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Using hydrological models and Geographic Information Systems for water resources evaluation: GIS-VISUAL-BALAN and its application to Atlantic basins in Spain (Valiñas) and Portugal (Serra da Estrela)

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Abstract This paper presents a distributed hydrological model for the evaluation of water resources, which has been obtained by extending the capabilities of VISUAL-BALAN V2, a lumped hydrological code developed by the University of La Coruña, and coupling it to a GIS. VISUAL-BALAN is a lumped hydrological model, which solves the water balance equations in the soil, the unsaturated zone and the aquifer. It requires only a few parameters and incorporates user-friendly interfaces for data input and post-processing of results. It evaluates hydrological components in a sequential manner. Besides the balance in the upper soil the code also solves the water balance equations in the unsaturated zone and the underlying aquifer. This allows the computation of daily groundwater levels, as well as basin water discharge rates. Computed heads and streamflows can be compared to measured values for the purpose of model testing and calibration. VISUAL-BALAN accounts for irrigation sources and return flows. It also allows for snow precipitation, melting and runoff. Two advanced options have been developed: (1) automatic parameter estimation using groundwater level and streamflow data; and (2) sensitivity analyses of the main components of the water balance with respect to model parameters.

Key words GIS, hydrological models, recharge estimation, VISUAL-BALAN, water balance

INTRODUCTION

Any hydrological study requires performing water balances on different hydrological components that 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 by hydrochemical (chloride balance) and isotopic methods, and with aquifer flow models. However, balance methods have some limitations, caused mainly by the difficulties and uncertainties for the estimation of some model parameters such as the available water capacity and AET. In 1988 a lumped hydrological model—BALAN code—was developed 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. It has been used by many Spanish and Latin American scientists and technicians in different hydrological fields. An interactive version of the code, VISUAL-BALAN V1.0, was released in 1999 (Samper *et al*., 1999). It incorporates a user-friendly environment, not only for data input but also for post-processing of results. The code allows computing sensitivities to model parameters and perform automatic estimation of such parameters. Here we present the most recent work implemented in VISUAL-BALAN V2.0, which has been tested on a small pyrenaic watershed of the Tor River, a tributary of the Noguera Pallaresa River. Finally, the on-going work to couple VISUAL-BALAN to Geographic Information Systems is described.

VISUAL-BALAN

VISUAL-BALAN V2.0 considers three components. The soil in which rainfall infiltration (and also the water coming from irrigation), transpiration and evapotranspiration processes takes place. The outputs are evapotranspiration and downward vertical flow, sometimes called effective rainfall by some authors (Samper & García Vera, 1992). Perched aquifers can exist in the unsaturated zones, which may lead to subsurface flow (interflow). The vertical downward flow corresponds to percolation or aquifer recharge.

Precipitation P (once discounted interception by vegetation) is distributed between surface runoff (Es) and infiltration (I). A part of infiltration comes back to the atmosphere by evapotranspiration (AET), another part increases the water content in the soil and the remaining part contributes to potential recharge (Pe), which is the input of water to the vadose zone. Inside of this zone, the water can flow horizontally to the atmosphere, as interflow (Qh), or it can percolate vertically to the aquifer (Qp). Percolation is therefore similar to aquifer recharge. Groundwater discharge (Qs) is the natural aquifer output to the river or any other surface water body. The state variables of each one of these three components are water content, usually expressed as water equivalent height (volume per unit surface) in mm.

VISUAL-BALAN V2.0 performs sequential daily water balances in the soil, the unsaturated zone and the aquifer. The main aspects of the balance are the input of precipitation and irrigation, the output by water interception, surface runoff, evapotranspiration, interflow and groundwater flow, soil water variation and water level in the aquifer. The program works with hydrological years considering the presence of leap-years. It evaluates each one of the balance aspects sequentially, beginning with precipitation and irrigation, which are known, interception (evaluated by Horton or Singh methods), surface runoff (by Horton's law or Curve Number method from US Soil Conservation Service) and actual evapotranspiration, and finishing with recharge.

Potential evapotranspiration can be evaluated by any of the following methods: Thornthwaite, Blaney-Criddle, Makkink, Penman, Turc, Hargreaves, or data provided by the user. Calculating AET from the PET is possible by means of four methods: Penman-Grindley, a method where the fraction AET/PET is a linear function of the water deficit in the soil, a third method in which this function is given by an exponential term, and a modification of Penman-Grindley's method.

