porto, Portugal. e-mail: jespinha@fc.up.pt

Abstract A distributed hydrologic model for water resources evaluation is presented (GIS-BALAN) which has been derived by enlarging the capabilities of a lumped hydrologic code (VISUAL BALAN V2.0) and coupling it to a GIS. GIS-BALAN evaluates hydrologic components in a sequential manner and performs a daily water balance in the upper soil, the unsaturated zone and the underlying aquifer. It requires only a few parameters and incorporates user-friendly interfaces for data input and post-processing of results. Computed groundwater levels and stream flows can be compared to measured data for the purpose of model testing and calibration which can be performed automatically by minimizing a least-squares criterion. The code has been widely used as a tool for water resources evaluation, groundwater recharge estimation, and groundwater pollution studies. Here we describe its main features and illustrate its application to Atlantic basins of Northern Spain and Portugal.

Key words: GIS; GIS-BALAN, hydrologic models; recharge estimation; VISUAL BALAN; water balance

INTRODUCTION

Evaluation of water resources requires performing water balances on different hydrologic components. Usually such balances must be solved numerically. Aquifer recharge estimation requires balance methods (Custodio *et al.*, 1997). The results of these balances must be tested with groundwater level and streamflow data. It is also convenient to verify its coherence with the results obtained with hydrochemical and isotopic methods and aquifer flow models. Hydrological balance methods, however, have some limitations caused mainly by difficulties and uncertainties in the estimation of model parameters such as the available water capacity and evapotranspiration. Samper *et al.* (1997) developed in 1988 a lumped hydrological model (BALAN) to estimate the aquifer recharge. This code solves the balance equations in the soil, the unsaturated zone and the aquifer, and requires a small number of parameters. An interactive version of the code, VISUAL BALAN V1.0, was released in 1999 (Samper *et al.*, 1999) which provided user-friendly interfaces for both data input and post-processing of results. BALAN and VISUAL BALAN have been used by many Spanish and Latin American hydrologists in different hydrologic fields (Samper & García Vera, 1992, 1997). Some of their main applications include:

(a) Water Planning: García Vera used BALAN to model water resources in hundreds of Ebre River basins (García Vera & Arqued, 2000; Samper & García Vera, 2000, 2004). Heredia & Murillo (2002) modelled several subbasins in the Southeast of Gran Canaria island;

(b) Groundwater recharge estimation (Samper & García Vera, 1997; Samper, 1998);

(c) Water resources evaluation in karstic areas of Baleares, Catalonia and Vasque Country (Valls, 2001);

(d) Hydrological studies for low-level radioactive waste management and uranium migration through the Andújar alluvial aquifer (Samper & Carrera, 1995). VISUAL BALAN has been used also for paleohydrologic studies within the PADAMOT European Project;

(e) Hydrologic characterization for toxic waste disposal in low permeability zones (Aliaga *et al.*, 2004);

(f) Wetland hydrology of Doñana, Monegros (Samper & García Vera, 1997; Castañeda & García Vera, 2004; Castañeda, 2004) and Gallocanta areas (Blasco *et al.*, 2004);

(g) Hydrology of humid basins in Galice, Spain (Soriano & Samper, 2000; Samper & García Vera, 2004);

(h) Hydrology of granitic basins in Galice (Samper *et al.*, 2000; Soriano & Samper, 2000);

(i) Recharge evaluation in coastal aquifers and the study of seawater intrusion (Romero *et al.,* 2004);

(j) Evaluation of the influence of a reservoir on an underlying aquifer (García-Aróstegui *et al*., 2001).

Here we report the most recent developments implemented in GIS-BALAN, especially those dealing with the coupling of VISUAL BALAN to a Geographic Information System. These developments are illustrated in two Atlantic basins of Northern Spain and Portugal.

