

## AQUIFER RECHARGE EVALUATION BY A COMBINATION OF SOIL WATER BALANCE AND GROUNDWATER FLOW MODELS

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**RESUMEN.** *La evaluación de la recarga subterránea es difícil y por ello se debe abordar mediante la combinación de diferentes métodos. En este trabajo se presenta una metodología de evaluación de la recarga basada en la combinación de un modelo de balance de agua en el suelo (resuelto con el código BALAN) y un modelo de flujo subterráneo (resuelto con el código CORE). Se ha aplicado a la estimación de la recarga en el aluvial del Guadalquivir en Andújar (Jaén), donde se localiza la antigua Fábrica de Uranio de Andújar (FUA). El acuífero ha sido estudiado y modelizado desde el año 1988. Las versiones originales del modelo de balance de agua en el suelo proporcionaban estimaciones de la recarga excesivamente elevadas que se debían reducir a la hora de utilizarlas como entrada en el modelo de flujo del acuífero. Esta inconsistencia se ha soslayado mediante la recalibración del modelo de balance hídrico. La combinación del modelo de balance de agua en el suelo con el modelo de flujo subterráneo proporciona una estimación fiable y robusta de la recarga diaria tanto en las zonas de regadío como en la zona urbana, excepto en episodios de lluvias mensuales excepcionales con periodos de retorno entre 20 y 50 años. Se presenta la comparación de los niveles piezométricos calculados con BALAN usando una representación simplificada del acuífero, y con un modelo de flujo detallado resuelto con CORE. El modelo de flujo simplificado tiene una precisión suficiente para calcular los niveles piezométricos en las zonas de regadío.*

**ABSTRACT.** *Evaluation of groundwater recharge is a difficult task that must be undertaken by a combination of different approaches. Here we report a case study where a soil water balance model (solved with BALAN) has been combined with a groundwater flow model (solved with CORE) for the estimation of groundwater recharge in the Andújar alluvial aquifer (Jaén) near the Andújar uranium factory (FUA). The Guadalquivir alluvial aquifer near Andújar has been studied and modeled since 1988. The original period of water balance has been extended from 1988 to 2007. Early versions of the water balance model provided too large recharge estimates that had to be scaled down to reproduce measured groundwater levels. The water balance model has been recalibrated to overcome such limitation. The combination of water balance model and groundwater flow model provides robust and accurate estimates of daily groundwater recharge in cultivated and urbanized areas, except for a episodes of exceptional rainfall (monthly rainfall values of return periods of 20 to 50 years). Piezometric heads calculated with BALAN by using a simplified representation of the aquifer are compared to those computed with a detailed groundwater flow model solved with CORE in five points. The simplified model computes accurate piezometric levels in the irrigated area.*

### 1. INTRODUCTION

Aquifer recharge can be evaluated by a wide range of chemical, experimental and numerical methods. Reviews of different methods can be found in Gee and Hillel (1988), Allison *et al.* (1994), Grismer *et al.* (2000) and Scanlon *et al.* (2002). Grismer *et al.* (2000) focus on *field methods* for the evaluation of aquifer recharge in arid and semiarid regions. Field methods include soil-water balance, chloride mass balances and soil moisture monitoring. Numerical methods provide the recharge rate at the scale of the whole aquifer or a part of it (Samper,

1997). Soil-water balance models provide a way to quantify the water that percolates down to the water table. One of the main limitations of the water balance method is that it uses empirical parameters which sometimes are hard to calibrate. Recharge episodes usually produce the rise of the water table. Therefore, the recharge produced by a rainy episode can be inferred from piezometric rise data (Samper, 1997). However, this method is prone to errors due to difficulties to estimate storage coefficient and water table elevations (Rushton, 1987; Samper, 1997). Here we report a method to estimate the spatial and temporal variability of groundwater recharge by combining a soil water balance model a groundwater flow model. This method has been tested for the estimation of groundwater recharge in the Andújar alluvial aquifer (Jaén) near the Andújar uranium tailings pile (FUA). The applicability of this approach has been studied and tested by Samper *et al.* (1988), Davies-Smith *et al.* (1988), Handman *et al.* (1990) and Schuh *et al.* (1993). More recently, surface water and groundwater models have been integrated (Scanlon *et al.*, 2002). Sophocleous and Perkins (2000) coupled SWAT and MODFLOW to estimate aquifer recharge in Kansas, USA. Some physically-based, fully-distributed codes such as Mike-SHE have the capability of computing the soil water balance and the groundwater flow in an integrated manner (DHI, 2004).