Potential recharge has two components. The first one corresponds to preferential flow (direct recharge) through fissures, macropores, roots, etc. In this mechanism the recharge is directly proportional to the water supplied to the soil. The second component obeys Darcy's law and flows slower than the first component, being conditioned by the soil vertical hydraulic conductivity at saturated conditions. VISUAL-BALAN V2.0 provides three options to calculate this component as a function of the water content in the soil.

VISUAL-BALAN V2.0 computes the water balance in the unsaturated zone. Potential recharge is the inflow to the unsaturated zone. Once the volume of this zone is updated, considering the input P_e, outflows—interflow Q_h and vertical percolation Q_p—are computed by explicit or implicit numerical schemes. For the aquifer, the code solves the aquifer flow equation, using an explicit finite difference method. It allows evaluating the piezometric levels at different locations, which can be compared to measured heads.

The total flow is computed as the sum of the interflow or subsurface flow, groundwater flow and surface runoff. These results can be compared with measured streamgauge data. The program has the capability of automatically estimating model parameters based on Powell's multidimensional minimization method (Samper *et al.* 1999).

Since VISUAL-BALAN V2.0 is a lumped model, its results are mostly representative for homogeneous and small basins. To overcome this limitation, the program is prepared to accept the subdivision of the main basin into several sub-basins, where independent balances can be performed. Results of each sub-basin are combined afterwards to obtain the results for the total basin (see Fig. 1). It is possible to work with several hydrometereological stations to fulfil possible data gaps or to compute weighted averages of different stations.

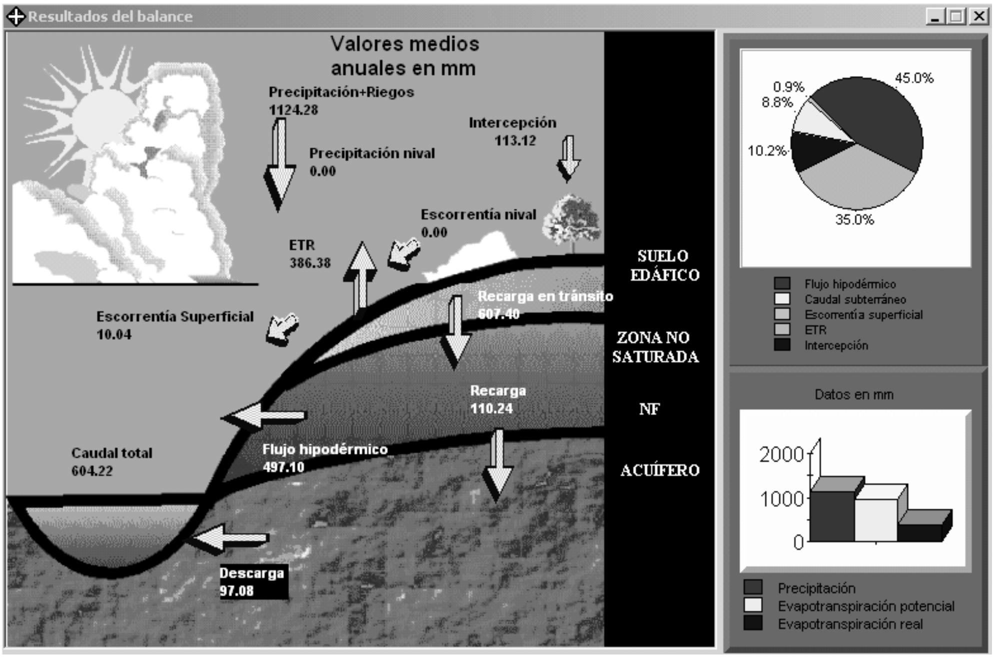

Fig. 1 Main window of VISUAL-BALAN V2.0 output results.

VISUAL-BALAN V2.0 has interfaces for data input and processing computation results. In this way, it is an interactive code that allows a fast data input and the possibility to easily interpret the results. All the information needed by the user is shown by plots and graphs, which illustrate the behaviour of hydrological variables. These capabilities make manual or automatic model calibration easy.

