Recharge Processes of Karst Massifs: Examples from Southern Italy

F. Fiorillo and M. Pagnozzi

Abstract Recharge of karst aquifers occurs when rainfall (or snowmelt) infiltration crosses the soil mantle and percolates through the vadose zone. In karst environments, the infiltration can occur in both concentrated and diffuse forms. In several areas of the Mediterranean, karst massifs are important sources of drinking water. In southern Italy, karst massifs are generally characterized by wide endorheic basins with seasonal lakes, which constitute large parts of the spring catchments. The origin of these endorheic basins is related to tectonism during the upper Pliocene-Pleistocene epochs and subsequent erosion and karstification. These endorheic basins constitute the most important recharge areas of karst massifs in central-southern Italy, and have been designated as groundwater protection areas. This study focuses on the karst massifs of the Picentini Mountains, which is characterized by rugged, steep landscape, and comprised of mainly dolostone and limestone. These karst massifs feed many basal karst springs with discharges up to thousands of liters for second, and constitute the main water resource in the region of Campania. The hydrological processes in these basins are simulated using a Geographic Information System (GIS)-based model on an annual scale. The results of the annual scale model have been used to successfully calibrate a daily time step model of infiltration and run off.

Keywords Karst massif · Recharge · Southern Italy · Spring discharge

1 Introduction

Recharge of aquifers occurs when rainfall (or snowmelt) infiltration crosses the soil mantle and percolates through the vadose zone. In karst environments, the infiltration can occur in both concentrated and diffuse forms. The first is connected to

F. Fiorillo (✉) · M. Pagnozzi
Dipartimento di Scienze e Tecnologie, University of Sannio, Benevento, Italy
e-mail: francesco.fiorillo@unisannio.it

sinkholes and shafts, which allow rapid drainage of surface runoff and rapid transmission through the vadose zone and to the saturated zone. Diffuse recharge occurs by slower drainage from the soil mantle and fractured limestone. The percolation time can take weeks to months to reach the water table depending on the thickness and hydraulic conductivity of the vadose zone (Fiorillo and Doglioni 2010).

The hydraulic characteristics of the Terminio and Cervialto massifs were analyzed. Each of these massifs is characterized by large endorheic basins with high discharge basal springs. Several decades of spring flow and chemistry data exists thus allowing to accurately estimate the recharge values for the spring catchments. In particular, the role of the endorheic areas has been distinguished from the other zones of the spring catchment. The endorheic areas do not allow the escape of the run off from the spring catchment, whereas in the latter, here namely "open areas," the run off processes allow the escape of water from the spring catchment, especially during intense storms.

The GIS-based hydrological model first estimates the recharge on an annual scale and is subsequently used to calibrate the daily time step recharge-runoff model (Fiorillo et al. 2014).

2 Geological and Hydrogeological Framework

The northern sector of the Picentini mountains (Fig. 1) contains the Cervialto and Terminio massifs which were formed by Quaternary tectonic uplift. These steep, rugged mountains have several fault-scarps in the carbonaceous rocks with high slope angles. The endorheic areas of the Terminio and Cervialto massifs occupy 39 and 25 % of the total spring catchment area, respectively. The Cervialto massif has the highest elevation and highest precipitation of the two.

The ground elevation reaches 1,809 and 1,806 m a.s.l. for the Mt. Cervialto and Terminio massifs, respectively (Fig. 2). Limestone and limestone–dolomite (Late Triassic-Miocene) dominates these massifs with thicknesses ranging between 2,500 and 3,000 m. Recent pyroclastic deposits from the Somma-Vesuvius volcanoes cover the Picentini mountains with thicknesses between a few centimeters on the steep slopes to several meters within the flatter areas. These deposits play an important role in the infiltration of water into the karst substratum.

The Terminio and Cervialto karst massifs feed several basal karst springs (Fig. 1) with discharges up to thousands liters per second, and constitute the principal water resource in Southern Italy.

