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Water criticality in the Colli Albani (Rome, Italy)[1]

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ABSTRACT. The Colli Albani Hydrogeological Unity has a good regional water resource. The geological setting of the area has been defined reconstructing the morphology of roof of prevolcanic substratum and the geometry of the aquifers by the realization of cartographies made of several profiles to different scales. The project of hydrogeological surveying of wells, springs and discharge's streams have been led to define the state of conservation of water resources. The results of this research have underlined a distributed and relevant drawdown of ground water table and of river capacity network. Specific studies, supported by cartographies elaborated by GIS, have been led to define all the parameters concerning the hydrogeological balance: precipitation, evapotranspiration, runoff, effective infiltration, withdrawals. The analysis of the hydrogeological balance, have led to a definition of specific rules for the management of water resources in order to recover the situations of over-exploitation.

Key terms: Aquifer, Aquifer drawdown, Hydrogeological balance, Latium Italy, Alban Hills

Introduction

The Colli Albani volcano has been the most important water resource of the city of Rome since Roman times. The volcanic succession, which overlies a clayey aquiclude of Pliocene age, can be considered as an individual aquifer, although the permeability associated with interbedded lavas and pyroclastic rocks is highly variable, both laterally and vertically.

The area was rapidly urbanized during the second half of the 20th century, with the consequent proliferation of urban and industrial settlements, as well as intensive farming activities.

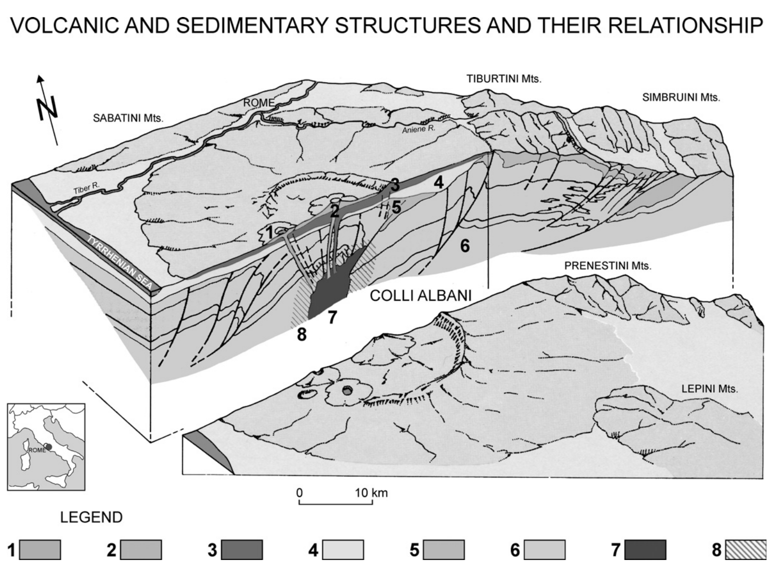

FIG. 1:Volcanic and sedimentary structures and their relations (Modified after DE RITA *et alii*, 1988). LEGEND: 1) Product of the Albano activity; 2) Product of the Faete activity; 3) Product of the Tuscolano-Artemisio activity; 4) Marine and/or continental clay and sand deposits Pliocene-Quaternary; 5) Clayey arenaceous Miocene flysch; 6) Carbonate succession Mesozoic-Cenozoic; 7) Intrusive magmatic body; 8) Thermometamorphic facies.

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At present, water pumping in the area is intense and largely uncontrolled, leading to over-exploitation of the aquifer so that the groundwater table is lowered by several tens of meters and locally by up to 100 m. This finding suggests that water pumping is such as to deplete the local strategic reservoir, making it necessary to implement correct water management policies and practices.