## 2. COMBINATION OF WATER BALANCE AND GROUNDWATER FLOW MODELS

The combination of a water balance method with a groundwater flow model integrates two complementary methods. The combined method is tested with measured piezometric head data. Samper *et al.* (1988, 2004) were able to show that the integrated use of a water balance model and a groundwater flow model could provide an excellent estimation of groundwater recharge in the Guadalquivir alluvial aquifer. Samper *et al.* (2004) coupled a water balance code, BALAN (Samper *et al.*, 2007), and a groundwater flow code, CORE<sup>2D</sup> V4 (Samper *et al.*, 2003; 2009), to compute aquifer recharge.

BALAN computes the water balance in the soil, the unsaturated zone and the aquifer (Samper and García-Vera, 2004; Samper *et al.*, 1999, 2007). It considers rainfall and irrigation as inputs to the system and computes daily values of surface runoff, actual evapotranspiration and recharge. Figure 1 shows the sketch of the proposed methodology to compute groundwater infiltration recharge by a combination of water balance and groundwater flow modeling.

A first *a priori* estimate of recharge,  $R(t)$ , is obtained by assuming some initial hypotheses about infiltration mechanisms and for some initial parameter values of the water balance. Parameters of the water balance model are calibrated by solving the inverse problem. Discrepancies between computed and measured piezometric heads are used to modify the parameters and hypotheses of the water balance and groundwater flow models. The process of updating the models is performed in an iterative manner until computed piezometric heads reproduce measured values. According to Samper *et al.* (1995), this methodology leads to excellent results, although it requires a hard work to analyze the results in a critical manner.

## 3. EVALUATION OF RECHARGE OF ANDÚJAR ALLUVIAL AQUIFER

### 3.1 Introduction

The Andújar uranium tailings pile (FUA) is located in the Southwestern region of Andújar (Andalucía, Spain) in the left bank of the Guadalquivir river (see Figure 2). The tailings are located on the alluvial terrace of Guadalquivir river. The tailings have an approximate volume of  $10^6 \text{ m}^3$  and occupy an area of nearly 10 ha. The aquifer is located in the SW of Andújar. The limits of the aquifer are: 1) The river to the North; 2) The marls outcropping to the South; 3) Lines perpendicular to the river to the West and to East.

The main geological materials are Quaternary alluvial deposits (gravel, sand and silt) that are sub-horizontally disposed over the Miocene marls. These marls constitute almost an impermeable boundary. There are five levels of fluvial terraces at a regional scale, but only two of them are in the study zone. The study area is located in these two terraces. The contact of Quaternary materials and Miocene marls is from 6 to 10 m deep, and its depth increases from E to W. Alluvial deposits have the typical arrangement of meandering rivers with silt and clay on the top, sand in the middle and gravel at the bottom. The aquifer rests over the lower layer of gravel. The phreatic level is close to the base of the unit.