The Serino group of springs, located in the valley of the Sabato River along the north-western boundary of the Picentini massif, includes the Acquaro-Pelosi springs (377–380 m a.s.l.) and the Urciuoli spring (330 m a.s.l.). These springs are fed by the Terminio massif (Civita 1969; Fiorillo et al. 2007), with an overall mean annual discharge of 2.25 m^3/s. Roman aqueducts (first century A.D.) were supplied by these springs and the Urciuoli spring was re-tapped between 1885 and 1888 by the Serino aqueduct, which is comprised of a gravity channel followed by
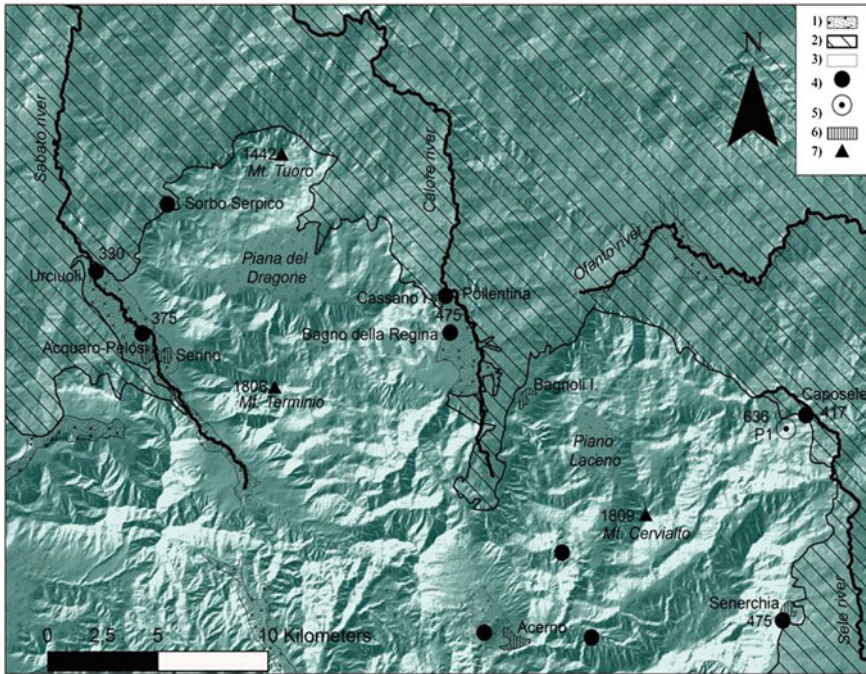
Fig. 1 Sketch of north-eastern sector of Picentini Mountains; Legend: *1* Slope breccias and debris, pyroclastic, alluvial and lacustrine deposits (Quaternary); *2* flysch sequences (Paleogene–Miocene); *3* calcareous-dolomite series (Jurassic–Miocene); *4* main karst spring; *5* monitoring well; *6* village *7* mountain peak

a system of pressured conduits that is used to supply water to the Naples area. Additionally, the Aquaro and Pelosi springs were also re-tapped in 1934 by the Serino aqueduct.

The Cassano group of springs is located in the Calore river basin along the northern boundary of the Picentini Mountains, and is formed by the Bagno della Regina, Peschiera, Pollentina, and Prete springs (473–476 m a.s.l.). Also these springs are primarily fed by the Terminio massif (Civita 1969), with an overall mean annual discharge of 2.65 m^3/s. In 1965, these springs were tapped to supply the Puglia region with water, and a gravity tunnel was joined to the Pugliese aqueduct.