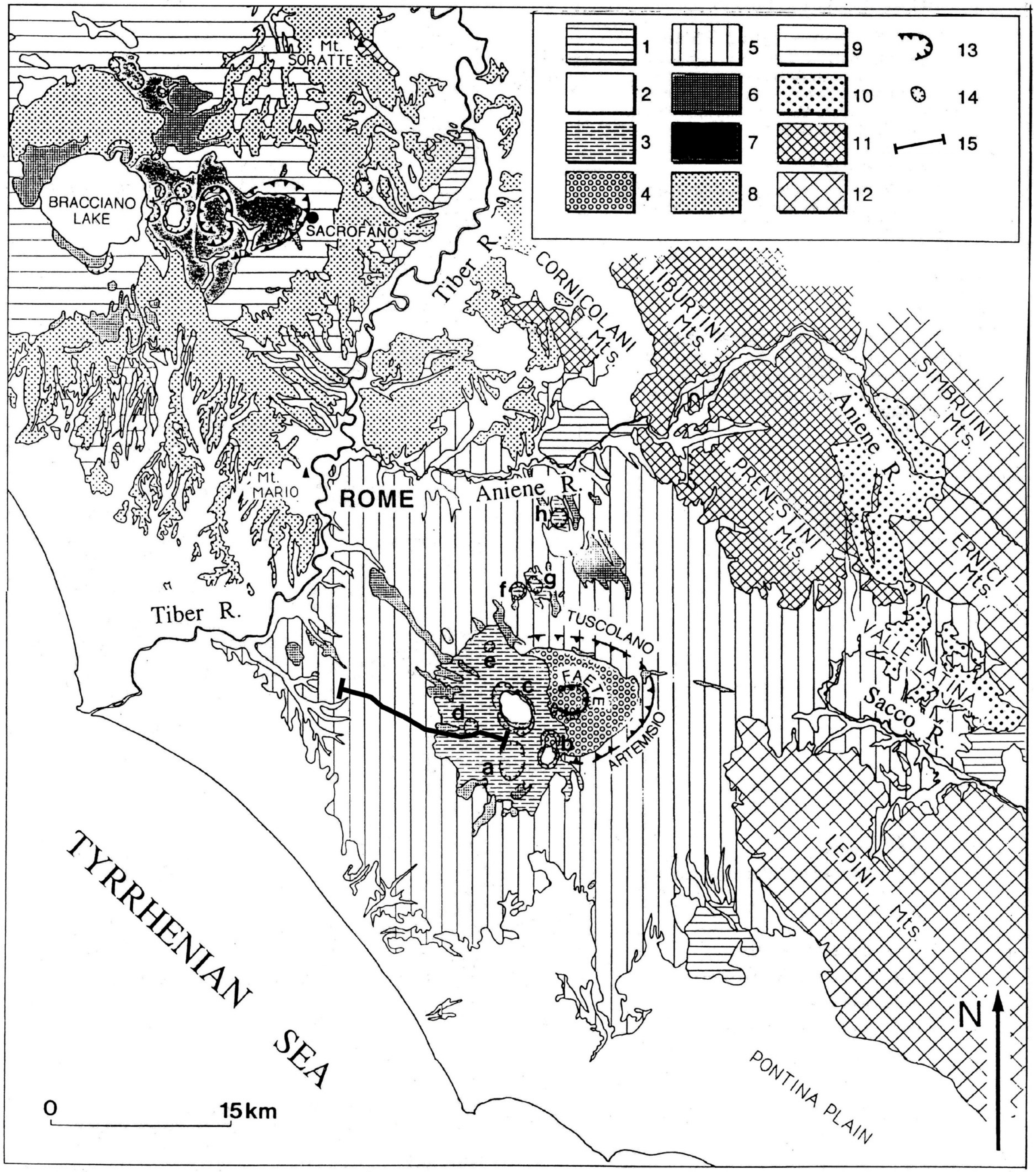

FIG. 2: Geological sketch map of the Colli Albani volcanic complex (DE RITA *et alii*, 1995). LEGEND: 1) Travertine; 2) Plio-Pleistocene sedimentary units; 3) Colli Albani final hydromagmatic phase products; 4) Colli Albani Faete phase products; 5) Colli Albani Tuscolano-Artemisio phase products; 6) Lava flows; 7) Sabatinian hydromagmatic units; 8) Sabatinian air-fall deposits; 9) Sabatinian ignimbrites; 10) Tortonian flysch (pelitic.sandy facies); 11) Meso-Cenozoic pelagic carbonate units (Sabina facies); 12) Meso-Cenozoic carbonate platform units (Latium-Abruzzi facies); 13) Caldera rims; 14) Crater rims: a) Ariccia, b) Nemi, c) Albano, d) Giuturna, e) Valle Marciana, f) Pantano Secco, g) Prata Porci, h) Castiglione; 15) Hydrogeological cross-section (see FIG. 3).

Geological setting

The Colli Albani volcanic succession rests on a post-orogenic Pliocene-Quaternary bedrock, which is made up of marine to continental deposits, mainly characterized by clayey and sandy sediments. These sediments cover a Mesozoic-Cenozoic carbonate and terrigenous succession orogenized in Miocene times (FUNICIELLO & PAROTTO, 1978) (FIG. 1).

