19

The Role of the Evapotranspiration in the Aquifer Recharge Processes of Mediterranean Areas

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1. Introduction

Evapotranspiration is an important natural process controlling the amount of recharge into the aquifers, and relative groundwater fluctuations.

The main factors controlling the evapotranspiration processes can be distinguished in: (i) temperature and humidity of the air, (ii) water condition of the soil, and (iii) land-use and pedological characteristic of the catchment.

Air temperature and humidity are the main climate variables controlling the evapotranspiration processes; based on theoretical formula, evapotranspiration is an non-linear function of the temperature and humidity, depending also on the radiation and wind velocity.

The evapotranspiration processes increase in function of the soil water availability; generally the maximum rate of the evapotranspiration occur when soil is at field capacity and decrease rapidly when soil water tends to be near wilting point, independently from other variables.

Land-use has a great importance in evapotranspiration processes, and in particular the type and distribution of the vegetable cover. Generally, in the Mediterranean climate area evapotranspiration processes reached the maximum stage during spring time, and can lead the soil to wilting point for some vegetable species. Only endemic and autochthonous species are able to resist over the dry season without any water supply.

Usually the actual evapotranspiration is difficult to evaluate, and generally is determined indirectly from water balance of the soil cover. In many practical cases, the evapotranspiration can be estimate from the comparison of rainfall with potential evapotranspiration.

Based on monthly scale, the difference between rainfall and potential evapotranspiration is a first useful tool to evaluate the recharge processes of aquifers. However, a detailed approach needs an evaluation of the hydrological soil balance at daily scale, which allows to identify the amount of the rainfall which is free to percolate into the aquifer, recharging the water table, or run out from the aquifer.

An application on two nearby karst systems, the Terminio-Tuoro and Cervialto system, belonging to Picentini mountain, Southern Italy, have been carried out. These karst systems feed important karst springs, which supply with water several million of people in Campania and Puglia regions. They are monitored by several climate stations, and spring discharges are measured since the beginning of last century.

In the karst systems the runoff amount can be very small due to both high permeability of the rock outcropping which favours infiltration processes and the presence of wide endorheic areas. These characteristics allow to compare the output (spring discharge) with input (afflux), evaluating the role of the evapotranspiration on the recharge processes.

2. Geological and hydrogeological features

The Picentini Mountains constitute a large karst system in the Campania region of Italy, over 600 km^2 wide (Fig.1).

Outcropping rocks in the region primarily belong to the calcareous and calcareous-dolomite series (Late Triassic-Miocene), are 2500 m thick, heavily fractured and faulted and frequently reduced to breccias. These karstic rocks are mantled by pyroclastic deposits of Vesuvius activity, which play an important role in the infiltration of water into the karst substratum below. The calcareous-dolomite series are tectonically bounded by terrigenous and impermeable deposits, constituting complex argillaceous (Paleocene) and flysch sequences (Miocene). Quaternary continental deposits, including slope breccias and debris and alluvial and lacustrine deposits, cover the marine substratum. General geological features of the Southern Apennine can be found in Parotto and Praturlon (2004) and ISPRA (2009).

All the slopes are covered by pyroclastic deposits, due to late Pleistocene-Holocene volcanic activity of Vesuvius. As a consequence of volcanic eruptions and weathering processes between deposition events, the pyroclastic mantle is generally composed of several irregular, ashy pumiceous layers, alternating with buried soil (Fig.2). Generally the thickness varies from steep slopes to flat/gentle slopes, from few decimetres to several metres. However, along the Cervialto slopes, rarely the pyroclastic mantle reaches 1 m thick, due to higher distance from Vesuvius. Some geotechnical characteristics of the pyroclastic mantle are shown in Table 1. These slopes are covered mainly by trees of beech and chestnut, and subordinately by trees of pine, fir, birk and oak.

From a hydrogeological point of view, the northern sector the Picentini mountain is formed by two main karst systems: the Terminio-Tuoro and Cervialto. These karst systems feed powerful springs, generally located along the tectonic contact between the carbonate rocks and flysch sequences.

The main karst springs fed by the Termino-Tuoro system (Civita, 1969) are the Serino springs (Acquaro-Pelosi, 377-380 m a.s.l., and Urciuoli, 330 m a.s.l.) located on the western side, along the Sabato river; the Sorbo Serpico springs located on the northern side; the Cassano springs (Bagno della Regina, Peschiera, Pollentina and Prete springs, 473-476 m a.s.l.) located on the eastern side, along the Calore river.

The Cervialto system (Celico & Civita, 1976) feeds the Caposele spring (Sanità, 417 m a.s.l.) located on the eastern side, which constitutes the main outflow from the aquifer.

The two karst systems present a different distribution of the ground-elevation, as can be seen in figure 3. In particular, over 70% of the Cervialto catchment lies above 1000 m a.s.l., with the peak at 1200-1300 m a.s.l, whereas only 30% of the Terminio-Tuoro catchment lies above 1000 m a.s.l., with a peak at 800-900 m a.s.l. These different features have an important role in the snow accumulation during the winter period and have consequences on the spring regimes.