MAIN FEATURES OF GIS-BALAN

GIS-BALAN evaluates hydrologic components in a sequential manner and performs daily water balances in the upper soil, the unsaturated zone and the underlying aquifer. Net rainfall (after accounting for interception), irrigation and snow melting are the main inputs in the soil. Infiltration can be computed either with a Horton equation or the SCS Curve Number method. The amount of surface runoff is equal to the difference of water input and water infiltration. Infiltrated water is made available to fulfil evapotranspiration (AET) needs, increase soil water content and contribute to potential recharge which is the main input of water to the vadose zone. Potential evapotranspiration values (PET) can be provided by the user or evaluated with one of the following methods: Thornthwaite, Blaney-Criddle, Makkink, Penman, Turc and Hargreaves. AET is calculated from PET using either the original Penman-Grindley method or smoothed modifications of such method. A key feature of GIS-BALAN is the consideration of fast preferential flow through the soil. Soil drainage (or potential recharge in our notation) may have two components: 1) Preferential flow or direct recharge which may occur through fissures, cracks or macro-pores and is equal to a fraction of the total water supplied to the soil; and 2) Darcian drainage which obeys Darcy's law, is slower than preferential flow and depends on soil field capacity and hydraulic conductivity.

GIS-BALAN assumes that water in the unsaturated zone can flow horizontally and discharge to the atmosphere as interflow or percolate vertically downwards to the aquifer providing for aquifer recharge. Percolation is therefore equivalent to aquifer recharge. A formulation based on Darcy's law under the presence of perched aquifers is used to evaluate water percolation. Water balance in the unsaturated zone includes a single inflow (potential recharge) and two outflows (interflow and vertical percolation). The equation is solved by either explicit or implicit numerical schemes.

Groundwater recharge is the main input to the aquifer. For the purpose of water balance in the aquifer GIS-BALAN provides the option to select a single cell model or a set of interconnected cells. Fluxes across cells are computed using an explicit finite difference approximation of the transient 1-D groundwater flow equation. Groundwater discharge is the natural aquifer output to a river or any other surface water body. Changes in water stored in the aquifer ΔV_a per unit surface area are related to changes in piezometric levels Δh through $\Delta V_a = S\Delta h$ where S is aquifer storage coefficient.

Water contents of the three components are expressed as volume per unit surface (usually in mm). The program works with hydrological years and allows for leap-years.

The total outflow from a basin is computed as the sum of surface runoff, interflow and groundwater discharge. The program has the capability of automatically estimating model parameters by minimizing a least squares objective function using Powell's multidimensional method (Samper *et al*., 1999).

GIS-BALAN has interactive interfaces which facilitate data input and post-processing of model results. These interfaces include: (a) Menus with supporting information, (b) Tables with recommended values of hydrologic parameters and (c) plots and graphs of relevant hydrological variables such as infiltration rate as a function of soil water content.

To fulfil the needs of GIS-BALAN users, the following improvements were also implemented: (a) Allow for the common standards of meteorological and stream gauge data commonly used by Spanish Water Authorities; (b) Consider time series of up to 100 years; and (c) Incorporate snow precipitation, melting and runoff processes.

RECENT DEVELOPMENTS

A pre-processor has been developed as an input interface to GIS-BALAN. Beginning with a digital elevation model and using the geomorphologic data in the GIS (Geographic Information System), the pre-processor obtains input data such as subbasin delineation, drainage network and morphologic parameters (average slope, soil type and use of soil). The model can handle complex basins with spatial variation in model parameters and surface runoff propagation. GIS provides average parameter values for each subbasin delineated by the pre-processor. Available meteorological data from different stations are processed in the GIS to create maps that describe their spatial variability. This information is then processed to obtain series of average values for each subbasin. Connectivity between subbasins is established and flow accumulation is calculated for each subbasin (see Fig. 1).