VISUAL-BALAN V2.0 includes the following improvements to: (a) Working directly with precipitation, weather and streamgauge data files commonly used by water authorities; (b) consider time series up to 100 years; (c) incorporate snow precipitation, retention, melting and runoff processes; and (d) perform balances on several sub-basins. Snow melting is a mechanism of surface runoff generation in mountain basins. Precipitation episodes, which coincide with melting phases, can lead to large flow rate peaks and contribute to snow melting.

VISUAL-BALAN APPLICATIONS

VISUAL-BALAN V2.0 code and its predecessors, BALAN (Samper & García Vera, 1992) have been applied to several basins of diverse hydroclimatologic and geologic conditions (Samper & García Vera, 1997).

Soriano & Samper (2000) present the study in the Valiñas River, a tributary of the Mero River, located near La Coruña. It is a small basin of 34 km^2 in area (see Fig. 2). The main course of the river has a length of 12 km and is entirely located on granite rocks. These rocks present a surface alteration up to a depth between 5 and 20 m (Samper *et al.*, 1997). To perform the water balance between 92/93 and 97/98, initial parameter values were estimated based on the Valiñas basin characteristics. Model parameters were calibrated using only streamflow data. The calibrated parameters were: field capacity (the final result was 0.307), soil thickness (1.4 m), vertical hydraulic conductivity (1.9×10^{-6} m s^{-1}) and the Penman-Grindley method coefficients for AET calculation. In all cases, the Penman-FAO method was used to calculate PET. Later, the calibration was performed using streamflow and groundwater level data. The final fit is excellent for both groundwater and streamflows (Soriano & Samper, 2000; see Figs 2 and 3).

Espinha Marques *et al.* are developing the hydrogeological study in Serra da Estrela (Portugal). The Serra da Estrela study area consists of the river Zêzere catchment upstream of the Manteigas village (corresponding to an area of 28.04 km^2). Serra da Estrela (the highest mountain in the Portuguese mainland) is located in the Central-Iberian Zone of the Iberian Massif. The basin altitude varies from 875 m, at the Manteigas streamflow gauge station weir, to 1993 m a.s.l. at the Torre summit. The Serra da Estrela climate has Mediterranean features, with mean annual precipitation reaching 2500 mm in the most elevated areas; snowfall is frequent and snow persists for long periods above 1700 m a.s.l. Mean annual air temperatures are below 7ºC in most of the plateau area, but in the Torre vicinity they may be as low as 4ºC. The modelling process, by means of VISUAL-BALAN, requires temperature and precipitation data from two meteorological stations located in the vicinity of the basin: the Penhas Douradas station (1383 m a.s.l.) and the Manteigas station (815 m a.s.l.). The definition of sub-basins is in course and is closely related to the definition of the