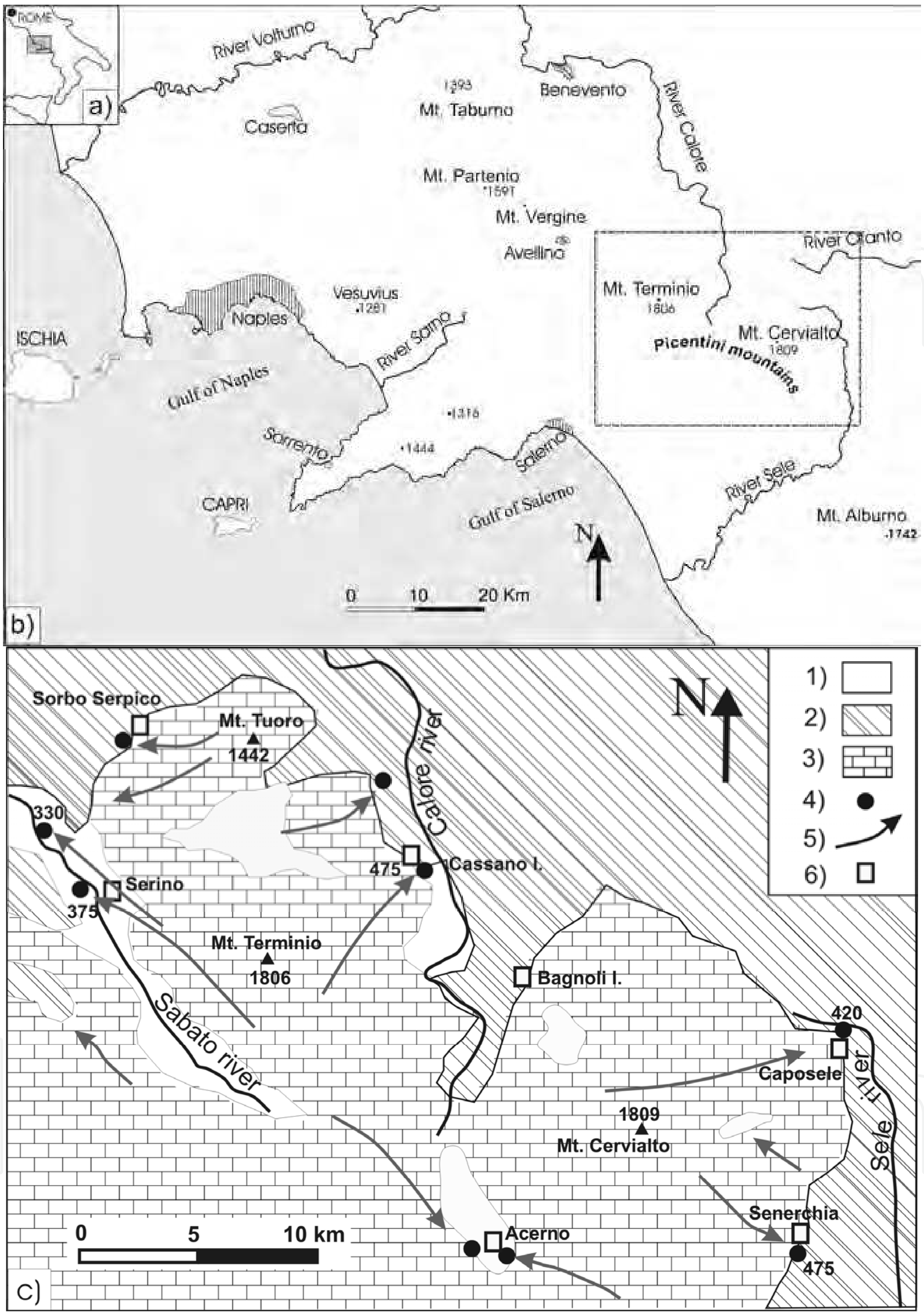


Fig. 1. a) Southern Italian peninsula. b) Map of the Western Campania region. Delimited rectangular area is detailed in c). c) Hydrogeological map of the Northern Picentini Mountains. 1) Slope breccias and debris, pyroclastic, alluvial and lacustrine deposits (Quaternary); 2) argillaceous complex and Flysch sequences (Paleogene–Miocene); 3) calcareous-dolomite series (Jurassic–Miocene); 4) main spring; 5) groundwater flow direction; 6) main village.

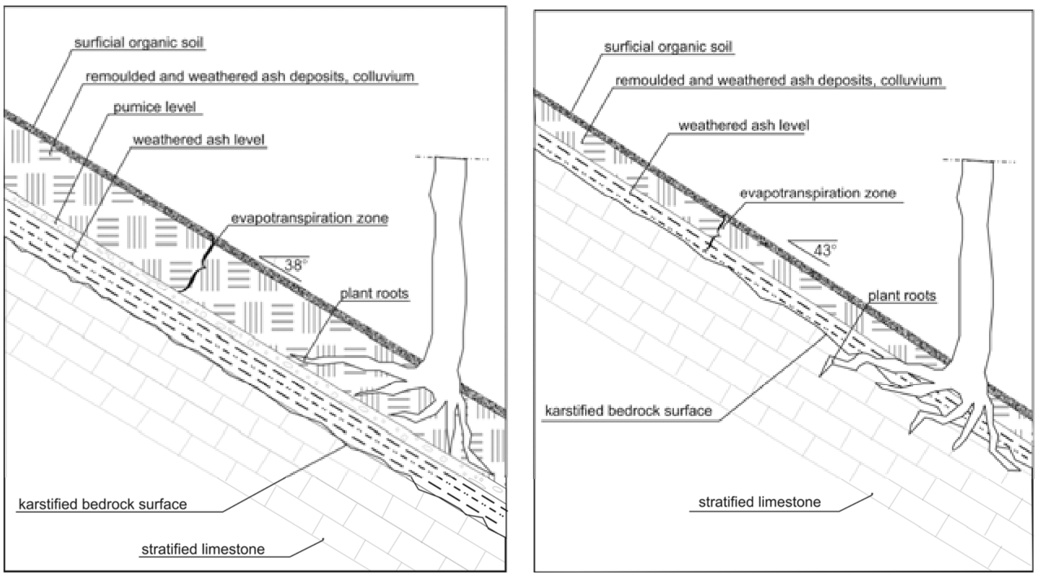


Fig. 2. Schematic profile of a typical slope of high-elevated zones of the Campania region (overlapping and thickness of the levels are schematised). Pumice levels limit plant roots development in the upper zone of the soil mantle (left); plant roots reach the karst substratum if pumice levels are absent (right).

Level	Gs (-)	clay (%)	silt (%)	sand (%)	gravel (%)	γ_d (kN/m^3)	n (-)	n_{eff} (-)
B_w	2,55	5	20	54	21	10,8	0,57	0,05÷0,07
C	2,55	-	2	52	46	8,1	0,68	0,33÷0,37
B_t	2,55	15	25	60	-	8,3	0,67	0,05÷0,06

Table 1. Some geotechnical characteristics of the pyroclastic soil (extracted from Fiorillo & Wilson, 2004). B_w, weathered and remoulded ash deposits; C, pumice level; B_t, weathered ash level; G_s, specific gravity; γ_d, dry bulk density; n, total porosity; n_{eff}, effective porosity.