The Caposele group of springs is formed by the Sanità spring (417 m a.s.l.), which is located at the head of the Sele river basin along the north-eastern boundary of the Picentini Mountains. This spring, which is primarily fed by the Cervialto mountain (Celico and Civita 1976), has a mean annual discharge of 3.96 m^3/s. The spring was tapped in 1920 by the Pugliese aqueduct, which passes through the Sele-Ofanto divide via a tunnel and supplies the Puglia region with
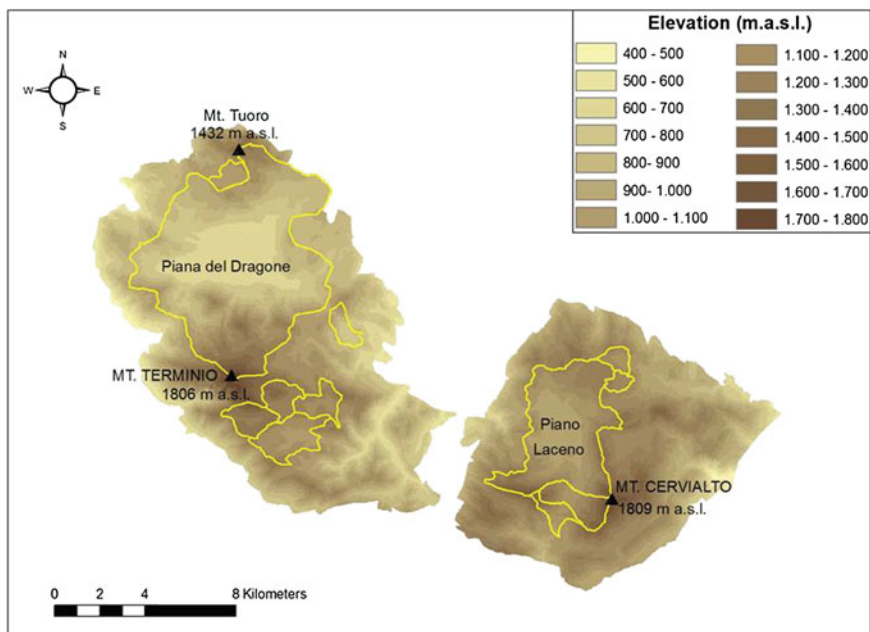
Fig. 2 Elevation distributions for the Terminio and Cervialto catchments; endorheic areas are outlined by *yellow line*

water. On the basis of geological and hydrogeological features, the Cervialto and Terminio massifs can be considered large spring catchments, with areas of 110 and 163 km^2, respectively.

These massifs are characterized by large internally drained (endorheic) basins (Fig. 2) with high recharge coefficients. The origin of these endorheic basins is related to tectonism during the upper Pliocene-Pleistocene epochs and subsequent erosion and karstification. The Terminio massif is characterized by several endorheic basins (Fig. 3) with the largest being the Piana del Dragone (55.1 km^2). Several sinkholes drain this endorheic basin however their combined capacities are not sufficient to prevent flooding in the area. Drainage was improved by engineering works at the *Bocca del Dragone* sinkhole and limit wet season flooding. Tracer tests have confirmed hydraulic connection between this sinkhole and the Cassano springs (Celico et al. 1982).

The Cervialto massif is characterized by the several endorheic basins with the largest being Piano Laceno (20.5 km^2). A permanent lake exists in this basin which is surrounded by several sinkholes which limit the extent of the lake during the wet season.
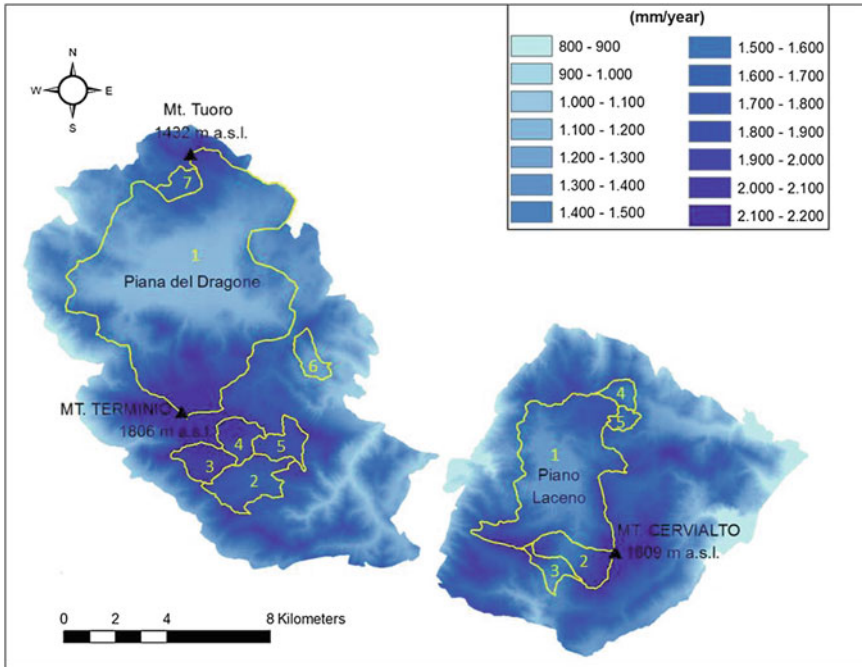
Fig. 3 Effective precipitation distribution for the Terminio and Cervialto massifs. Endorheic areas are outlined in *yellow*; and associated with a specific number in Table 1 (modified from Fiorillo et al. 2014)