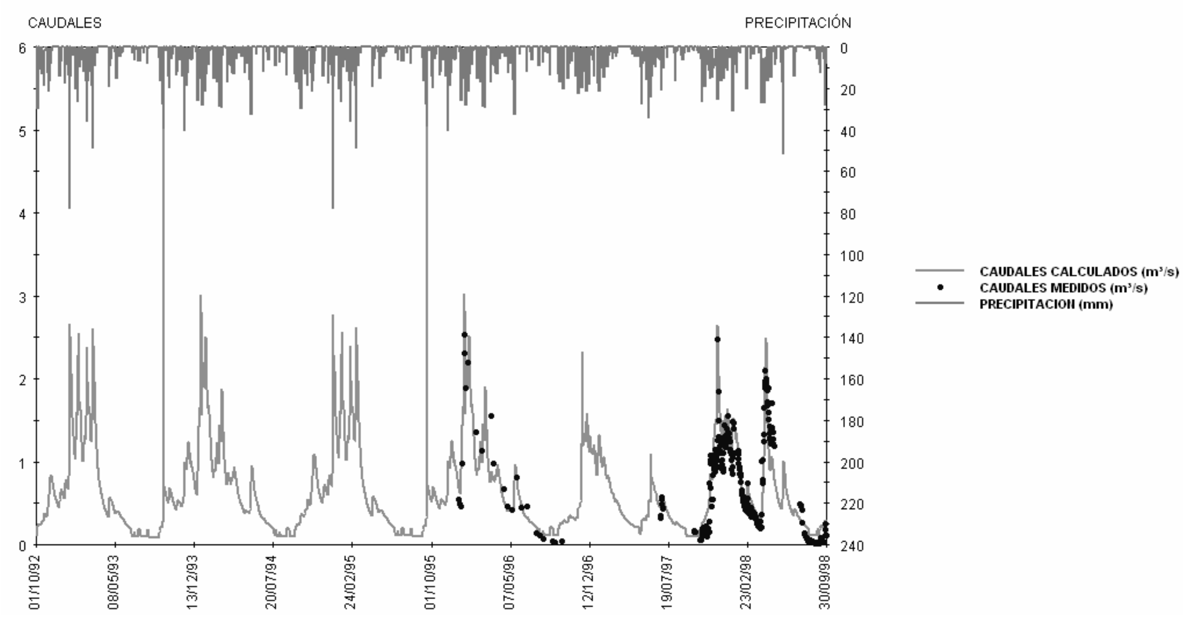

Fig. 2 Comparison between measured and computed streamflows in the Valiñas River basin performed with VISUAL-BALAN V2.0.

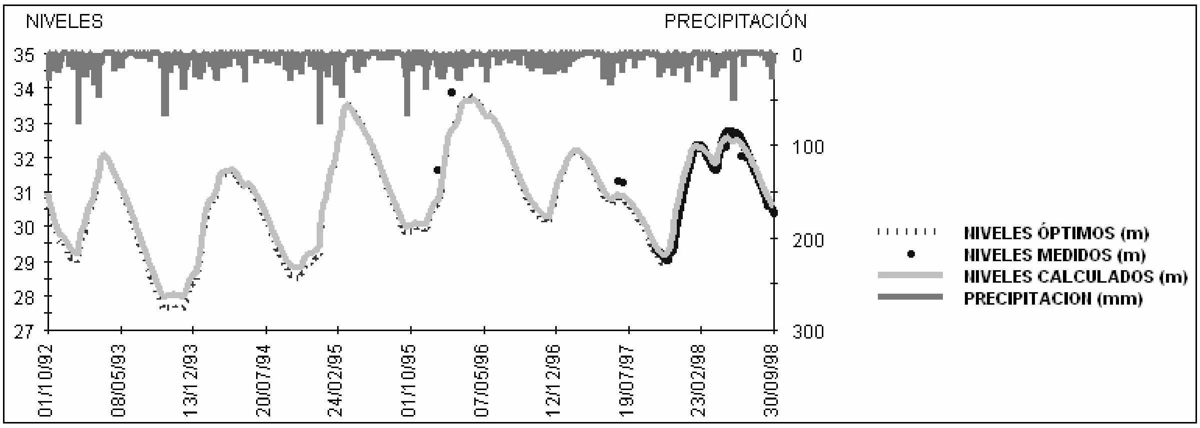

Fig. 3 Comparison between measured and computed piezometric head in the Valiñas River basin performed with VISUAL-BALAN V2.0.

hydrogeomorphological units. For this purpose, several criteria are being considered—geology, hydrogeology, geomorphology, climate, soil type and land use—in order to achieve the best possible representation of the basin complexity. The climate data treatment is an especially delicate task due to the presence of strong temperature and precipitation vertical gradients.

BALAN and VISUAL-BALAN V2.0 have been widely used in Spanish basins and many South American countries. Some of the main applications of VISUAL-BALAN include: (a) Water Planning: García Vera has modelled water resources of hundreds of Ebre River sub-basins (García Vera & Arqued, 2000; Samper & García Vera, 2000). Heredia & Murillo (2002) have modelled several sub-basins in the southeast of Gran Canaria island; (b) Groundwater recharge evaluation by means of water balances