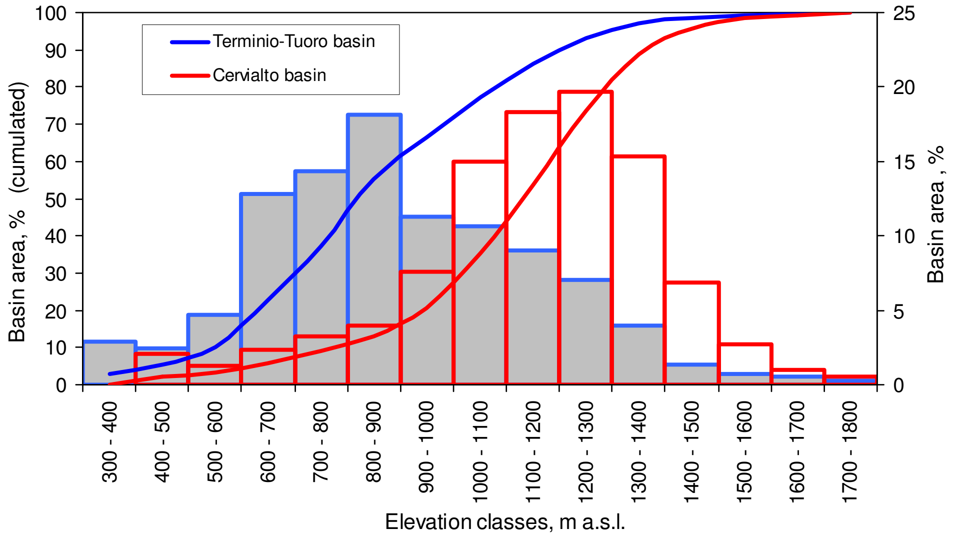


Fig. 3. Elevation classes distribution of the Terminio-Tuoro and Cervialto basin.

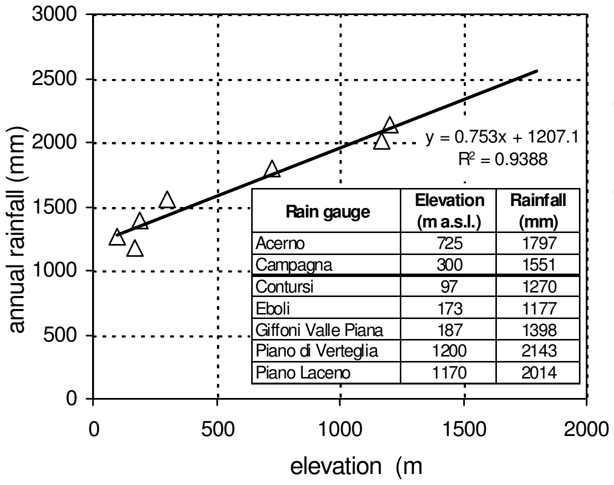
3. Climate and hydrological features

The region is located in an area characterised by typical Mediterranean climate, with dry and warm summer and a wet period that occurs during autumn, winter and spring. Table 2 reports some climate parameters of four local stations, with exception of the high-elevation Montevergine climate station (20 km NW from Mt. Terminio, figure 1a), which records data since 1884.

Station, m a.s.l.	autumn		winter		spring		summer		year	
	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P (mm)	T (°C)	P; σ (mm)	T (°C)
Caposele, 426	390	10,9	471	5,5	298	14,3	123	19,3	1250; *255*	12,2
Cassano, 456	434	11,2	490	5,4	297	11,1	117	20,0	1344; *320*	11,9
Serino, 374	432	12,1	502	5,1	301	10,8	115	19,7	1352; *280*	11,9
M.Vergine, 1270	662	9,5	705	1,0	500	6,2	193	16,1	2174; *587*	8,2

Table 2. Seasonal (autumn, winter, spring and summer) and annual mean values of the Caposele, Cassano, Serino and Montevergine climate stations. P, precipitation; T, temperature; σ, standard deviation. Mean of precipitation period 1930-2006 (1884-2006 for Montevergine rain gauge) and mean of temperature period 1950-2000.

Rainfall spatial distribution depends strongly on the ground-elevation as can see in figure 4. Figure 5 shows the annual mean rainfall distribution along the northern sector of the Picentini mountains, based on the available rain gauge stations, and adding further fictitious rain gauges in the high-elevated zones. Rainfall distribution rapidly decrease along the northern and eastern sector of the Picentini mountains, as consequence of the Atlantic origin of the main meteorological storms.



Rain gauge	Elevation (m a.s.l.)	Rainfall (mm)
Acerno	725	1797
Campagna	300	1551
Contursi	97	1270
Eboli	173	1177
Giffoni Valle Piana	187	1398
Piano di Verteglia	1200	2143
Piano Laceno	1170	2014

Fig. 4. Annual mean rainfall in relation to elevation. A high-significance regression line is obtained using rain gauges located along the western side of the Picentini mountains, as the main precipitations come from Atlantic zone.

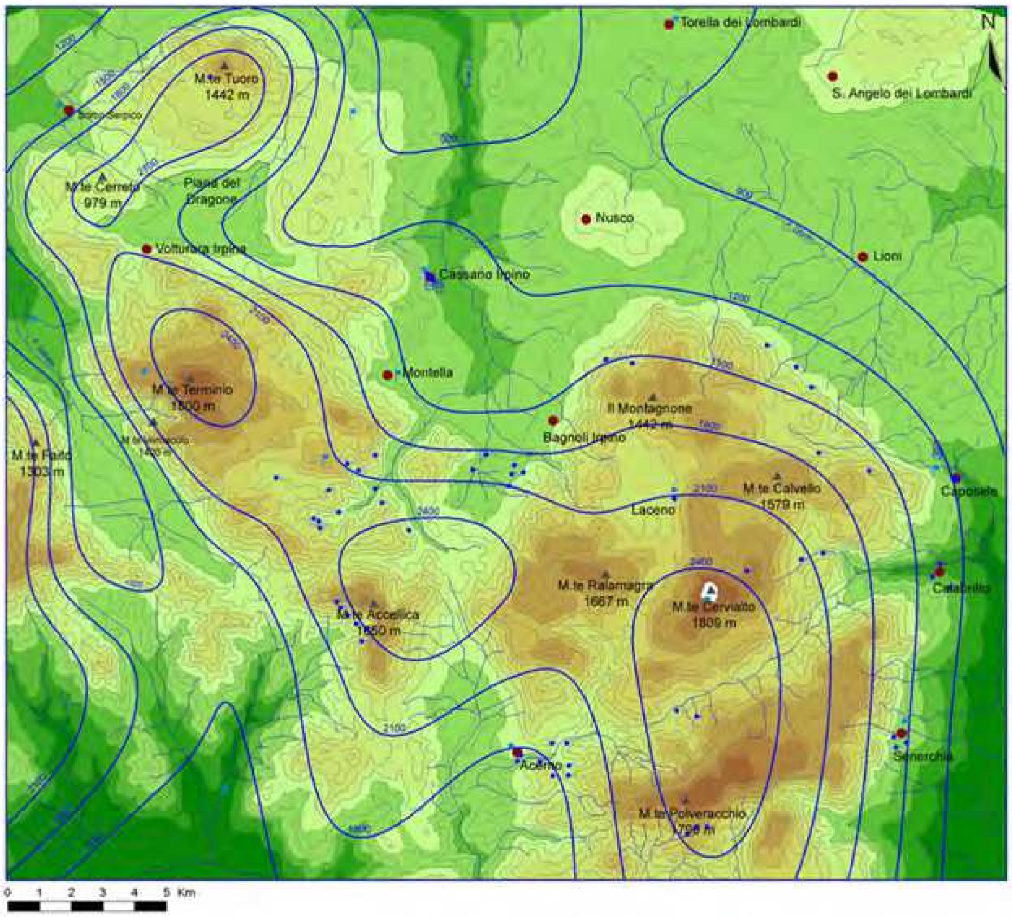


Fig. 5. Annual mean rainfall along the northern sector of the Picentini mountain, based on available rain gauges and other added following the relation in Fig.4. IDW method has been used to plot isohyets.