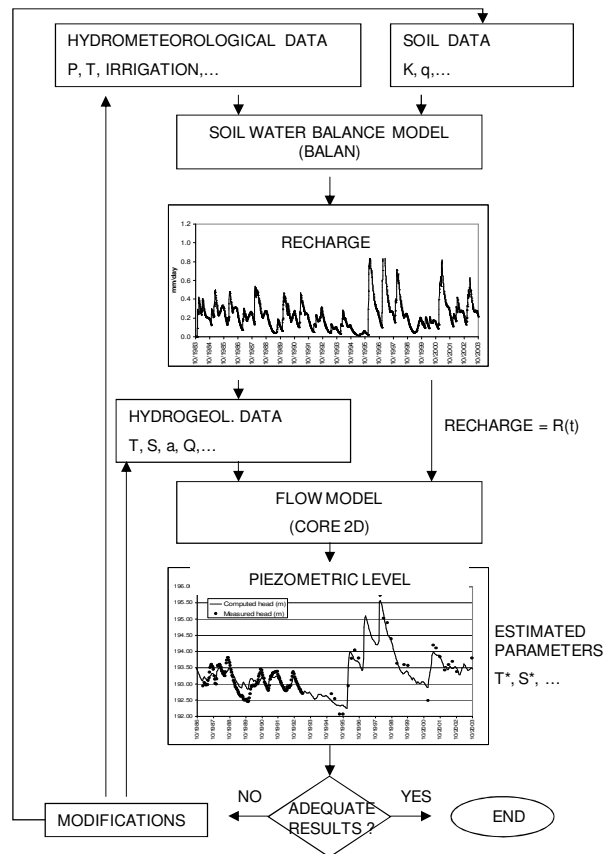


Figure 1. Flowchart of the iterative procedure for calculating aquifer recharge by a combination of a water balance model and a groundwater flow model (see Samper *et al.*, 1988).

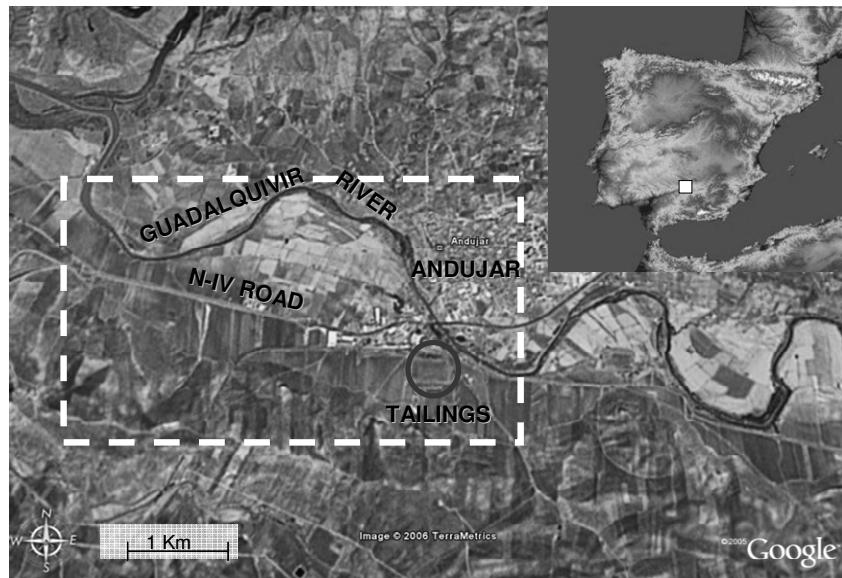


Figure 2. Location of the study area.

The general trend of the flow is SE to NW, but there are some local modifications due to the presence of paleochannels.

Water quality and piezometric data indicate that the aquifer is primarily recharged from irrigation return flow and rain infiltration. Leakage from below at the contact with the marls and mountain front recharge are negligible. Therefore, groundwater can be treated as two-dimensional. While the aquifer is phreatic, the fact that the most permeable materials are at the bottom of the aquifer suggest that except for exceptionally humid periods, transmissivity variations in response to water level changes are small (see Samper et al., 1988). On that basis, Samper et al. (1988) assumed that transmissivity was constant in time. Data collected from 1994 to 2004, however, showed that variations in saturated thickness were very important during exceptionally rainy periods (see Samper et al., 2004).

The spatial distribution of sediments is relatively homogeneous on a regional scale. However, the coarsest materials can be found in irregular deposits that locally modify the infiltration velocity. Aquifer discharge essentially consists of the outflow to the river, that can be free or submerged. Downstream of the Nuevo Puente de Andújar (Andújar's New Bridge), the Guadalquivir River is hydraulically connected with the aquifer. Upstream of this point the aquifer discharges to the river through natural springs. Groundwater discharge by pumping are negligible compared to natural discharges, except for very dry years.

### 3.2 Available data

A large amount of data have been used to construct the flow and transport model of the Andújar aquifer since the first version (Samper *et al.*, 1988) to the last update (Samper *et al.*, 2008). These data include: (1) Hydrometeorologic data, (2) Irrigation data, (3) Pumping data, (4) Changes in elevation of Marmolejo reservoir, (5) Chemical data and piezometric levels, and (6) Data on soil use.