Extensional tectonics, related to the opening of the Tyrrhenian Basin, faulted the sedimentary bedrock, resulting in a NW- and NE-trending horst and graben structure.

The study area includes not only the Colli Albani volcanites, but also peripheral areas. The reference geological setting (FIG. 2) derives from studies conducted as part of the CARG Project.

The geology and structure of this volcano (inferred from a 1:10,000 scale geological survey and from stratigraphic analyses of over 600 drill-holes) are outlined below.

The Quaternary volcanic succession records the occurrence of three epochs of activity (DE RITA *et alii*, 1988).

Tuscolano-Artemisio Epoch (600-300 ka) – During this period, over 283 km^3 of products were emplaced (DE RITA *et alii*, 1995), building the Tuscolano-Artemisio central edifice. Several, dominantly explosive eruptions emplaced large volume, low aspect ratio, tephritic to K-foiditic ignimbrites. These ignimbrites cover an area of more than 1500 km^2 around the volcano center. Large volumes of phono-tephritic lava flows were also emplaced, filling tectonically controlled, NW- and NE-trending paleovalleys, which reflect the tectonic trends of the pre-volcanic bedrock. A 10 x 10 km-wide, composite caldera was formed in the central area of the volcano as a consequence of large-volume eruptions. In the investigated area, NW-trending caldera faults were identified, which downthrow the volcanic succession by several hundred meters towards NE (FIG. 3). The volcanic succession overlies a Pliocene-Middle Pleistocene sedimentary succession, with dominant clayey and sandstone lithologies. The morphology of the top of the sedimentary bedrock (inferred from drill-holes and geoelectric data) shows valleys and ridges at an elevation of, respectively, -70 m below and 50 m above sea level.

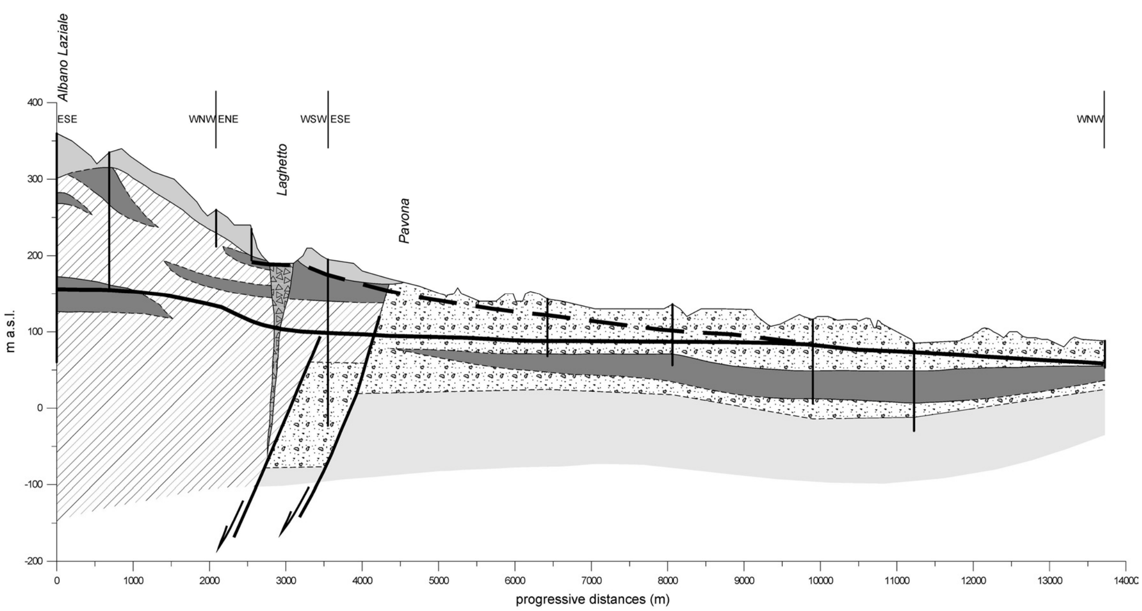

FIG. 3: Geological and hydrogeological cross-section. (LEGEND: – 1): Products of the Albano activity a) Conduit breccia; 2): Products of the Faete activity; 3): Ignimbrites of the Tuscolano-Artemisio activity; 4): Lava; 5): Pre-volcanic bedrock; 6): Well; 7): Fault; 8): 1999 isopiezometric level; 9): 1972 isopiezometric level) *(Modified after GIORDANO et alii, 2000).*

