Hydrogeological Water Balance in a Carbonate Hydro-Structure

SALVATORE MANFREDA, FRANCESCO SDAO, AURELIA SOLE
Dipartimento di Ingegneria e Fisica dell'Ambiente
Università degli Studi della Basilicata
via dell'Ateneo Lucano 10, 85100 - Potenza
ITALY
http://www.unibas.it/utenti/manfreda

Abstract: - Carbonate hydro-structures represent a strategic resource acting as a natural reservoir able to absorb incredible amount of water during rainfall events and releasing a significant outflow with reduced variability. This is typical of groundwater resources, but this structure may provide an extraordinary baseflow contribution to the streamflow. The present work focuses on a carbonate hydro-structure located over the Mountains of Lauria (Southern Italy). The eastern sector of this hydro-structure is the “Monte La Spina” aquifer formed by limestone and dolomitic limestone with different degrees of fissuring and, in places, karstic features. The study investigates on the hydrogeological water balance of the “Monte la Spina” aquifer using two different models: one based on an Inverse Water Balance scheme and the second based on a conceptual scheme for the water balance prediction. The modelling application highlighted the peculiarity of this aquifer in terms of temporal behaviour, using an extended simulation period, and the potential of the two models as a tool for water resources management.

Key-Words: - Hydrogeological Water Balance, Carbonate Hydro-Structures, Southern Italy.

1 Introduction

In view of an increasing water demand for various purposes like domestic, agricultural, and industrial use, a greater emphasis is laid for a planned and optimal use of groundwater resources. This makes more pressing the necessity to provide accurate estimates of the groundwater potentials in terms of effective recharge (e.g., volumes of effective infiltration) and groundwater outflows accounting for the temporal fluctuations of groundwater storage.

Investigations on ground water resources require an approach based on yearly or multiple years scale, because the processes involved evolve extremely slowly with time. For this reason, it is mandatory to base the analyses on a time window of at least one year that in most of the cases may be not sufficient to close the water budget.

Direct groundwater balance may be pursued straightforward adopting climatic, hydrogeological, geological data and data about artificial recharges or withdrawals (urbanizations, irrigations, etc). Moreover, a detailed description of water exchanges between neighbouring aquifers and superficial water bodies is also required.

In most of the cases, this amount of information is not available and, for this reason, one has to proceed with different methods. One may refer to the inverse technique proposed by Lerner et al. [8] and later modified by Civita [1]. This technique, also known as the inverse hydrogeological water budget, provides a first description of the mean annual components of the water budget.

Dealing with natural aquifer with reduced interconnections and in absence of irrigation of artificial withdrawals, one can also refer to schematic physically based models forced by meteorological data (e.g., daily rainfall, temperature, etc.). An example of a distributed model for the hydrogeological water balance is given by Portoghese at al. [12], where a simple scheme for soil water balance was adopted to evaluate agricultural water demands under different climatic and management scenarios in a semiarid environment. Furthermore, a lumped model (named AD2), describing the soil water balance and the groundwater recharge, is described in Fiorentino and Manfreda [7] and is applied in the present work to describe the soil water budget over time.

This paper deals with the hydrogeological water balance of the carbonatic aquifer of “Monte La Spina”. Analyses are carried out by means of the Inverse Water Balance scheme and the AD2 model with the aim to reproduce the yearly and daily dynamics of the considered carbonatic aquifer highlighting its peculiarities. Furthermore, adopted models may represent a useful tool for water resources management.

2 Hydrogeological and Morphological Features of the Hydro-Structure

The Basilicata Region (Southern Italy) is rich of good quality and barely contaminated groundwater resources, mainly flowing within large and deep carbonate and karstic hydro-structures of the main ridge of the Lucanian Apennines. One of the most important carbonate hydro-structure of the region, made-up by five huge aquifers, is located over the Mountains of Lauria. The Lauria's Mounts are constituted by an alignment of several mounts, such as La Spina Mt., Zaccana Mt., Rossino Mt. and Fossino Mt., that mark the boundary between Basilicata and Calabria regions, and, from a structural point of view, are made up of a series of parallel ranges, N120° trending, corresponding to positive morphostructures located in the western part of the Pleistocene fluvial-lacustrine basin of the Mercure river.