Monthly rainfall distribution, evapotranspiration and recharge have been evaluated for an high and low elevation zone (Figs. 6-7). Figures 6a and 7a show the monthly rainfall distribution, P_i; to consider the effect of the evapotranspiration, the effective rainfall, P_{eff}, has been also plotted as difference P_i-E_p=P_{eff}, where E_p is the potential evapotranspiration computed by the method of Thornthwaite (1948); for values of P_i<E_p, effective rainfall has been fixed null (P_{eff}=0). The effective rainfall expresses the amount of rainfall which is free to charge the soil moisture, to percolate and charge the groundwater, or runs off. Generally during the spring and mainly the summer, due to high rate of evapotranspiration, the effective rainfall, P_{eff}, is null; however, high-elevation areas (Figure 6a) present higher precipitation and lower temperature, and are characterised by shorter period of null effective rainfall.

As consequence of the rainfall increase and evapotranspiration processes decrease with ground-elevation, high-elevated zones are characterised by value of recharge (R=1582, figure 6) more than twice respect to low-elevated zone (R=755 mm, figure 7). However, the recharge values of figures 6 and 7 should be reduced, as unknown amount of rainfall runs off. A further evaluation of the recharge and of the evapotranspiration processes can be deducted from the ratio between output from the catchment (spring discharge) and the annul mean rainfall of each hydrogeological catchment.

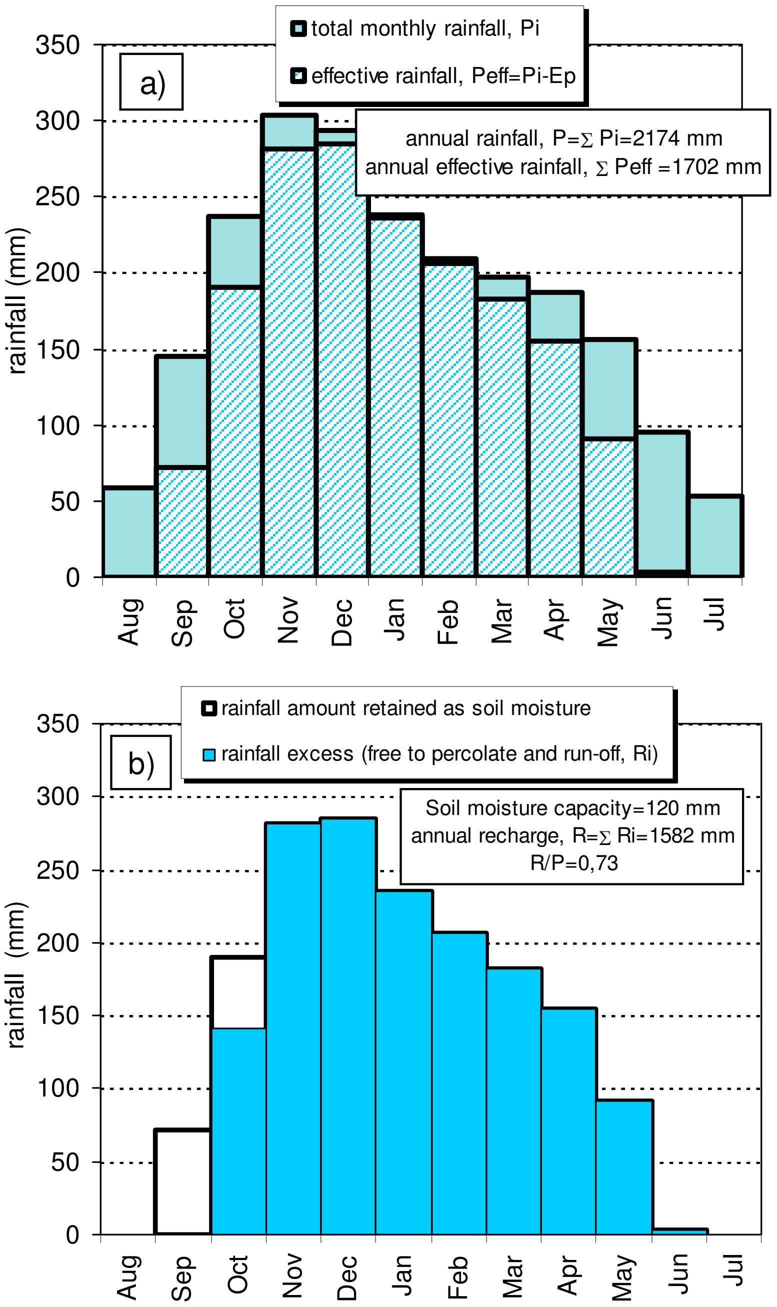


Fig. 6. High-elevated rain gauge (Montevergine, 1270 m a.s.l.). a) monthly rainfall, P_i, and effective rainfall, P_{eff}, through the hydrological year. Monthly potential evapotranspiration, E_p, has been computed by the Torthwaite (1948) method. b) rainfall free to infiltrate and percolate, R_i, though the hydrological year, obtained subtracting the soil moisture capacity (c=120 mm) from the effective rainfall, P_{eff}. The annual recharge, R, is obtained by difference between annual effective rainfall and soil moisture capacity (R=1702-120=1582 mm).