The following inputs are obtained from GIS:

(a) Geographic data (latitude);

(b) Hydrometeorological data including daily rainfall and mean daily temperature and, if needed, sunshine values, relative humidity and wind speed data;

(c) Soil data such as thickness, porosity, field capacity, and vertical hydraulic conductivity which are obtained from geological and soil digital maps;

(d) Vegetation data and crop types and irrigation rates for irrigated areas;

(e) Rainfall interception data which are derived from vegetation type and mean height;

(f) Surface runoff data which include either Horton infiltration parameters or SCs curve numbers for each subbasin. Curve numbers are estimated from DTM and soil maps;

(g) Unsaturated zone data such as hydraulic conductivity, interflow and percolation depletion coefficients are obtained from geological maps; and

(h) Aquifer data such as depletion coefficient, storage coefficient and transmissivity which are obtained from a combination of streamflow and hydrogeological data.

Other parameters such as those for snow precipitation and melting, preferential flow, and evapotranspiration are usually estimated from model calibration.

A post-processor has been developed within GIS-BALAN to post-process the results of the hydrologic model.

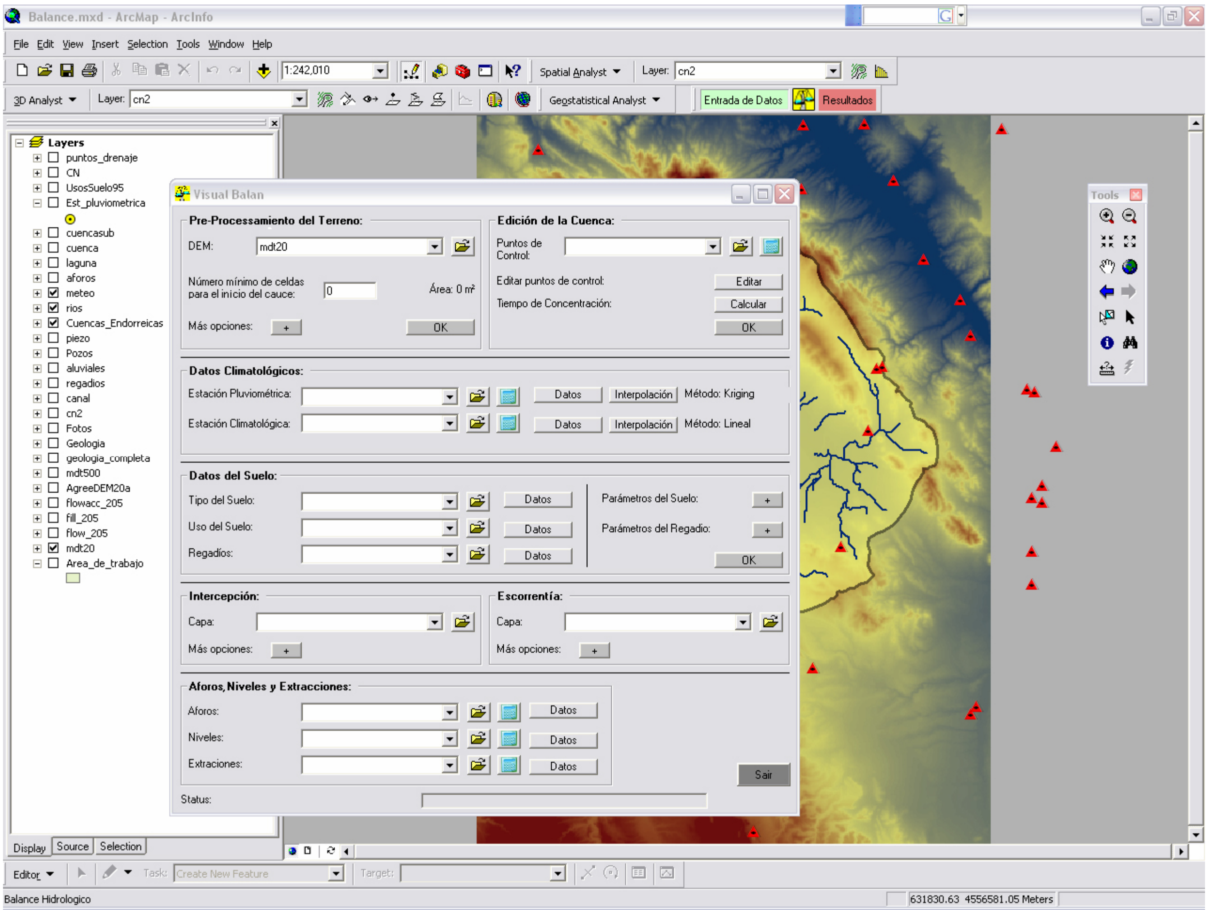

Fig.1. Main window of GIS-BALAN pre-processor.

APPLICATION TO ATLANTIC BASINS

GIS-BALAN has been applied to Atlantic basins in Spain and Portugal. The Valiñas River basin is located near La Coruña (Soriano & Samper, 2000). It is a small basin with 34 km^2 of area. The main course of the river has a length of 12 km and is entirely located on granite rocks which present a surface alteration up to a depth between 5 and 20 m (Samper *et al.* 1997). Water balance was performed between 92/93 and 97/98. The Penman-FAO method was used to calculate PET. Model parameters were calibrated first using only stream flow data. Calibrated parameters include: field capacity (its calibrated value is 0.307), soil thickness (1.4 m), and soil hydraulic conductivity (1.9 10^{-6} m s^{-1}). Later, model calibration was extended to cope with both stream flow and groundwater level data. The final fit is excellent for both groundwater levels and stream flows (see Fig. 2 and 3). Fig. 4 illustrates the annual values of hydrologic components in the Valiñas River basin as they are output by GIS-BALAN.

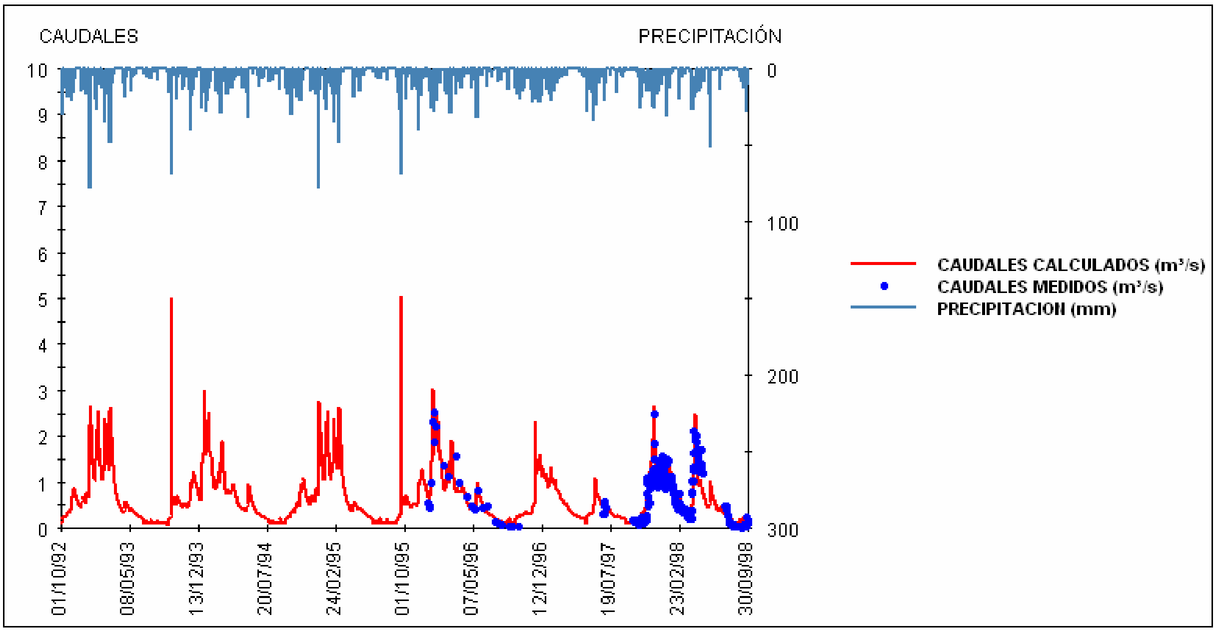

Fig. 2. Comparison of measured and computed stream flows in the Valiñas River basin with GIS-BALAN.