(Samper & García Vera, 1997; Samper, 1998); (c) Water resources evaluation in karstic areas of Baleares, Catalonia and Vasque Country (Valls, 2001); (d) Radioactive waste management: The modelling was performed for the safely assessment near waste facilities at Andujar and El Cabril in Spain, as well as in paleohydrological studies (PADAMOT European Project; Samper & García Vera, 1997); (e) Hydrological characterization for the location of toxic waste disposal in low permeability zones (Aliaga *et al*., 2004); (f) Wetland hydrology in Doñana, Monegros (Samper & García Vera, 1997; Castañeda, 2004; Castañeda & García Vera, 2004) and Gallocanta (Blasco *et al*., 2004); (g) Hydrology of humid basins in Galice, Spain (Soriano & Samper, 2000); (h) Hydrology of granitic basins. Applications to Galice (Samper *et al*., 1997; Samper *et al*., 2000; Soriano & Samper, 2000); (i) Hydrology of coastal aquifers: Hydrogeological characterization, recharge evaluation and study of salt intrusion (Romero *et al.,* 2004); (j) Influence of a reservoir on the underlying aquifer: modelling of the Motril-Salobreña aquifer (Granada, Spain) which is affected by Rules Reservoir (García-Aróstegui *et al*., 2001).

ON-GOING WORK

A pre-processor has been developed as an input interface to VISUAL-BALAN V2.0. Beginning with a digital elevation model and using the geomorphologic data in the GIS (Geographic Information System), the pre-processor interprets the model input data: sub-basin delineation, drainage network, morphologic parameters (average slope, characteristics, soil type and use of soil). Some improvements are expected to be able to model complex basins considering the spatial variation of model parameters (distributed parameter model) and surface runoff propagation. GIS will provide average parameter values for each sub-basin delineated by the pre-processor in the first step. Available meteorological data from different stations will be processed in the GIS to create maps that describe the spatial variability of weather variables. This information will then be processed to obtain a series of average values for each sub-basin, in the same way as morphologic parameters. Connectivity between sub-basins will be established and so flow propagation will be calculated for the entire basin. A further step is planned in the future to be able to apply the balance equations to smaller areas, taking full advantage of the capabilities of the GIS. The following input data will be obtained from GIS: (a) geographic data: latitude; (b) hydrometeorology data: daily rainfall and mean daily temperature; depending on the PET method: daily bright sunshine values, relative humidity and windspeed data; (c) soil data: soil thickness, porosity, field capacity, wilting point, initial water content and vertical hydraulic conductivity; GIS information about morphologic parameters, soil type and its use, and geology, among others, will provide data; (d) crop type and irrigation rates: monthly irrigation rates, initial and last day of irrigation in each month and growing season duration (all of these obtained from data base and soil type); (e) rainfall interception: vegetation type and mean vegetation height (from soil type and forest inventory); (f) surface runoff computation: a-Horton's law: highest and lowest rate of infiltration (depending on morphologic parameters, soil type and use) and/or b-Curve Number: initial abstraction, number of sub-basin zones (specified by the user) and curve number for each zone (computed by the model from terrain and soil properties); (g) snow precipitation and melting processes (optional): these parameters will be fixed and calibrated by the user; (h) preferential flow (direct recharge), if selected: coefficients derived from the same data as soil parameters; (i) evapotranspiration: parameters used in each of the four available methods will be fixed by the user or obtained from the database and then calibrated; (j) unsaturated zone data: vertical hydraulic conductivity, interflow and percolation depletion coefficients; these parameters might be obtained from geologic information; (k) aquifer data: depletion coefficient, storage coefficient, transmissivity and reference water head; these parameters will be obtained from streamflow and hydrogeological data.

A post-processor to VISUAL-BALAN V2.0 output interface is being planned. The results of the hydrological model will be post-processed and then integrated in the basin GIS. Developments and modifications are being tested in the Valiñas River basin (La Coruña) and several representative sub-basins of the Ebre River basin in alluvial and karstic formations.

CONCLUSIONS

The main aspects of the VISUAL-BALAN V2.0 code have been presented. Its most recent developments include snow precipitation and evaluation of water balance in several sub-basins. On-going work is being performed to couple VISUAL-BALAN V2.0 to a GIS and develop pre- and post-processing interfaces. Current capabilities of VISUAL-BALAN are being extended to cope with distributed parameters for both surface water and groundwater, surface runoff routing, full integration of surface water and groundwater; and a physical representation of unsaturated water flow. These developments are being applied to two Atlantic basins in Spain (Valiñas River basin near La Coruña) and Serra da Estrela (Portugal), and a representative sub-basin in the Ebre River Basin.

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