Hydrometeorologic data include daily precipitation and mean daily temperature from 1983 to present day. Data about irrigation are incomplete. Annual volumes of irrigation are available, but their monthly distribution is unknown and had to be deduced from records of water distribution in a zone larger than the modeled one. The records of annual volumes cover the period from 1983 to 2003. The volumes of water pumped from the aquifer are recorded from 1989 to 1994. However, there are great uncertainties about these data, mainly related to uncertainties on the information provided by well owners.

The Marmolejo reservoir is used to generate electricity. Its water level determines the water level in the river upstream of the reservoir. Reservoir levels are recorded from 1989 to 1993 and from 1999 to present day.

Piezometric and chemical data are available for 132 wells and 81 boreholes, covering the period from 1977 to 2007. The current radiological monitoring network in the aquifer includes 14 wells and 7 boreholes where water samples are taken and every 3 months. Data on soil use and types of crops are available from aerial photographs, official records and field work.

### 3.3 Delineation of recharge zones

The primary sources of aquifer recharge are irrigation return flow and rain infiltration, accounting for nearly 95% of the groundwater flow. The remaining 5% comes from the Eastern boundary. Infiltration groundwater recharge has a strong influence on groundwater flow and uranium transport (Samper *et al.*, 1988). Therefore, the main mechanisms of the surface recharge have to be carefully analyzed in order to adequately model aquifer hydrodynamics.

The identification of recharge zones was carried out by a careful analysis of groundwater hydrographs. Hydrographs were arranged in several groups reflecting differences in soil use and thickness. Nine different recharge zones were delineated, including a urban zone near the tailings, 6 zones with irrigation crops, a zone near the train station and another zone which surrounds the uranium tailings inside the FUA property. Water balances were computed for each one of them (Figure 3).