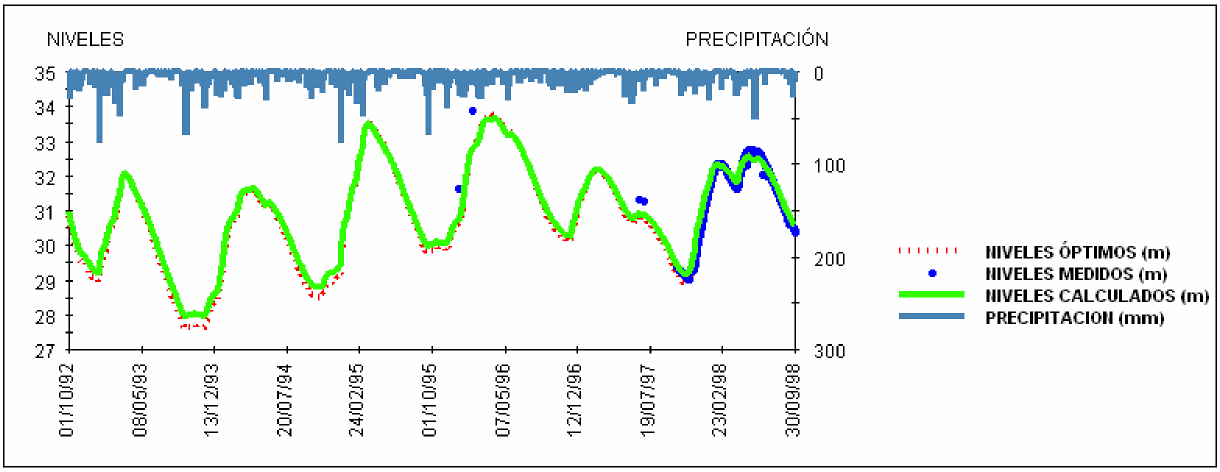

Fig. 3. Comparison of measured and computed piezometric heads in the Valiñas River with GIS-BALAN.