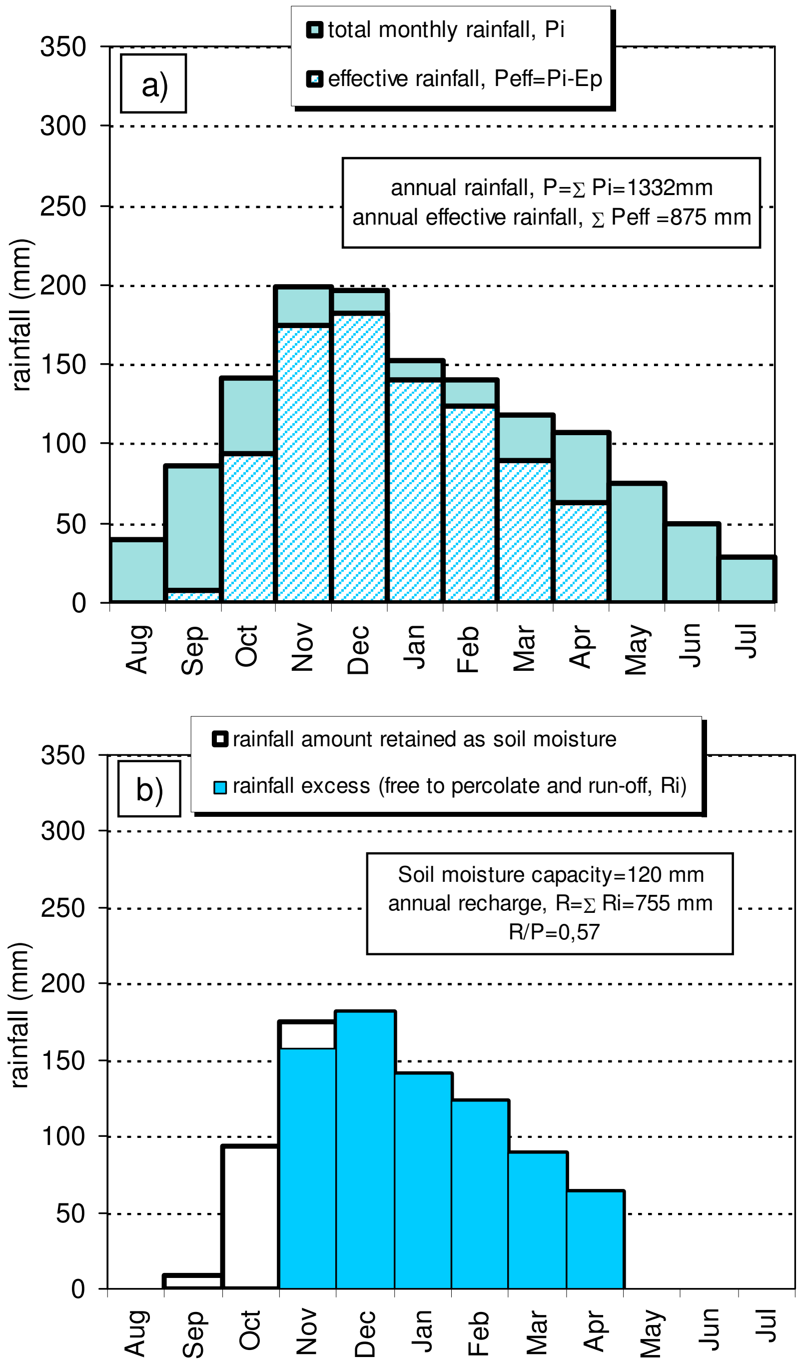


Fig. 7. Low-elevated rain gauge (Serino, 374 m a.s.l.). a) monthly rainfall, P_i, and effective rainfall, P_{eff}, trough the hydrological year. Monthly potential evapotranspiration, E_p, has been computed by the Torthwaite (1948) method. b) rainfall free to infiltrate and percolate, R_i, though the hydrological year, obtained subtracting the soil moisture capacity (c=120 mm) from the effective rainfall, P_{eff}. The total recharge, R, is obtained from the difference between the total effective rainfall and the soil moisture capacity (R=875-120=755 mm).

The annual mean rainfall of each hydrogeological catchment (afflux) has been evaluated in *Arc*GIS environment, using the regression found in figure 4a. The results are shown in Table 3.

Elevation classes (m a.s.l.)	Computed rainfall (mm)	Terminio-Tuoro basin		Cervialto basin	
		Area (Km^2)	Afflux (m^3 x10^6)	Area (Km^2)	Afflux (m^3 x10^6)
300 - 400	1455	5.14	7. 48	0	0
400 - 500	1545	4.31	6.66	2.43	3.75
500 - 600	1621	8.36	13.55	1.42	2.30
600 - 700	1696	22.68	38.47	2.71	4.59
700 - 800	1771	25.42	45.03	3.71	6.57
800 - 900	1847	32.18	59.43	4.59	8.48
900 - 1000	1922	19.98	38.41	8.7	16.72
1000 - 1100	1997	18.83	37.61	17.3	34.56
1100 - 1200	2072	15.97	33.10	21.09	43.72
1200 - 1300	2148	12.44	26.72	22.66	48.68
1300 - 1400	2223	7.03	15.63	17.7	39.36
1400 - 1500	2298	2.46	5.6	7.9	18.16
1500 - 1600	2374	1.33	3.16	3.13	7.43
1600 - 1700	2449	0.9	2.20	1.16	2.84
1700 - 1800	2524	0.46	1.16	0.63	1.59
Total		*177.49*	*334.31*	*115.13*	*238.77*

Table 3. Annual mean rainfall distribution of different elevation classes, computed by the regression line of figure 4. Afflux is the product of the area and rainfall height.

The outputs from the catchments have been computed by the annual mean discharge from the springs, and are shown in Table 4. The recharge of the Cervialto basin is higher than that of Terminio-Tuoro basin, according to higher ground-elevation of the basin which favours an higher afflux. Besides, the recharge values computed in table 4 are lower than the mean of the recharge computed in figures 6 and 7, confirming that an amount of rainfall leaves the catchments as run off.

However, each procedure presents some doubts: in the first case (Figs.6-7), the main uncertainty is the evaluation of the effective rainfall, as any method to compute potential evapotranspiration cannot be considered foolproof (Ward and Robinson, 2000).

The second procedure presents the main uncertainty in the evaluation of the rainfall distribution with ground-elevation, which can only roughly determined. A recent method to estimate the recharge has been proposed by Andreo et al. (2008) by a parametric method developed in GIS environment, which considers the altitude, slope angle, lithology, infiltration and soil nature (APLIS).