3 Groundwater Recharge Model

Recharge can be defined as the downward flow of water reaching the water table, adding to the groundwater reservoir (De Vries and Simmers 2002). Following this definition, we estimate the amount of precipitation (rainfall and snow) which is not lost by evapotranspiration processes, by run off, or accumulated into soil without percolating downward. The difference between precipitation P, and the actual evapotranspiration AET, provides an estimation of the amount of precipitation which is free to infiltrate into soil or to develop run off. This difference can be evaluated at daily, monthly or annual scales, and is defined as effective precipitation, P_{eff} (Fig. 3):

$$P_{eff} = P - AET \tag{1}$$

At daily or monthly scale, most of procedures simply evaluate the effective precipitation as the difference between precipitation P, and potential evapotranspiration, PET:

Table 1 Main hydrological parameters obtained by the analysis of Terminio and Cervialto endorheic areas; F, Afflux; F_{eff}, Effective Afflux; RO Run-off; Q_P water amount pumping from the endorheic areas; R recharge; C_R, effective recharge coefficient; C'_R, recharge coefficient (modified from Fiorillo et al. 2014)

Springs Group		Massif	Area	Item	Elevation (minimum) m a.s.l.	km²	F m³ × 10⁶	F eff m³ × 10⁶	RO m³*10⁶	Q_p m³ × 10⁶	R m³ × 10⁶	C_R	C'_R
m³/s	m³ × 10⁶												
Caposele 3.96	128.5	Cervialto	Piano Laceno	1	1047	20.5	43.8	32.9	0.0	0.0	32.9	1	0.75
			Piano Acernese	2	1168	3.3	7.4	5.8	0.0	0.0	5.8	1	0.78
			Piano dei Vaccari	3	1164	1.4	3.0	2.3	0.0	0.0	2.3	1	0.77
Bagnoli Irpino 0.07			Valle Rotonda	4	1156	1.1	2.3	1.8	0.0	0.0	1.8	1	0.78
			Raia dell'Acera	5	1246	0.7	1.5	1.2	0.0	0.0	1.2	1	0.80
			Closed areas, A_E	–	–	27.0	58.0	44	0.0	0.0	44.0	1	0.76
Others 0.10			Open areas, A_O	–	–	83	172.4	128.3	43.8	0.0	84.5	**0.66**	0.49
			Springs catch., A_C	–	–	110	230.4	172.3	43.8	0.0	128.5	0.75	0.56
Serino 2.25	170.5	Terminio	Piana del Dragone	1	668	55.1	103.9	71.6	0.0	6.3	65.3	0.91	0.63
			Acquadelle Pietre	2	1061	4.3	8.9	6.7	0.0	0.0	6.7	1	0.75
Cassano Irpino 2.65			Campolaspierto	3	1279	2.3	5.1	4	0.0	0.0	4.0	1	0.78
			Piani d'Ischia	4	1210	2.1	4.6	3.5	0.0	0.0	3.5	1	0.76
			Piano di Verteglia	5	1177	2.1	4.4	3.4	0.0	0.0	3.4	1	0.77
Sorbo Serpico 0.43			Piana di Cetola	6	752	1.4	2.6	1.8	0.0	0.0	1.8	1	0.69
			Piana Sant'Agata	7	1047	1.3	2.6	2.1	0.0	0.0	2.1	1	0.81
			Closed areas, A_E	–	–	68.6	132.1	93.1	0.0	6.3	86.8	0.93	0.66
Montella 0.15			Open areas, A_O	–	–	94.3	180.2	125.0	41.4	0.0	83.7	**0.67**	0.46
			Springs catch., A_C	–	–	162.9	312.3	218.1	41.4	6.3	176.8	0.81	0.57

$$P_{\text{eff}} = P - \text{PET} \tag{2}$$

assuming $P_{\text{eff}} = 0$ when $P < \text{PET}$.