Faete Epoch (300-100 ka) - After the last caldera collapse in the Tuscolano-Artemisio period (338 ka; DE RITA *et alii*, 1995), the volcanic activity concentrated within the collapsed area, where the 6 km^3 Faete volcanic edifice filled the caldera with lavas and strombolian to subplinian pyroclastic products. Some of the lavas overflowed the caldera wall (e.g. Capo di Bove lava, 285 ka), reaching the area presently occupied by Rome.

Albano Epoch (100-<20 ka) – The latest period of volcanic activity was dominantly characterized by phreatomagmatic eruptions from eccentric, monogenic and coalescing maars, tuff rings and tuff cones, some of which are presently filled by lakes (e.g. Lake Albano). In the investigated area, the phreatomagmatic centers are aligned along the NW-trending caldera faults and more recent N-trending lineaments. In this epoch, a further reduction in the volume of erupted magma is likely to have favored the efficiency of magma-water interaction.

At present, the Colli Albani volcano is commonly regarded as non-active, because its most recent products were dated between 19,000 and 36,000 years B.P. (FORNASERI, 1985; VOLTAGGIO *et alii*, 1994). However, the Colli Albani area is characterized by frequent episodes of seismic activity, local uplift, hydrothermal circulation and gas emissions, pointing to the presence of a cooling magma body lying beneath the volcano, at a depth of approximately 6 to 18 km (AMATO & CHIARABBA, 1995).

Hydrogeological setting

The Colli Albano volcano is a Hydrogeological Unit (CAHU) bounded by the Aniene River to the north, the Tiber River to the northwest, the Tyrrhenian Sea to the southwest, the Acque Alte Floodway to the southeast, and the Sacco River to the east (FIG. 4).