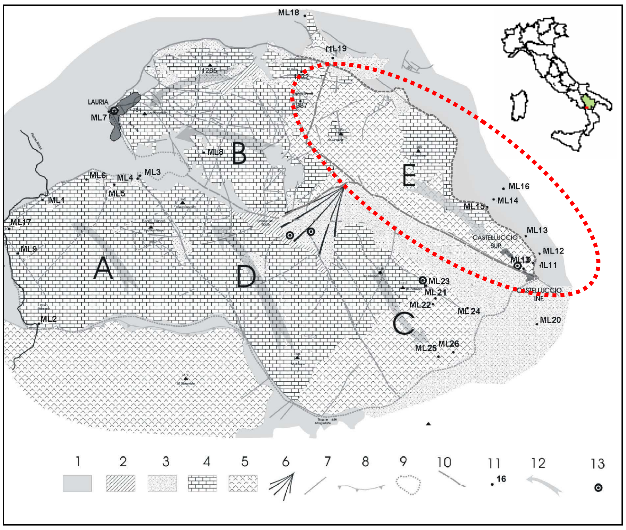

Fig. 1 – Hydrogeological description structure of Lauria's Mounts with the study area (sector E). La Spina Mt. 1) Clayey-marly complex; 2) detritic complex; 3) fluvio and lacustrine complex; 4) calcareous complex; 5) calcareous-dolomite complex; 6) detritic fan; 7) Faults; 8) Overthrust; 9) Boundary of Lauria Mountain hydrostructure; 10) watershed; 11) main springs; 12) groundwater flow directions; 13) wells.

The hydro-structure of Lauria's Mounts has an extend of about 100 Km^2, it is represented by a several-hundred-meters-thick calcareous-dolomitic hydrogeological complex characterized by high permeability due to secondary porosity. This hydro-structure is confined by important tectonic lineaments (faults and thrusts) that separate it from the other hydrogeological complexes characterized by lower permeability. It is fractioned in five large aquifers, characterized by peculiar hydrogeological and hydrodynamic features and distinct groundwater circulations, which are bounded by important faults and hydrogeological divides, along which interaquifer water exchange may occur. The groundwater system is generally phreatic and gushes out from 26 important springs characterized by an average overall discharge of about 1900 l/s producing an average volume of about 60 Mm^3/year.

The eastern sector of the "Monti di Lauria" hydro-structure is constituted by "Monte La Spina" aquifer. This last is the object of this study and is formed by limestone and dolomitic limestone that show different degrees of fissuring and, in places, karstic features (Fig. 1). This area is monitored since April 2004 with a meteo-climatic station, piezometric wells and a hydrometric equipment adopted with the aim to collect the spring water amount of the carbonatic aquifer and the eventual runoff contributions of the relative hydrological basin.

3 Rainfall Regime

The study area of "Monte La Spina" is one of the most humid of the Basilicata Region. In fact, the annual rainfall of the area may exceed 2000 mm per year as one may observe in Fig. 2 where the recorded annual rainfall (Fig. 2.A) and the standardized rainfall (Fig. 2.B) are plotted as a function of time.