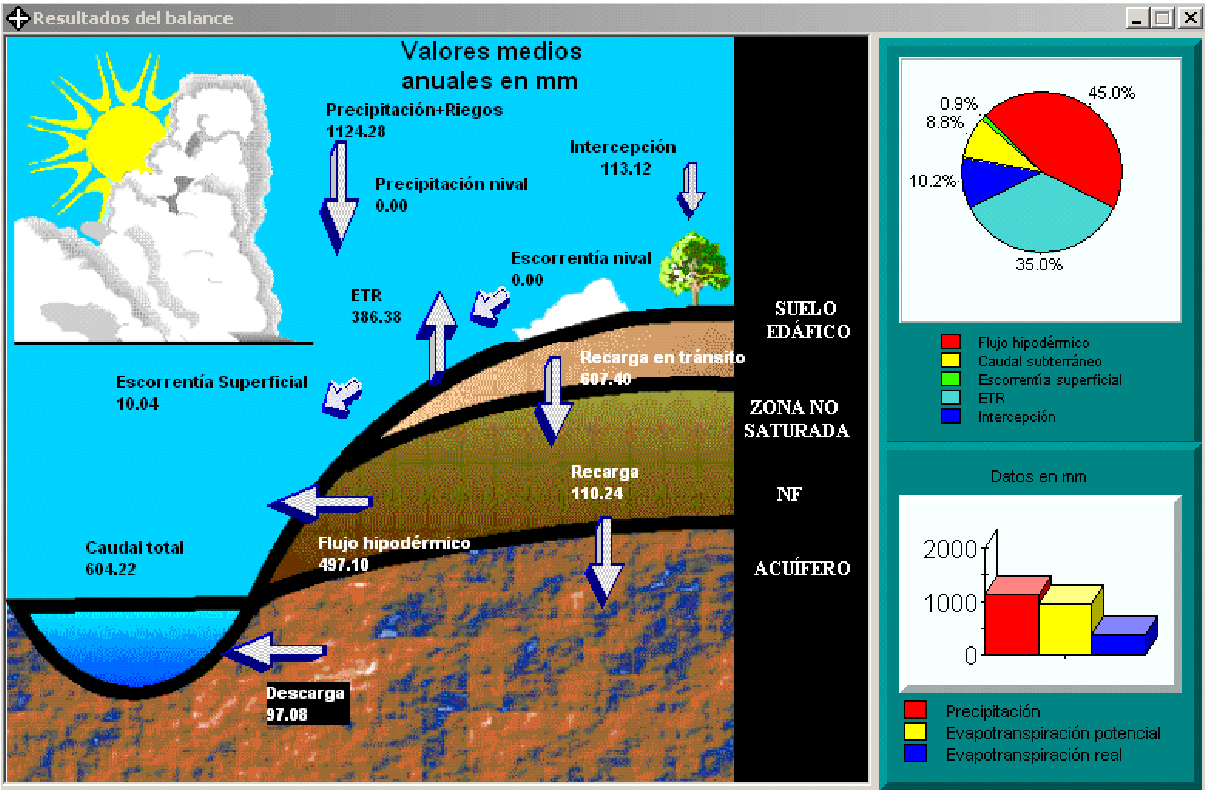

Fig. 4 Main window of GIS-BALAN output results for the Valiñas River basin.

GIS-BALAN has been used also to model the hydrology of Serra da Estrela in Portugal as part of the Ph.D. dissertation of Jorge Espinha Marques. Serra da Estrela is the highest mountain in the Portuguese mainland and is located in the Central-Iberian Zone of the Iberian Massif. The Serra da Estrela study area consists of the Zêzere River catchment, upstream the

Manteigas village (corresponding to an area of 28.04 km^2). The basin altitude varies from 875 m a.s.l at the Manteigas streamflow gauge station weir to 1993 m a.s.l. at the summit. The Serra da Estrela climate has Mediterranean features, with mean annual precipitation reaching 2 500 mm in the most elevated areas. Snowfall is frequent and snow persists for large periods above 1 700 m.a.s.l.. Mean annual air temperatures is below 7 ºC in most of the plateau area, but in the summit they may be as low as 4 ºC. One of the major challenges for hydrological modelling of Serra da Estrela basin is caused by the strong variations in temperature and rainfall with elevation. Temperature and precipitation data are available at two meteorological stations located at Penhas Douradas (1 383 m a.s.l.) and Manteigas (815 m a.s.l.) near the outlet of the basin. Available meteorological data in neighbour areas have been used to derive sensible linear approximations for the temperature and precipitation dependence on elevation for each season. Preliminary model results indicate that calibration of stream flows can only achieved by a proper characterization of the strong gradients of temperature and precipitation.

Delineation of subbasins has been made on the basis of hydro-geo-morphological units using several criteria based on geological, hydrogeological, geomorphologic, elevation, climatic, soil and land use data. Fig. 5 illustrates the geometry of the 9 units identified in the Serra da Estrela area.

CONCLUSIONS

The main aspects of GIS-BALAN have been presented. Recent developments have been described including the coupling of VISUAL BALAN V2.0 to a Geographic Information System. These developments have been illustrated in two Atlantic basins: Valiñas River basin (Spain) and Serra da Estrela (Portugal).