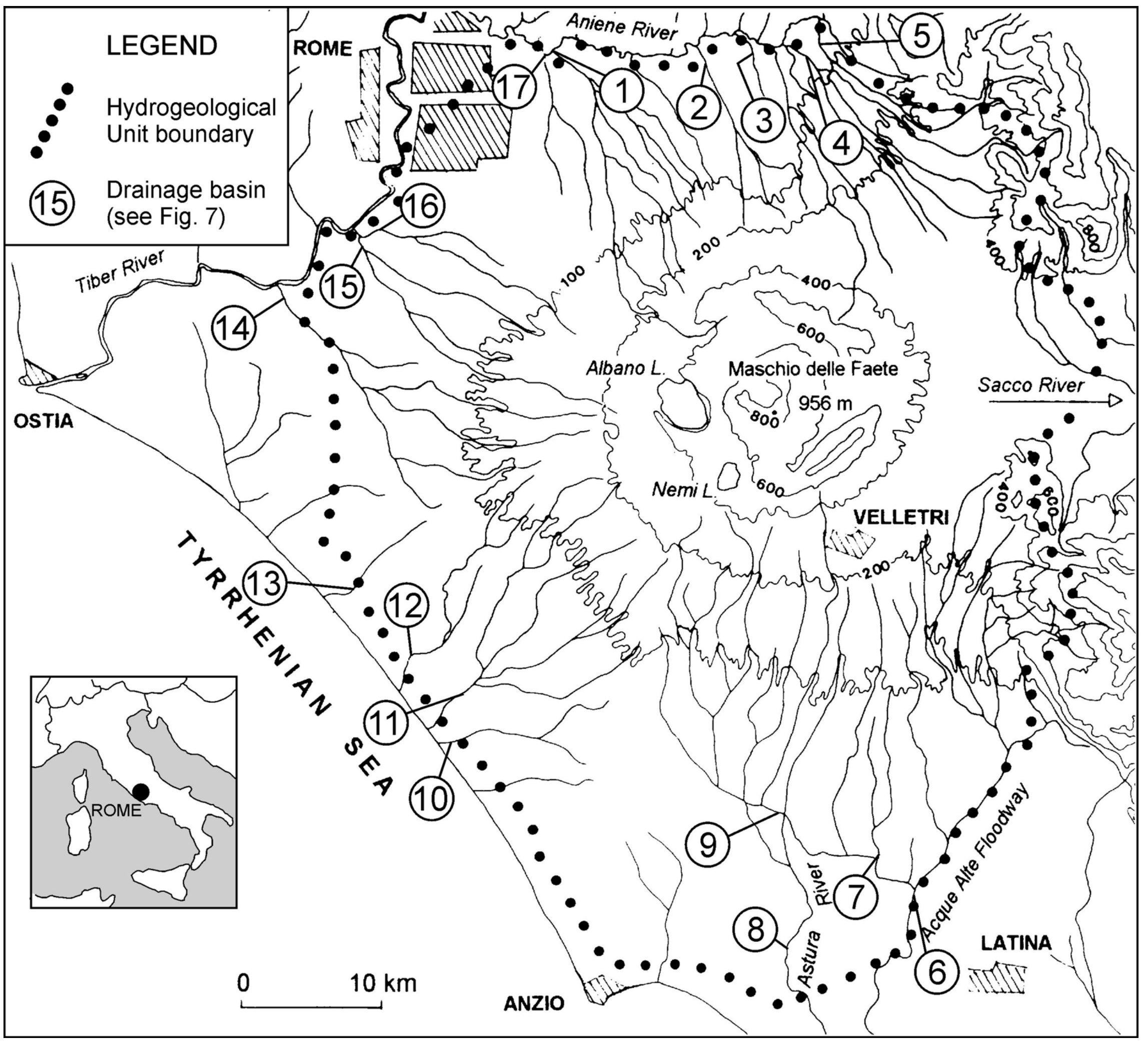

FIG. 4: Location map showing the Albano Volcano and its surrounding area (Modified after BONI *et alii*, 1995).

The volcanic succession and its aquifers (hereinafter collectively referred to as "the volcanic aquifer") lie over a thick, marine, clayey succession of Pliocene-Pleistocene age, several hundred meters thick. This succession represents the lower aquiclude, which also bounds a deeper geothermal aquifer, hosted in the underlying Mesozoic-Cenozoic carbonate succession. The geometry of the top of the clayey aquiclude has been reconstructed via geophysical analyses and deep-well data (ENEL, 1990; DE RITA *et alii*, 1992), indicating that several extensional fault systems (NW-, NE- and N-trending systems) cut it into a horst and graben structure. The aquiclude is also downthrown in the vicinity of the central caldera of the volcano (FIG. 3). Preferential groundwater flowpaths have been recognized within the aquiclude lows (i.e. graben). The faults favor the rise of deep-seated fluids (gas and thermal water), which locally contaminate the volcanic aquifer (e.g. specific conductivity of 14000 µS/cm in one of the Solforata wells, 1200 µS/cm in the Solforata and Cava de' Selci areas, 2100 µS/cm in the Ardea area).

The overall hydrogeology of the CAHU may be outlined as follows (CAPELLI *et alii*, 1998):

- the intra-caldera sector is the upper portion of the volcano and hence the recharge area of the aquifer, which crops out in Lake Albano.
- the extra-caldera sector is characterized by flowpaths which are radial and centrifugal with respect to the volcano center. The three-dimensional lithological variability of the volcanic bodies gives rise to locally perched aquifers, as well as confined aquifers.

Assessment of water resource conservation

In the Lake Albano area, a regional aquifer and a shallower, perched aquifer were identified (REGIONE LAZIO, 1999). s well as confined aquifers. The regional piezometric level (FIG. 5) is presently located at approx. 200 m above sea level and its drainage has a SW direction.