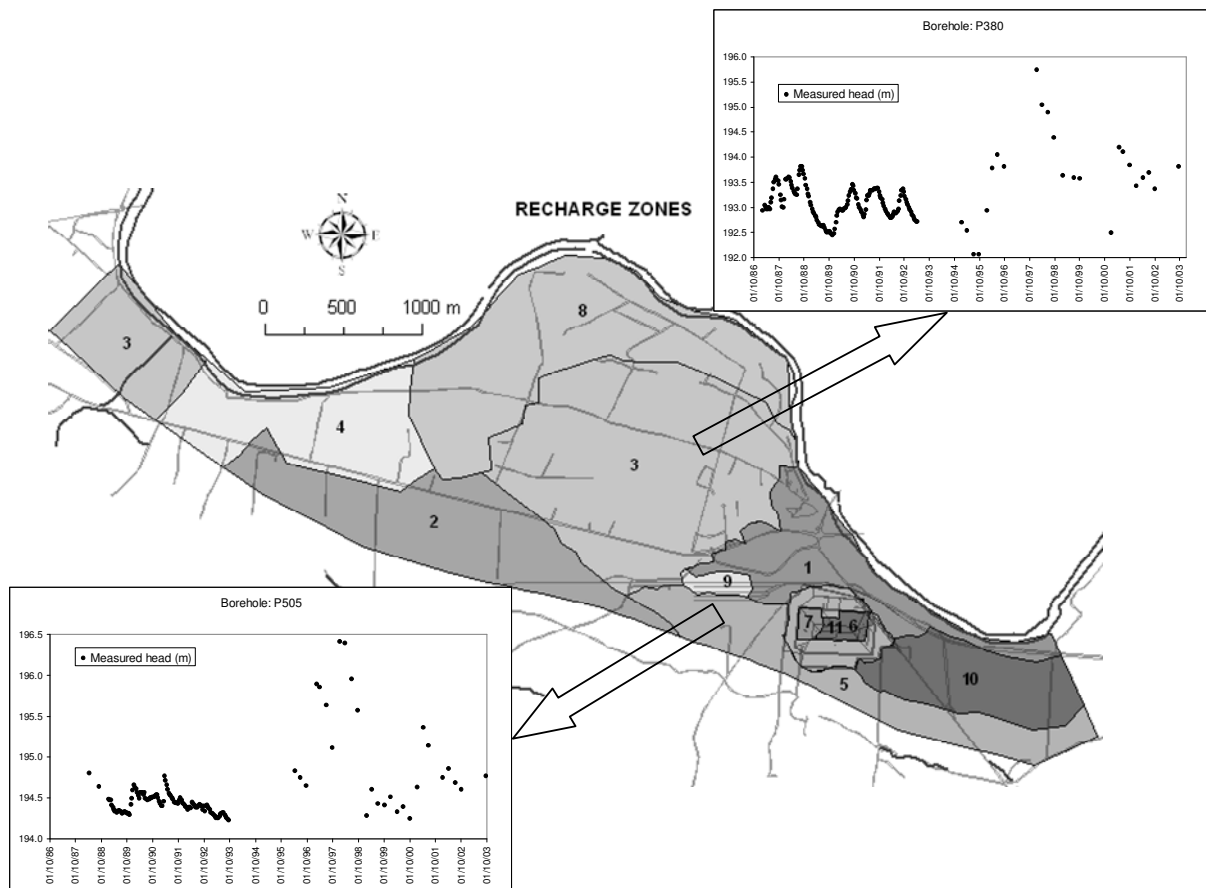
### 3.4 Recharge calibration

The calibration of recharge is part of the general process of model calibration, including parameters of the water balance and the groundwater flow models. The model was calibrated with data from 10/1983 to 09/2003. Calibration was carried out by trial and error, fitting computed heads to measured heads by visual comparison. A recharge time function  $R_i(t)$  was derived for each recharge zone  $i$ .

Recharge in the urban zone, near the tailings, is approximately 35 mm/year. Mean annual recharge values in irrigated zones range from 79 to 207 mm/year (see Table 1).

Four episodes of exceptionally large rainfall occurred from November 1995 to March 2001 (Table 2). Such episodes caused large surface runoff, infiltration and aquifer recharge. Due to these exceptional conditions, it was not possible to adequately calculate recharge with the water balance model. Consequently, recharge during these episodes was derived from water table data. Estimated recharge values for the rainy episodes are listed in Table 2.

Figure 4 shows computed and measured heads in two boreholes located in different recharge zones. The fit of computed heads to measured heads is quite acceptable, even for the rainy episodes of 1996-2001. The comparison between computed heads, before and after revising recharge during the rainy episodes, is also shown in Figure 4.



**Figure 3.** Map of recharge zones in the Andújar alluvial aquifer. Also shown are two illustrative hydrographs of zones 3 and 5 (adapted from Samper *et al.*, 2004).

### 3.5 Heads computed with BALAN

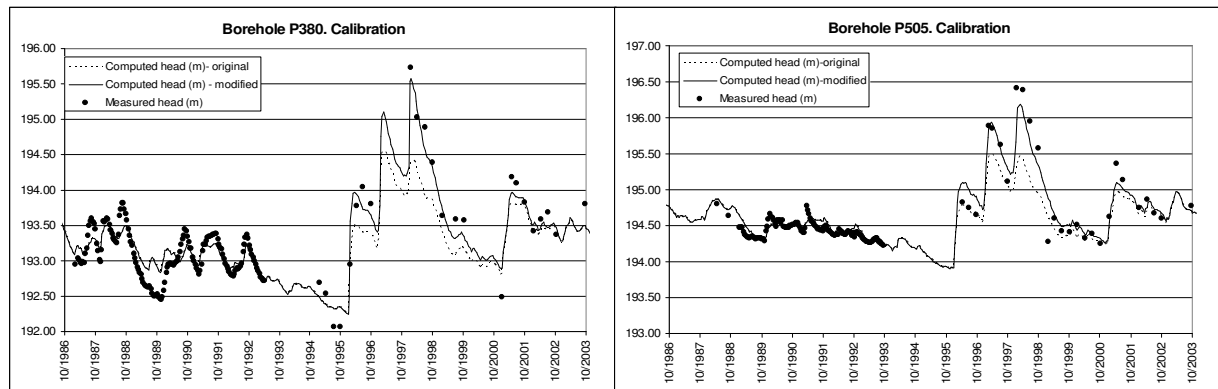
A study was conducted to evaluate if water table data could be reproduced with a simplified flow model. BALAN computes piezometric heads using a 1D finite difference method. Aquifer parameters were calibrated for 5 boreholes. Water heads were compared to those computed with a detailed flow model (Figure 5). In general, both models produce similar results and both fit well measured data. The results of the comparison show that a simplified flow model is sufficient to compute groundwater heads. Needless to say that the detailed flow model is still necessary to perform the simulation of uranium transport through the aquifer.