In GIS environment, the spatial distribution of the precipitation allows to estimate the total amount of the afflux, F, in a specific area, A, by:

$$(F)_A = \frac{\sum\limits_1^n P}{n} \times A \tag{3}$$

where n is the number of cells in the area A. If the actual evapotranspiration AET, is subtracted from the rainfall (Eq. 1), the effective afflux, F_{eff}, in a specific area A, is:

$$(F_{\text{eff}})_A = \frac{\sum\limits_1^n P_{\text{eff}}}{n} \times A \tag{4}$$

In endorheic areas, A_E, the recharge amount, R, can be considered equal to effective afflux.

Table 1 shows results obtained in this study for each massif, where values of each endorheic area are also reported.

The Cervialto and Terminio massifs constitute a useful hydrogeological condition to evaluate the recharge, because the groundwater of these massifs is almost completely drained by spring outlet. In fact, these karst systems are bounded by impervious terrains, and only along the western boundary a limited groundwater drainage toward alluvial of Sabato river exists (Fig. 1).

The estimation of effective afflux F_{eff}, and the spring output measurements, provides a gross estimate of the recharge coefficients. The recharge coefficient, $C'_R = R/F$, and the effective recharge coefficient, $C_R = R/F_{\text{eff}}$, are computed at an annual scale and refer to a long term period of time; if these coefficients are computed for a specific year, they can vary from a year to another. This occurs because the spring discharge may have a memory effect of the previous years, especially after dry years (Fiorillo 2009). Also, the monthly rainfall distribution may have an important role, so that the same total annual rainfall on a specific spring catchment could provide different values of spring discharge outlet, as noted by Bonacci (2001).

The long-term period used to estimate C_R allows to smooth the influence of a specific year, and provides useful tools to find the amount of rainfall which feeds the spring outlet.

The coefficient C'_R is more easily evaluated, but it depends on the temperature and rainfall distributions. Literature provides several examples, even if they were computed without GIS support. For the karst aquifers of central Italy, Boni et al. (1982) found a rough estimation of C'_R around of 0.7; for a Dinaric karst aquifer Bonacci (2001) a value around 0.56; for a Greek karst aquifer Soulios (1991)
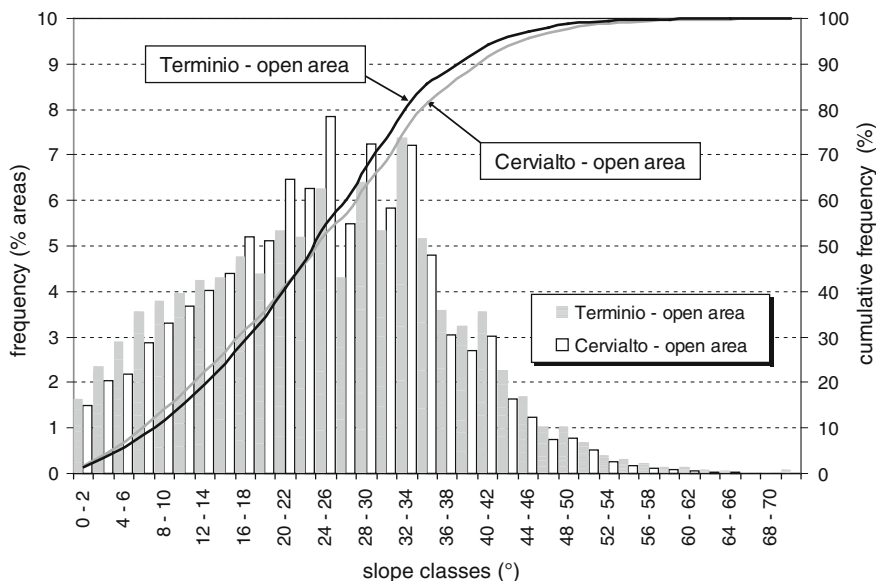
Fig. 4 Slope angle distribution for Terminio and Cervialto massifs (*open areas*), modified from Fiorillo et al. 2014

found a value almost 0.5. Allocca et al. (2014) estimated the annual mean recharge of aquifers of central southern Italy based on regional approach; for the Terminio and Cervialto massifs they found values smaller than that of Table 1, due to difference on evaluating the afflux and definition of the catchment boundaries.