Basin	Springs group	Annual mean discharge (m^3/s)	Annual mean discharged volume (m^3x10^6)	*Total afflux* (m^3x10^6)	Recharge (%)
Terminio-Tuoro	Serino	2.25	69.98	*334.31*	50.1
	Cassano I.	2.65	82.43		
	Sorbo S.	0.43	13.37		
	Montella	0.15	4.67		
	Total	*5.48*	*170.45*		
Cervialto	Caposele	4.00	124.42	*238.77*	54.3
	Bagnoli I.	0.07	2.18		
	Others	0.10	3.11		
	Total	*4.17*	*129.70*		

Table 4. Output from Terminio-Tuoro and Cervialto basins by the annual mean spring discharge. Recharge has been computed by the ratio between Total output and Total afflux.

4. Daily scale analysis of recharge processes and evapotranspiration role

The soil mantle of the mountains here considered has a fundamental role in the evapotranspiration processes, as it retains an amount of rainfall at the beginning of the rainy season, to satisfy the water deficit accumulated during the previous dry period. The nature, physical characteristics and thickness of each soil stratum, together with the vegetation cover, control the soil storage capacity.

Below, some variables have been fixed on the basis of in situ observations, and allow to carry out a preliminary simulation of the evapotranspiration and recharge processes.

In the study area the soil undergoing evapotranspiration can be fixed at h=50 cm, as plant roots reach depth between 40 and 60 cm along the slopes of the Picentini mountains. Plan roots can cross the pyroclastic mantle and anchor directly into karst substratum. However, pant roots are unable to cross the pumice layers (Fig.2); these levels act as a drainage sheet, and break the root grooving deeply. As consequence, the evapotranspiration processes occur prevalently in the upper part of the pyroclastic mantle, deeply limited by the first pumice level. In situ suction measurements highlight the increasing of the suction toward summer, the decreasing towards autumn; below pumice level the suction tends to be constant during the year. Fiorillo and Wilson (2004) estimated the following parameters for the pyroclastic mantle of Campania slopes:

- (volumetric) water content at field capacity, θ_{max}, 51%;
- minimum water content reached at the end of dry season (summer), θ_{min}, 27%.

If the evapotranspiration processes occur similarly into all soil thickness (50 cm), and based on the technical characteristics of the soil mantle (table 1), the soil storage capacity, *m*, is 120 mm. The soil generally reaches the field capacity (θ_{max}) by October and November, and remains at or near that level until April. During this period, any additional rainfall percolates down, recharging the water table of carbonate aquifers, or runs off as surface stream flow. Between July and August, the moisture content of the pyroclastic cover is reduced to its minimum level (θ_{min}). To increase the water volumetric content from θ_{min} up to θ_{max}, an amount of 120 mm of water is needed, corresponding to the fixed soil storage capacity, *m*. Due to evapotranspiration processes, this amount of water corresponds to an higher amount of rainfall, up to 200-250 mm, depending on the temporal distribution of the daily rainfall.

In order to evaluate the soil moisture conditions and periods of the recharge periods, a hydrological balance of the pyroclastic soil has been carried out, based on the method of Thornthwaite (1948), adapted at daily scale (Fiorillo & Wilson, 2004). A wet and dry hydrological year are shown in figure 8 and 9, respectively.

Figure 8a shows daily rainfall of 2005-06; the total cumulative rainfall reaches the value of 1812 mm, which is higher than annual historical mean (1352 mm). In figure 8b, rainfall excess occurs during October and April, when soil moisture reaches the field capacity (Θ_{max}=51%); the rainfall excess is able to percolate deeply into the aquifer and recharge the water table, and a minor part is drained as runoff. Fig.8c shows the hydrograph of Bagno della Regina spring (Cassano Irpino group). Note that single rain event (daily rainfall) has no direct influence on the spring discharge, which generally is characterised by one or several smoothed peak during spring season (Fiorillo, 2009). These behaviour is connected to wide catchment area and to thickness of the vadose zone, which can reach value higher than 1000 m, specially for the Caposele spring catchment. The pyroclastic mantle reduces rapid infiltration into the karst system, which may also contribute to the smoothed shape of the spring hydrographs. The cumulative rainfall excess (Fig.8c) increases up late April; after that, due to rainfall decrease and evapotranspiration increase, no groundwater recharge occur. During this period, spring discharge decreases up to the next recharge, and the hydrograph generally shows a typical concave shape.

Note that at beginning and at the and of the hydrological year, the spring discharge is 1,07 and 1,16 m^3/s, respectively; this means that the recharge of wet years can influence positively the spring discharge of the following year (Fiorillo, 2009).

Figure 9a shows daily rainfall of 2001-02; the total cumulative rainfall reaches the value of 902,5 mm, which is well below than annual historical mean (1352 mm). The 2001-2002 was the driest year recorded in many rain gauges of southern Italy (Fiorillo & Guadagno, 2010), and caused an extreme hydrological drought (Tallaksen and Van Lanen, 2004) in a wide area of the Mediterranean basin. In figure 9b, rainfall excess occurs between late November and May; this amount of rainfall was unable to increase the spring discharge, which shows a continuous decreasing trend in Fig.9c. Besides, at the beginning and at the and of the hydrological year, the spring discharge is 0,67 and 0,19 m^3/s, respectively; this means that the recharge of the dry years influence negatively the spring discharge of the following year (Fiorillo, 2009).

During the 2001-02, about half of the total rainfall is lost by evapotranspiration processes (432 mm). This amount is comparable to that of 2005-06 wet year (485 mm), indicating that the amount of the evapotranspiration appears to be almost the same during dry or wet year in this area. Thus, the main factor influencing the recharge in this area seems to be the annual rainfall, as evapotranspiration processes waste almost the same amount in any hydrological year in this area.

However, the amount of the evapotranspiration water depends strongly on the soil moisture capacity, *m*. In order to evaluate the different role of the soil moisture capacity on the evapotranspiration water amount, the rainfall excess has been computed considering different value of *m*. Figure 10 shows the results obtained for the 2001-02 and 2005-06 years, where is possible to observe from the higher to smaller value of the soil moisture capacity