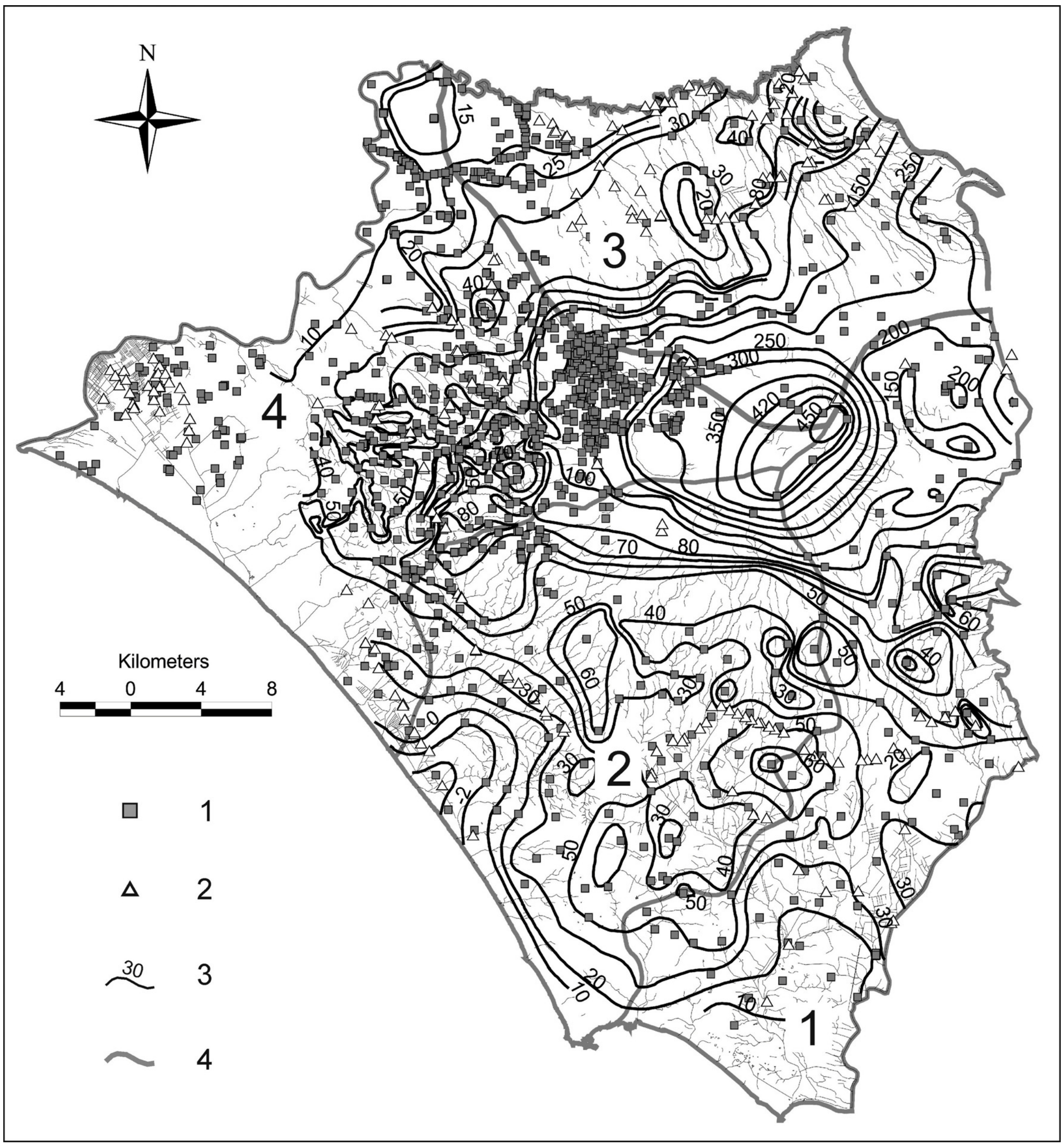

FIG. 5: Hydrogeological map of the Colli Albani volcanic complex. LEGEND: 1) Well; 2) Stream gauging station; 3) Regional piezometric level; 4) Ground water basin boundary with a reference number.

The piezometric level of the perched aquifer crops out in the lakes of Nemi and Albano. As Lake Albano is 175 m deep (about 120 m above sea level), it intercepts both water flows. Since 1848, the level of the lake has been measured with respect to the elevation of the inlet of a drainage gallery excavated during the Roman age (DRAGONI, 1998). Data from 1951 to 1990 indicate that the level of the lake fluctuated with rainfall (FIG. 6). By contrast, the trend of precipitation from 1990 to 1997 (latest official measurement) does not justify the steep decrease of Lake Albano's water level, which presently lies at least 3 m below the inlet.

The river network of the CAHU has a radial configuration, forming 26 drainage basins, the surface area of which ranges from 282 km^2 to 4 km^2. Seventeen of them are perennial and drain the regional aquifer at elevations comprised between 70 and 50 m above sea level. The comparison of the low-water discharge rates measured from 1978 to 1979 (BONI *et alii*, 1981; BONO *et alii*, 1983), from 1997 to 1999 (REGIONE LAZIO, 1999) and in 2002 by the local basin authorities (AUTORITÀ DEI BACINI REGIONALI DEL LAZIO & AUTORITÀ DI BACINO DEL FIUME TEVERE, 2003) shows: i) a substantial decrease, which started in the 1990s; and ii) an apparent stability in the last two water-level monitoring programs, which was due, among other things, to intense rainfall in the summer of 2002. Cumulated discharges, in the above-mentioned periods, are equal to 5,620 l/s, 3,050 l/s and 3,830 l/s, respectively (FIG. 7).