4 Hydrologic Parameters Estimation on Annual Mean Scale and Daily Mean Scale

The effective recharge coefficient computed for the open areas, $(C_R)_{Ao}$, appears to have comparable values for the Cervialto (0.66) and Terminio (0.67) massifs; the possible explanation can be found in the similar slope angle distribution (Fig. 4) and in a similar karst conditions. The Annual Mean Scale (ASR) model is based on the estimation of some fundamental hydrological parameters: the afflux and the evapotranspiration.

The Daily Mean Scale (DSR) model has allowed to fix a threshold for the daily recharge, and considers a single point to estimate the recharge/run off (1D model), located approximately in the middle of the Cervialto catchment. This could be a limitation of the model since it does not consider elevation and the related spatial distribution of recharge and runoff. A high resolution daily time step model for the entire catchment would need very strong computational power.

5 Conclusion

A GIS-based model was developed to assess groundwater recharge of two major karst aquifers located in southern Apennines (Terminio and Cervialto massifs), using two distinct time scales: an Annual Scale Recharge (ASR) which was used to calibrate the Daily Scale Recharge (DSR). The ASR model provides a useful approach for assessing long-term groundwater recharge, especially for large areas with strong morphological irregularities, and with limited hydrological data. In particular, the afflux, run off, and recharge are computed using GIS, allowing an estimation of the recharge and runoff coefficients, distinguished for open and endorheic areas, while the DSR model has been calibrated by the results of the ASR model, and allows to split the amount of daily rainfall which cause run off from that recharging the aquifer. The daily estimation of recharge is a useful tool for water management, allowing the control of recharge condition of aquifers, especially during dry years. The application of this method could help to improve the design of appropriate management models for groundwater and surface resources of karst aquifers as well as the elaboration of accurate strategies to mitigate the effects of climate and land-use change.

References

Allocca V, Manna F, De Vita P (2014) Estimating annual groundwater recharge coefficient for karst aquifers of the southern Apennines (Italy). Hydrol Earth Syst Sci 18:803–817

Bonacci O (2001) Monthly and annual effective infiltration coefficient in Dinaric karst: example of the Gradole karst spring catchment. Hydrol Sci J 46(2):287–300

Boni C, Bono P, Capelli G (1982) Valutazione quantitativa dell'infiltrazione efficace in un bacino dell'Italia centrale: confronto con analoghi bacini rappresentativi di diversa litologia. Geologia Applicata e Idrogeologia, Bari 17:437–452

Celico P, Civita M (1976) Sulla tettonica del massiccio del Cervialto (Campania) e le implicazioni idrogeologiche ad essa connesse. Boll Soc Nat Naples 85:555–580

Celico P, Magnano F, Monaco L (1982) Prove di colorazione del massiccio carbonatico del monte Terminio-monte Tuoro. Notiziario Club Alpino Italiano, Napoli 46(1):73–79

Civita M (1969) Idrogeologia del massiccio del Terminio-Tuoro (Campania). Memorie e Note Istituto di GeolApplUniv di Napoli 11:5–102

De Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. Hydrogeol J 10:5–17

Fiorillo F, Esposito L, Guadagno FM (2007) Analyses and forecast of the water resource in an ultra-centenarian spring discharge series from Serino (Southern Italy). J Hydrol 36:125–138

Fiorillo F (2009) Spring hydrographs as indicators of droughts in a karst environment. J Hydrol 373:290–301

Fiorillo F, Doglioni A (2010) The relation between karst spring discharge and rainfall by the cross-correlation analysis. Hydrogeol J 18:1881–1895

Fiorilllo F, Pagnozzi M, Ventafridda G (2014) A model to simulate recharge processes of karst massifs. Hydrological Processes (in press)

Soulios G (1991) Contribution à l'ètude des coubes de recession des souces karstiques: example du pays hellènique. J Hydrol 124:29–42