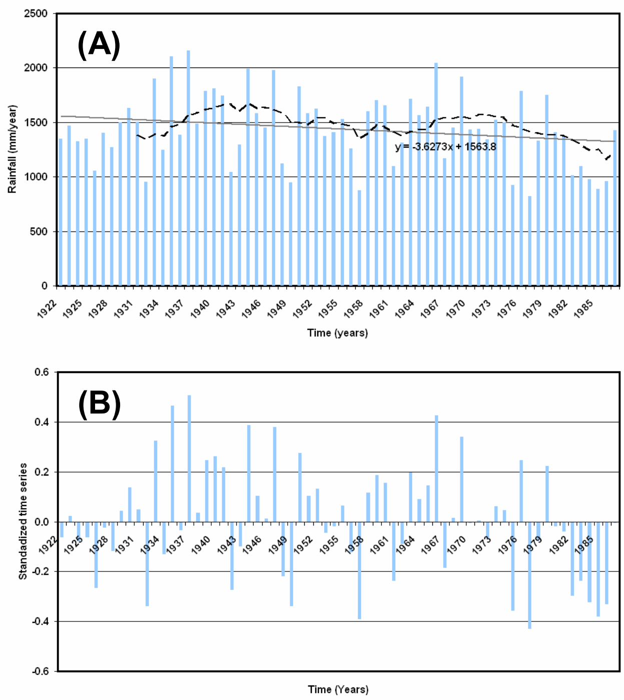

Fig. 2 – Rainfall time series recorded at Castelluccio Inferiore (Basilicata Region, Italy) during the period 1922-1987 (A) and standardized time series of rainfall (B). In the first graph, the continuous grey line describes the trend of the series through a linear fit to the data and the dashed line is the moving average over ten years. In the second graph, the standardized variable are obtained as the ratio between the reduced variable $(Y-\overline{Y})$ divided by the mean $\overline{Y}$.

The main characteristics of the rainfall regime are investigated using the records of the rain gauge of Castelluccio (located inside the territory of interest). Rainfall data covers a period of about 66 years (from 1922 up to 1987) and shows a critical reduction of the rainfall amount that is also confirmed by the moving average over ten years and by the linear fit reported in Fig. 2.A. This reduction may reflect negatively on ground water resources and requires deeper investigations that is carried out through the modelling applications described in Section 6.

4 Inverse Hydrogeological Water Balance

The Inverse Hydrogeological Water Balance [1,8,2,3] was proposed to evaluate the average annual active recharge (i.e. the effective infiltration - I) within a GIS environment. It is applied at each grid cell (EFQ) by which the territory of interest is discretised. It involves a series of steps which are summarized in the following points [3] (see also Fig. 3):

1. georeferencing the positions of the existing pluviometric and thermometric gauging stations inside or immediately outside the area of interest;
2. selection and reconstruction of contemporary records for sufficiently long periods (10 - 20 years);
3. calculation of the monthly and annual average of the pluviometric and thermometric data for each gauging station;
4. calculation of the corrected annual average temperature (T_C) as a function of the rainfall;
5. calculation of the rainfall-elevation [$P=f(q)$] and corrected temperature-elevation functions [$T_C=f(q)$].

The functions described above, valid for the whole study area, are used to compute the soil water balance within each elementary cell:

6. calculation of the mean elevation ($\overline{q}$) of each EFQ;
7. calculation of the specific rainfall ($\overline{P}$), on the basis of points 5 and 6;
8. calculation of the specific evapotranspiration ($\overline{Er}$), on the basis of points 4, 5 and 6, using the TURC model;
9. calculation of the specific effective rainfall ($\overline{Q}=\overline{P}-\overline{Er}$, for each element of the grid) on the basis of points 7 and 8;
10. identification of the *potential infiltration coefficients*, χ, on the basis of the surface lithology, the soil texture, the fracture index (FI), the karstification index (KI), the land use, etc. (for instance a set of coefficients χ is given in Table 1, but a more detailed description can be found in [13]);

Hydrogeological complex	Potential infiltration coefficients χ
Karst- fissured carbonate complex	0.85
Highly fissured carbonate complex	0.80
Fissured carbonate complex	0.70
Highly fissured dolomitic carbonate complex	0.70
Fissured dolomitic carbonate complex	0.60

Table 1 – potential infiltration coefficients as a function of the Hydrogeological complexes.

11. calculation of the specific active recharge ($\overline{I}$) and the specific surface runoff ($\overline{R}$), on the basis of points 9 and 10 ($\overline{I}=\overline{Q}\ \chi$; $\overline{R}=\overline{Q}-\overline{I}$).
12. calculation of the recharge and surface runoff.

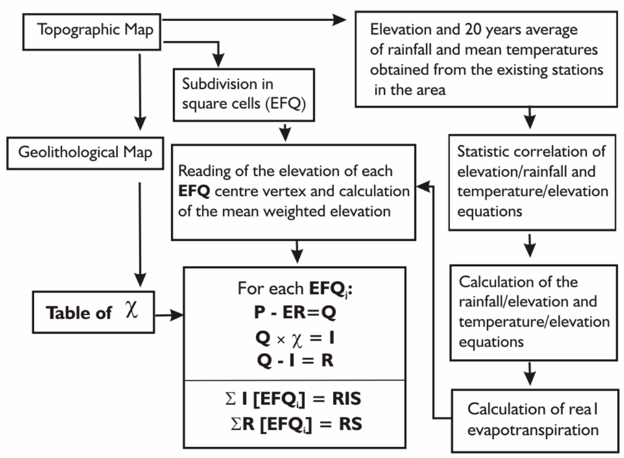

Fig. 3 – Flow-chart of the inverse balance method.