To assess changes in the regional piezometric level of the CAHU, a comparison was made of hydrogeological data collected in the past four decades. This comparison evidences a significant drawdown of the water table, reflecting locally over-exploited areas (FIG. 8).

For example, the drawdown recorded in the Pavona area in the past decade reached 100 m (FIGS 3 and 8). The plains surrounding the volcano display a generalized drawdown of the water table (10-20 m).

Locally, where the shallowing of the clayey aquiclude reduced the thickness of the aquifer to values comparable with the drawdown (for example Pomezia), the water resource is completely depleted.

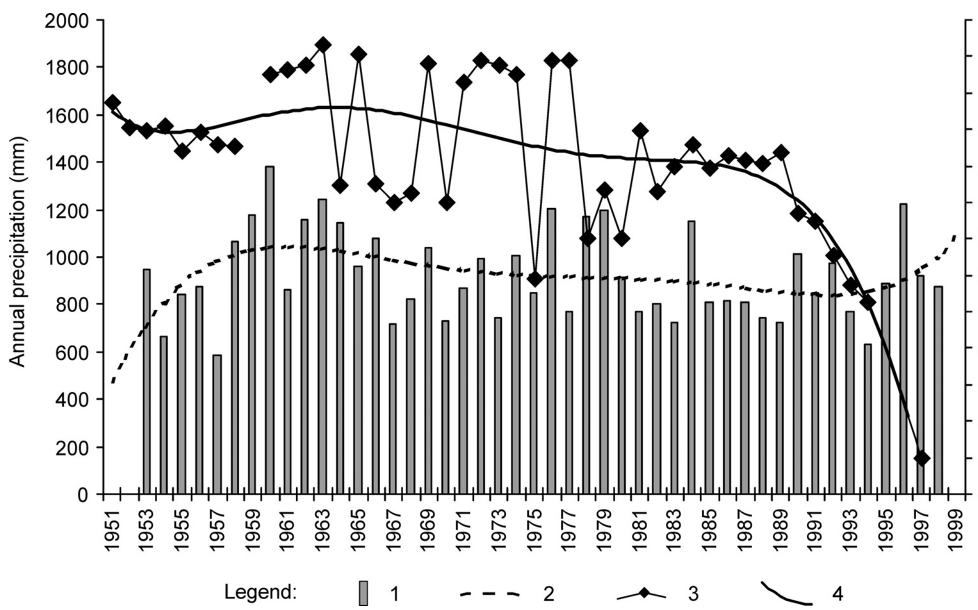

FIG. 6: Water level fluctuations in Lake Albano vs. yearly average rainfall recorded in the gauging stations of Agenzia Protezione Ambiente e Territorio of the Alban area. LEGEND: 1) Annual precipitation; 2) Polynomial precipitation curve; 3) Mean annual level of the Albano Lake; 4) Polynomial lake-level curve.

In the early 2000s, along the coast, groundwater levels lower than sea level were recorded for the first time. The only areas where the groundwater level rose were former farmland areas where water pumping had ceased.

Areas with significant drawdown of the water table are defined as critical. In such areas, under present conditions of recharge, "withdrawal is such as to disturb groundwater circulation and lower the level of the water table to a much greater extent than in surrounding areas, thus jeopardizing water supply to anthropic settlements and causing an unsustainable decrease of the natural discharge of the aquifer in the subsoil and towards the surface" (REGIONE LAZIO, 2004).