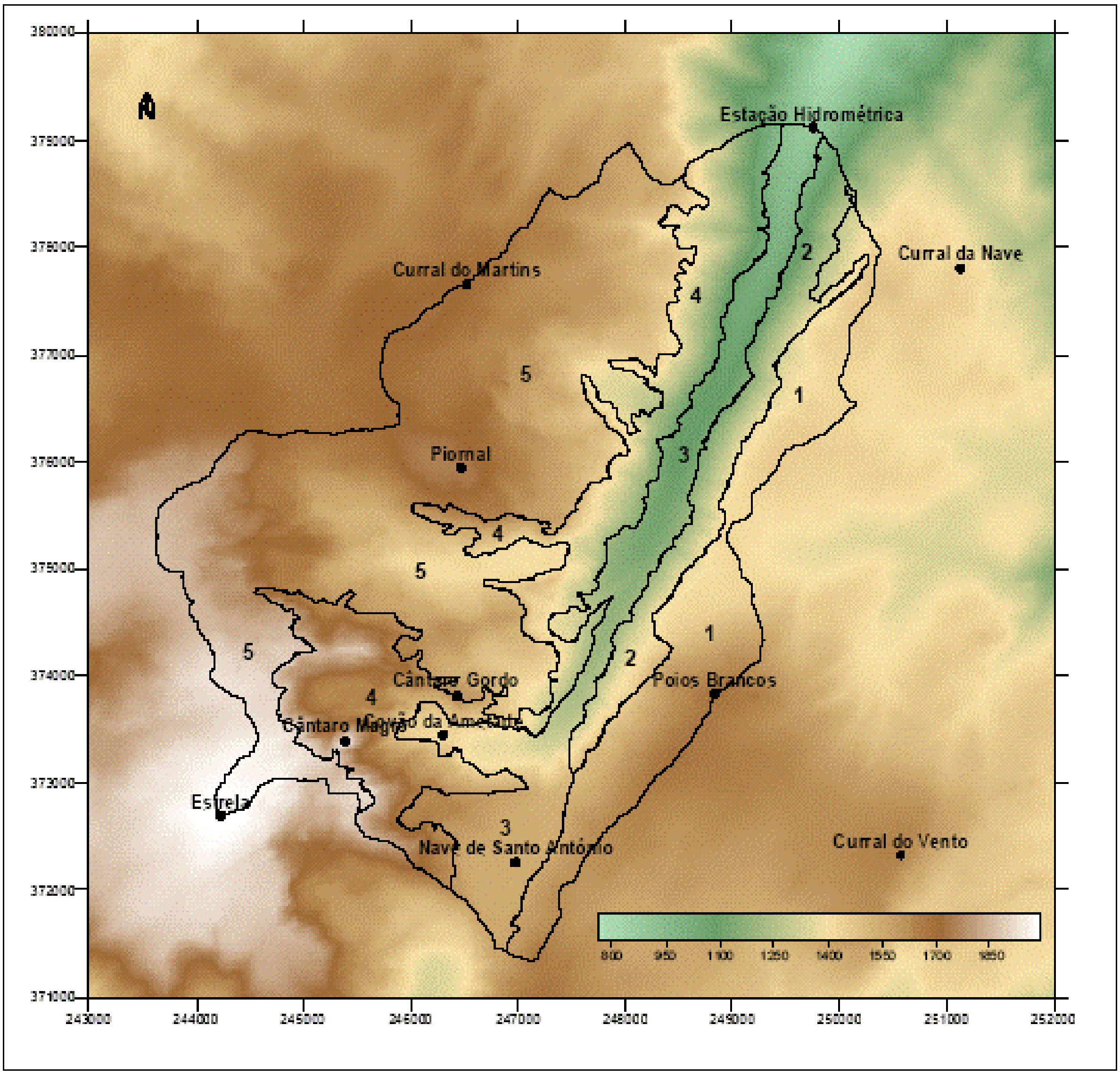

Fig. 5. Elevation map and subbasin delineation in Serra da Estrela hydrologic model.

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