For each cell, one has to calculate all hydrogeological water balance components described above. The results of the method applied to the "Monte La Spina" aquifer are reported in Table 2. The data of Table 2 shows that the amount of groundwater active recharge is around to 445 l/s. This value is averaged over 30 years of observations (1969 – 1999).

Variable	Mm^3/year	l/s
Specific Rainfall (P)	28.7	911
Specific Evapotranspiration (Er)	9.3	295
Specific Effective Rainfall (Q)	19.4	616
Specific Active Recharge (I)	14	445
Specific Surface Runoff (R)	5.4	171

Table 2 – Value of hydrogeological inverse balance parameters.

5 Daily Simulation: AD2 Model

In order to deepen our description of the aquifer dynamics, simulations have been extended at the daily scale using a lumped model, called AD2 model [7], able to reproduce the ground water recharge and soil water balance at basin scale. The model has been calibrated adopting the streamflow records of the hydrological watershed that collects the spring water of the described carbonatic hydrostructure.

The hydrological elements relevant for a correct soil water balance, at this scale, are: 1) the precipitation input; 2) superficial infiltration into the soil; 3) direct overland flows; 4) subsurface flow; and 5) deep infiltration into groundwater.

In the hydrological modelling, the soil state may significantly influences the basin behaviour [10] and it is therefore necessary to take into account its variability. To this end, Manabe [9] suggested that the land surface water balance can be simulated by using a simple model of effective soil storage. Farmer et al. [6] defined bucket models of appropriate complexity mainly oriented to ungauged basin prediction. In the present case, we defined a bucket scheme to simulate the soil water storage state over an extended time window.

The soil moisture storage is the quantity of water held, at any time, in the active soil layer. It varies in time depending on rainfall, interflow and groundwater recharge, according to the following water balance equation:

$$S_{t+\Delta t} = S_t + I_t - R_{out,t} - L_t - E_t \qquad (1)$$

where: $S_{t+\Delta t}$ [L] is the total water content of the bucket at time $t+\Delta t$, I_t ($I_t = P_t - R_t$) [L] the infiltration amount during the time-step Δt, $R_{out,t}$ [L] the subsurface out-flow in Δt, and L_t [L] the leakage in Δt.

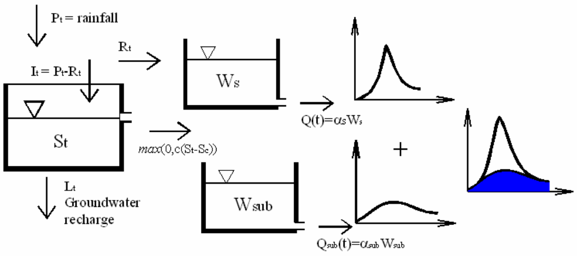

Fig. 4 – Lumped model scheme used to interpret the basin response.

The runoff is modelled adopting a runoff coefficient that depends on the water content [5], the original equation has been modified in order to account for the saturation effect of the soil:

$$R_t = \begin{cases} C\left(\dfrac{S_t}{S_{\max}}\right)P_t & se \quad P_t \le P_c = \dfrac{S_{\max}(S_{\max}-S_t)}{(S_{\max}-CS_t)} \\ P_t - (S_{\max}-S_t) & se \quad P_t > P_c = \dfrac{S_{\max}(S_{\max}-S_t)}{(S_{\max}-CS_t)} \end{cases} \qquad (2)$$

where R_t [L] is the amount of surface runoff, P_t [L] the precipitation, S_t [L] the total water content of the bucket at time t, S_{max} [L] the maximum water storage capacity of the bucket, and C [-] the default runoff coefficient. Equation 2 states that the runoff is proportional to the soil water content until the cell reaches the saturation state, after that point there is no more infiltration into the soil and all the precipitation becomes runoff.

The model accounts for the subsurface production assuming that the subsurface flow constitutes a fraction of the water exceeding a given threshold. The subsurface outflow is evaluated by the following equation

$$R_{out,\ t} = max\{0, c(S_t - S_c)\} \qquad (3)$$

where S_c [L] is the threshold water content for subsurface flow production, and c [1/T] is the subsurface coefficient.