**Table 1.** Mean annual results of the water balance (mm).

	Recharge zone						
	2	3	4	5	8	10	11
Precipitation	505	505	705	505	505	505	505
Irrigation	397	402	402	403	402	403	0
Potential evapotranspiration	1442	1442	1442	1442	1442	1442	1442
Actual evapotranspiration	665	643	754	670	668	670	338
Interception	0	40	0	37	0	37	37
Preferential flow	40	52	44	25	40	25	0
Delayed potential recharge	62	54	163	54	63	54	36
Surface runoff	135	118	144	122	135	122	95
Aquifer recharge	102	106	207	79	103	79	36

**Table 2.** Estimation of recharge for the exceptionally rainy episodes. (\*) Additional recharge is the part of recharge not explained by the water balance model.

Period	Precipitation (mm)	Average water table rise $\Delta H$ (m)	Total recharge (mm)	Additional recharge (mm) (*)
Dec 1995-Jan 1996	470	1.41	155	93
Dec 1996-Jan 1997	466	1.45	160	74
Nov 1997-Dec 1997	411	1.53	168	84
Dec 2000-Mar 2001	472	1.1	121	24



**Figure 4.** Comparison of measured heads and those computed before and after revising recharge during rainy episodes in boreholes 380 and 505.

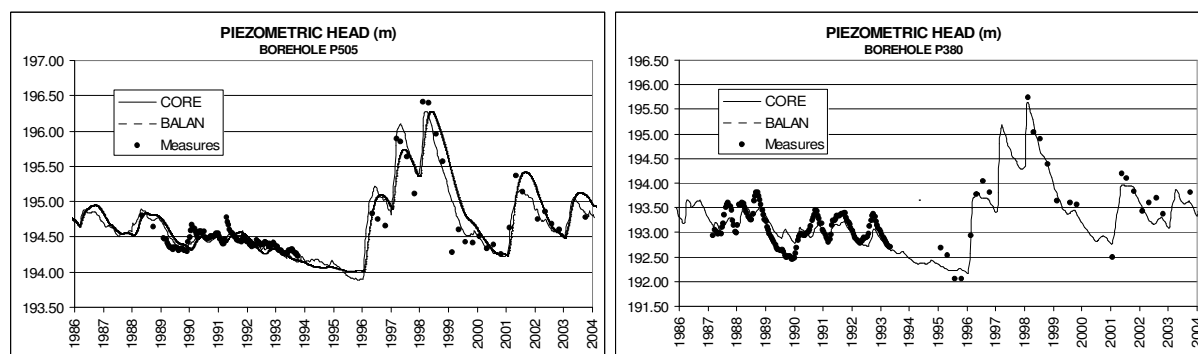


Figure 5. Comparison of measured and computed heads with CORE and a simplified flow model for boreholes 505 and 380.

#### 4. CONCLUSIONS

A robust method for evaluating the aquifer recharge has been presented which is based on the combined use of a water balance model and a groundwater flow model.

The water balance model incorporates geographical, physical, soil and daily hydrometeorological data. The methodology allows to estimate different recharge sources such as rainfall and irrigation.

The joint use of a soil water balance method with a flow model overcomes the lack of data for the water budget components which are frequently larger than recharge. Thus, accumulation of errors in recharge is minimized. The time evolution of recharge and its spatial distribution are usually difficult to estimate only with a flow model. This joint method overcomes such limitation.

The methodology has been applied to the Andújar alluvial aquifer. The water balance model is not able to estimate recharge during exceptionally rainy episodes. Recharge in such episodes had to be estimated from piezometric data.

A study has been conducted to evaluate if water table levels could be reproduced with a simplified flow model. The resulting water heads were compared with the results of a detailed flow model constructed with CORE. In general terms, both models produce similar results and a good fit to measured data. The results of the comparison show that a simplified flow model could be sufficient to compute piezometric heads in the aquifer.

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