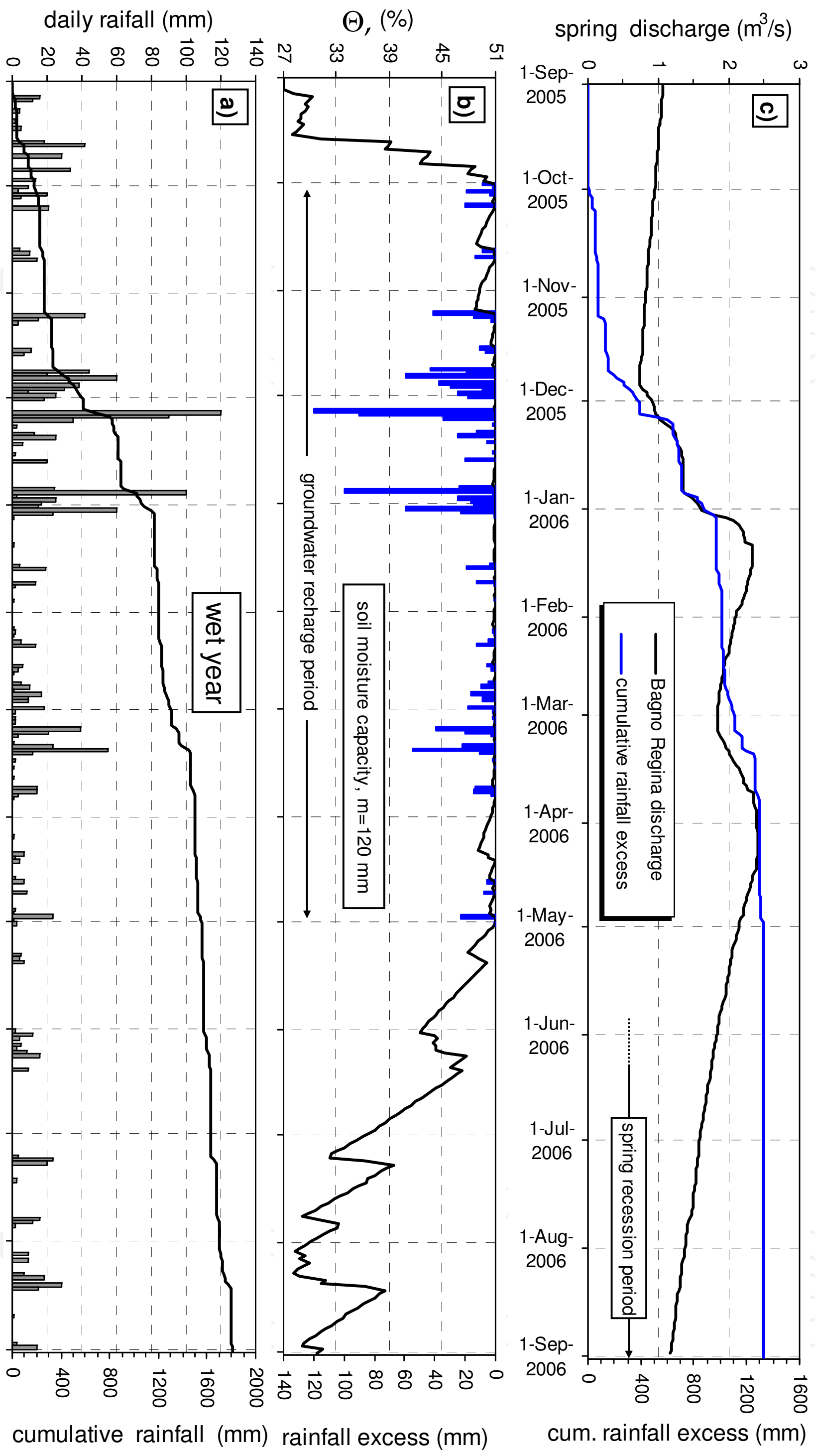


Fig. 8. Hydrological characteristics of the 2005-06 wet year; Serino rain gauge (374 m a.s.l.). a) daily and cumulative rainfall. b) (volumetric) water content, Θ, computed from daily hydrological balance (Θ_{min}=27% and Θ_{max}=51% have been fixed by laboratory test, Fiorillo and Wilson, 2004); rainfall excess (histogram) expresses the rainfall surplus after that maximum soil water content has been reached (Θ_{max}=51%). c) clean positive trend of the cumulative rainfall excess causes the spring discharge increasing; the flood of late March-early April has been connected to snow melting.