The evapotranspiration is assumed a function of the soil content and the potential evapotranspiration according to the following equation [11]

$$E_t = \max\left\{0, \min\left\{EP\left(\frac{S_t - S_w}{0{,}75\,S_c - S_w}\right), EP\right\}\right\} \qquad (4)$$

where EP [L] is the potential evapotranspiration, S_w [L] is the threshold water content for the evapotranspiration.

The groundwater recharge is evaluated according to Eagleson [4]

$$L_t = k_s\left(\frac{S_t}{S_{\max}}\right)^{\beta}\Delta t \qquad (5)$$

where: L_t [L] is the groundwater recharge in Δt, k_s is a parameter that interprets the permeability at saturation [L/T], β is a dimensionless exponent. Hydrological loss such as vegetation interception is neglected.

The discharge is computed adopting a linear reservoir schematization for the surface, subsurface and groundwater flow (Fig. 4). Therefore, the discharge at the outlet is evaluated as the sum of the following components:

$$Q(t) = Q_s + Q_{sub} + Q_b = \alpha_s W_s + \alpha_{sub} W_{sub} + \alpha_G W_G \qquad (6)$$

where: Q_s [L^3/T] is the discharge due to the superficial runoff, Q_{sub} [L^3/T] is the subsuperficial flow, Q_b [L^3/T] is baseflow contribution, W_s [L^3] is control volume of the generated runoff, W_{sub} [L^3] is control volume of the generated subsurface runoff, W_G [L^3] is control volume of the generated leakage, and finally α_s, α_{sub} and α_G [T] are the runoff recession constant, the subsurface runoff recession constant and the groundwater recession constant.

6 Model Applications and Results

The AD2 model has been applied to the present study case where streamflow records of the installed hydrometric station. The results of the monitoring campaign has been used in order to calibrate and validate the hydrological model AD2. An example of its application is given in Fig. 5, where one may appreciate a good agreement between the simulated hydrograph with the recorded one. This graph describes the model validation run over a time period of approximately one year (1/1/2006-1/2/2007) obtained using the calibration parameters of Table 3.

AD2 parameters	
Area [kmq]	19.22
C [-]	0.02979
S_{max} [mm]	534.76
S_c [mm]	417.13
S_w [mm]	288.46
k_s [mm/g]	7.14
β [-]	2.77
C [-]	0.01
α_{sup} [1/day]	1.0
α_{sub} [1/day]	0.488
α_G [1/day]	0.005

Table 3 – AD2 calibration parameters.

Model performances have been evaluated trough the use of the Root Mean Square Error (RMSE), the linear correlation R^2, and an efficiency coefficient CR1 that describes the ability of the model to reproduce low flows. In particular, CR1 is computed through the following equation

$$CR1 = 100\left(\frac{\sum_{i=1}^{n} \left(\log(Q_{ci} + r) - \log(Q_{oi} + r) \right)^2}{\sum_{i=1}^{n} \left(\log(Q_{oi} + r) - \log(\overline{Q}_o + r) \right)^2} \right) \quad (7)$$

where Q_{oi} = observed discharge, $\overline{Q}$ = mean value of the observed discharge, Q_{ci} = is the simulated discharge, and r is a positive arbitrary number used to avoid zeros in the logarithm operator.

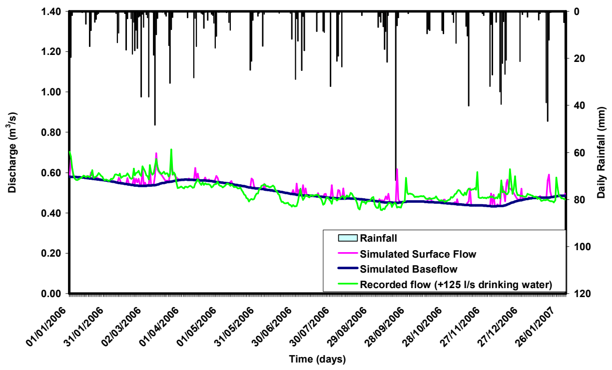

Fig. 5 – Comparison of the recorded streamflow and the AD2 simulation results referred to a period from 1/1/2006 to 1/02/2007 (RMSE = 0.028, R^2 = 0.75, CR1=74.3%).