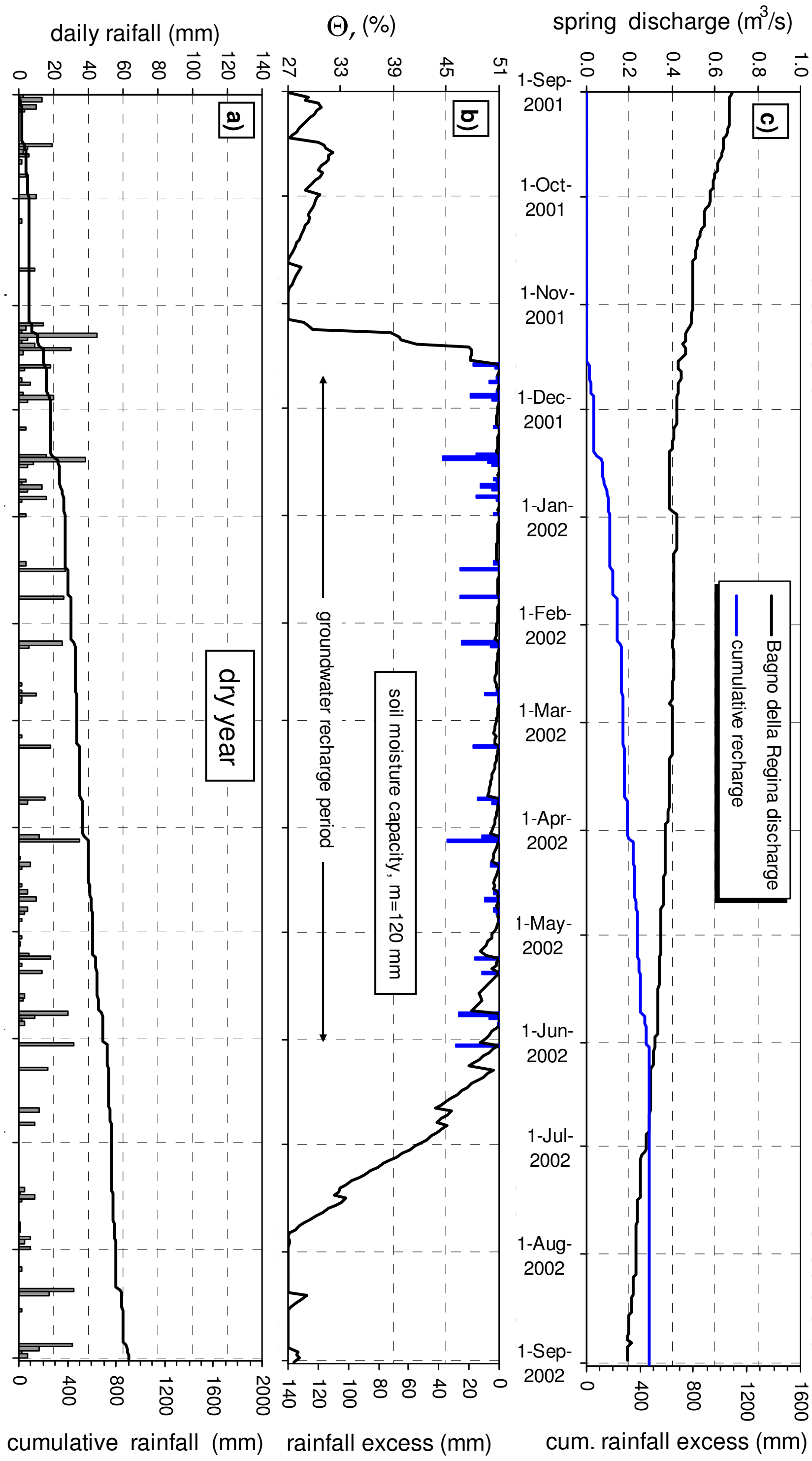


Fig. 9. Hydrological characteristics of the 2001-02 dry year; Serino rain gauge (374 m a.s.l.). a) daily and cumulative rainfall. b) (volumetric) water content, Θ, computed from daily hydrological balance (see figure 8). c) the weak positive trend of the cumulative rainfall excess is unable to increase the spring discharge, which show a continuous decreasing trend.

the linear decrease of the (cumulative) rainfall excess and the linear increase of the evapotranspiration. The trends are linear and parallel, indicating that (i) the differences of the rainfall excess between the two years are almost the same, and (ii) the amount of evapotranspiration, for a fixed soil moisture capacity, dos not depend on the annual rainfall.

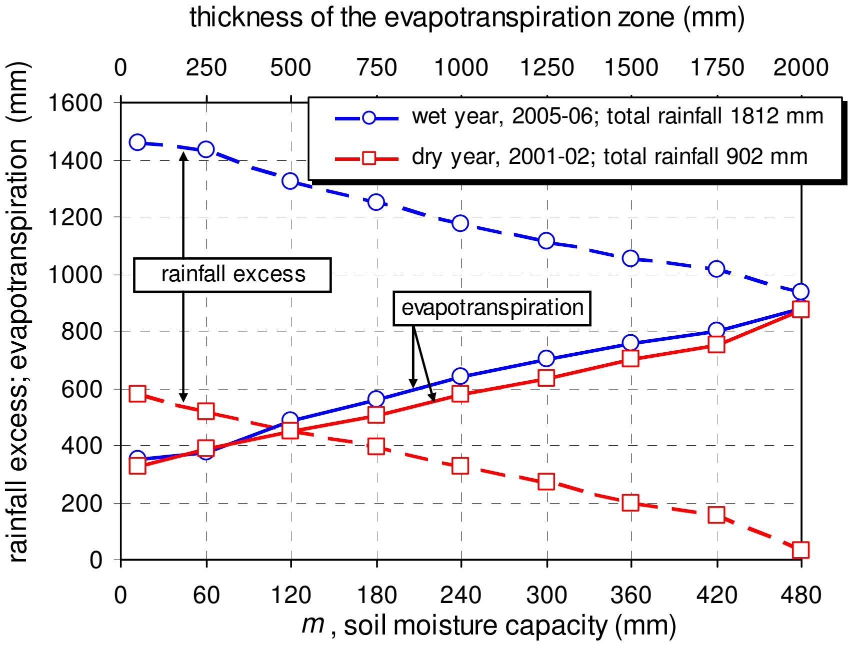


Fig. 10. The dependence of the rainfall excess and evapotranspiration from the soil moisture capacity (data from Serino rain gauge, 374 m a.s.l.). Thickness of evapotranspiration zone is also shown, under hypothesis of homogenous proprieties of the soil and uniform evapotranspiration processes (see text for details).

5. Conclusion

In a typical mountain karst environment of Mediterranean area, the effect of the evapotranspiration processes during the hydrological year cause important consequence on the groundwater recharge processes. During the spring season, due to decrease of the rainfall and increase of the temperature, generally recharge do not occur from late April, and remains almost null up to following autumn. Generally, rainfall occurring during the spring-summer period are completely lost by evapotranspiration processes or adsorbed by the soil mantle as soil moisture, to reduce the water deficit accumulated in previous days. During this period, groundwater is drained by springs, which present a typical recession hydrograph (Fiorillo, 2011). It is very important that recharge occur during autumn-winter period, when water lost by evapotranspiration processes is at minimum level. A different distribution of the rainfall through the hydrological year could reduce the spring discharge, inducing negative consequences for water supply.

A fundamental role has been played by the soil mantle which acts as "filter", regulating the amount of rainfall which reaches the karst substratum, and recharges the aquifer. Higher soil moisture capacity favour higher values of evapotranspiration (Fig.10), but the amount of evapotranspiration seems to be independent from the annual rainfall, as water lost by evapotranspiration processes is almost the same during dry and wet years, as occurred in 2001-02 (dry) and 2005-06 (wet) year. The amount of rainfall which recharge the aquifer decreases rapidly as annual rainfall decreases, and can reaches negligible values during extreme droughts.

A reduction of the rainfall excess can be induced also by warm years. The worldwide records of the temperature increasing suggest that also the evapotranspiration processes are increasing (Cassardo et. al, 2007), widening the period of no-recharge.

The effect of the evapotranspiration increased can be observe in many aquifers, characterized by the drop of groundwater. This drop is observed since the eighteens, coinciding with the marked beginning of the temperature increasing worldwide (Brunetti et al., 2006; MOHC, 2010), and is well-documented in the karst areas of Southern Italy (Fiorillo et al. 2007; Fiorillo & Guadagno, 2010).

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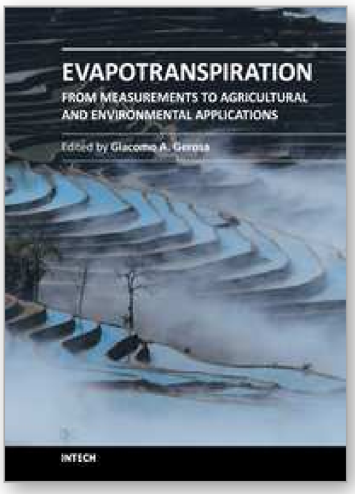

Evapotranspiration - From Measurements to Agricultural and Environmental Applications
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This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and student,s who intend to address these issues.

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