AD2 is also applied over a longer time window in order to allow further investigation on the behaviour in time of this aquifer. In particular, the model is applied in retrospective using a 66 years rainfall series from 1922-1987. Results of this application are shown in Fig. 6, where it is interesting to observe the behaviour of the simulated flow.

Even if the rainfall series have a clear decreasing trend over the considered period (see Fig. 2), this does not reflect significantly on the simulated streamflow series. The discharge has lowered its values in the last period but the time series does not have a marked negative trend. The only significant change that one can observe is that the surface runoff contribution has been reduced significantly (of approximately 75%) in the last period (1982-1987).

The soil water dynamics are preserved in the range of variability observed in rainfall. Nevertheless, further reductions in the rainfall amount may produce a non linear effect that will certainly reflect on the soil water balance and also on the ground water recharge.

Study period: 1922-1987	**mm/year**	**l/s**
Mean Rainfall	1442.3	879.0
Mean Evapotranspiration	586.7	357.6
Mean value of the surface and subsurface contributions to the streamflow	33.2	20.2
Mean active recharge	822.4	501.3
Mean streamflow	855.6	521.5

Table 4 – Mean values of rainfall, evapotranspiration and streamflow computed using the long term simulation obtained using rainfall data from 1922-1987.

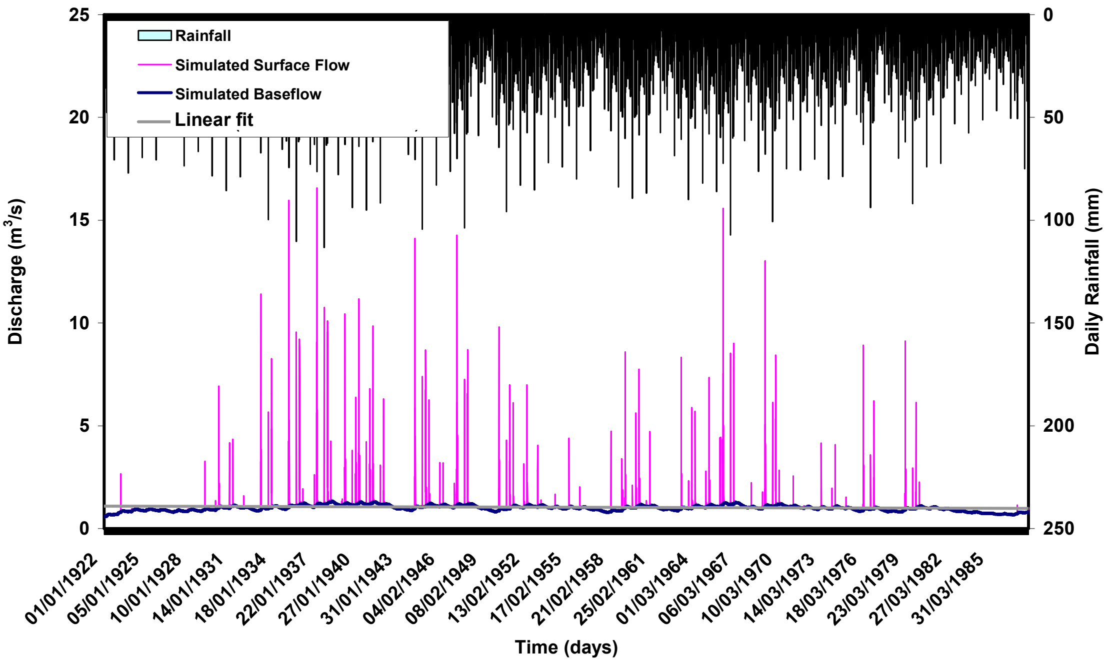

Fig. 6 – Reconstructed time series of streamflow obtained trough the AD2 forced by the rainfall time series recorded at the rain gauge of Castelluccio Inferiore (Basilicata Region, Italy). The grey line is a linear fit to our time series that is almost parallel to the x-axes.

7 Conclusion

The present study was aimed to define the hydrogeological water balance of the aquifer of "Monte La Spina" through the use of two models: one based on an inverse water balance scheme and the second based on a conceptual model for water balance prediction. The two models follow a different approach and use different time scales: the inverse hydrogeological water balance is based on mean annual rainfall computed over 30 years of records (1969-1999); the AD2 model is forced by daily data (1922-1987). Furthermore, the parameter of the model AD2 have been calibrated and validated using data recorded in the last two years (2005-2006) obtained through an experimental hydro-meteo station.

Results allowed to draw to following considerations: i) the inverse hydrogeological water balance is a rapid and efficient method to evaluated the average annual active recharge of the aquifer, in fact this last is very close to the one estimated by the AD2 model; ii) AD2 model allowed, using a finer time-scale (daily), the description of the aquifer dynamics in time and the quantification of the water balance budget.

Moreover, it is worthwhile to remark that the long-term simulations obtained via AD2 model highlighted that the aquifer outflow do not follow the same negative trend observed in the rainfall time series. This may be due to a drastic reduction of the surface runoff and may be in part due to the karstic nature of this aquifer.

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References:

[1] M. Civita, L'infiltrazione potenziale media annua nel massiccio del Matese (Italia meridionale). Atti 2° Conv. Intern, Acque Sotterranee, Palermo, 1973.

[2] M. Civita & M. De Maio, SINTACS: un sistema parametrico per la valutazione e la cartografia della vulnerabilità degli acquiferi all'inquinamento. Metodologia e automatizzazione. Pitagora Ed. Bologna, 1997.

[3] M. Civita, M. De Maio, Average groundwater recharge in carbonate aquifers: a GIS processed numerical model, VII Conference on Limestone Hydrology and Fissured media, Besancon Francia, 2001.

[4] P.S. Eagleson, Climate, soil and vegetation, *Water Resources Research*, 14, 705-776, 1978.

[5] F.H. De Smedt, L. Yongbo and S. Gebremeskel, Hydrologic Modeling on a Catchment Scale using GIS and Remote Sensed Land Use Information, *Risk Analysis II*, C.A. Brebbia (Ed), WIT press, Southampton, Boston, pp. 295-304, 2000.

[6] D.L. Farmer, M. Sivapalan and C. Jothityangkoon, Climate, soil and vegetation controls upon the variability of water balance in temperate and semi-arid landscapes: Downward approach to hydrological prediction, *Water Resources Research*, 39, NO. 2, 1035, 2003.

[7] M. Fiorentino and S. Manfreda, La stima dei volumi di piena dell'Adige a Trento con riferimento al rischio di inondazione, 29° Convegno di Idraulica e Costruzioni Idrauliche, Trento, ISBN 88-7740-382-9, Editoriale Bios, Vol. 2, p. 115-122, 2004.

[8] D.N. Lerner, A.S. Issar, I. Simmers, Groundwater recharge. A guide to understanding and estimatine natural recharge. IAH Int. Contr. To Hydrogeol., 8 Heise, Hannover, 345 pp, 1990.

[9] S. Manabe, Climate and the ocean circulation: 1. atmospheric circulation and the hydrology of the earths surface, *Mon. Weather. Rev.* 97(11), 739-774, 1969.

[10] S. Manfreda, M. Fiorentino, V. Iacobellis, DREAM: a distributed model for runoff, evapotranspiration, and antecedent soil moisture simulation, *Advances in Geosciences*, 2, 31–39, 2005.

[11] P. Milella, Uso integrato di modellistica matematica e di tecniche di telerilevamento per la stima del bilancio idrologico di un bacino (tutors: V. Iacobellis and I. Portoghese), Thesis of the Polytechnic of Bari, 2006.

[12] I. Portoghese, V. Uricchio, M. Vurro, A GIS tool for hydrogeological water balance evaluation on a regional scale in semi-arid environments, Computers & Geosciences, Vol. 31, No. 1, 15-27, 2005.

[13] F. Sdao and A. Sole, Consulenza scientifico-tecnica per la definizione dell'Idrologia, Idrogeologia e Potenzialità Idrica dell'Acquifero carbonatico di Monte La Spina e del fronte sorgentizio San Giovanni di Castelluccio Inferiore in Basilicata. Rapporto finale – Convenzione tecnico scientifica pp. 144, 11 allegati. DIFA UNIBAS – Comune di Castelluccio Inferiore, 2006.