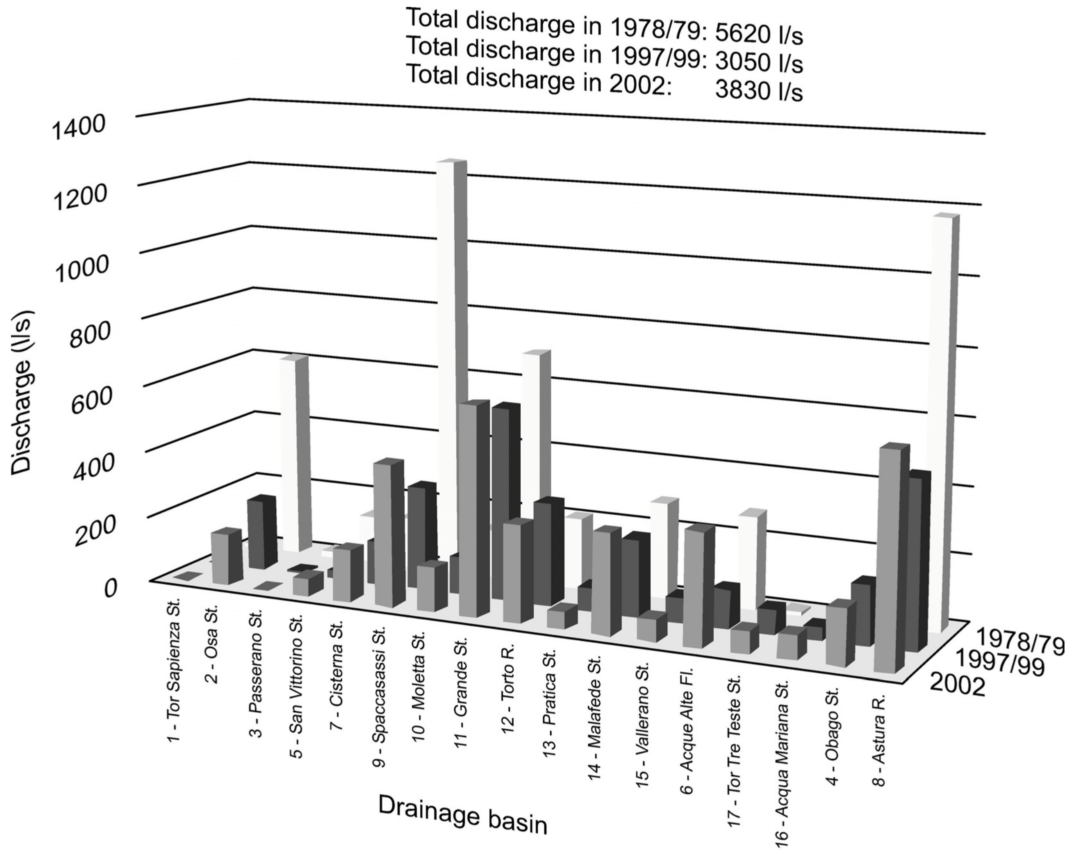

FIG. 7: Comparison between 2002, 1997-19/99 and 1978-19/79 discharge values of the hydrographic basins that drain the Colli Albani volcano area.

The criticality of the local aquifer was assessed by referring to its physical characteristics, evidence of depletion, water-withdrawing entities and water uses. On the basis of the findings from hydrogeological studies conducted in the Colli Albani area, the following critical factors were investigated:

- groundwater level anomalies – differences between the regional trend of the present groundwater level (reconstructed from the analysis of the regional trend defined as the mean value of the groundwater level within a radius of 3 km) and the groundwater level calculated on the basis of experimental measurements;
- thickness of the aquifer – difference between the groundwater level and the level of the top of the pre-volcanic substratum;
- density of known wells - obtained from the locations of all the wells stored in data bases (measured by the Authors, quoted in scientific papers and retrieved in the archives of the relevant authorities);
- location of water intakes (var. points of withdrawal of water) for drinking uses;
- areas of withdrawal for industrial uses;
- areas of withdrawal for farming uses;
- extensive over-exploitation of the water body (ratio of natural recharge to withdrawals).

The critical areas are identified via a Geographic Information System (using a grid with a 250-m side mesh) in an objective way, i.e. via a software program which indexes the above critical factors according to an assessment matrix. The higher the index, the heavier the weight of the critical factor on the criticality of the area. For each portion of the investigated aquifer, the total criticality is given by the summation of the various indices. The weight of the various critical factors was selected on the basis of strictly hydrogeological factors, assigning the maximum weight to the anomalies observed in groundwater level and to the presence and extent of withdrawals for aqueducts, i.e. the priority use of the resource. From a technical viewpoint, further insight into the issue might lead to a more accurate identification of the levels of risk and of the geometry of the critical areas.

This procedure thus represents a tool for investigating aquifer vulnerability, but also for formulating sustainable water resource management policies. The procedure also defined "attention" areas, whose criticality is mainly dependent on groundwater level anomalies, but where the calculated withdrawal is not particularly high.

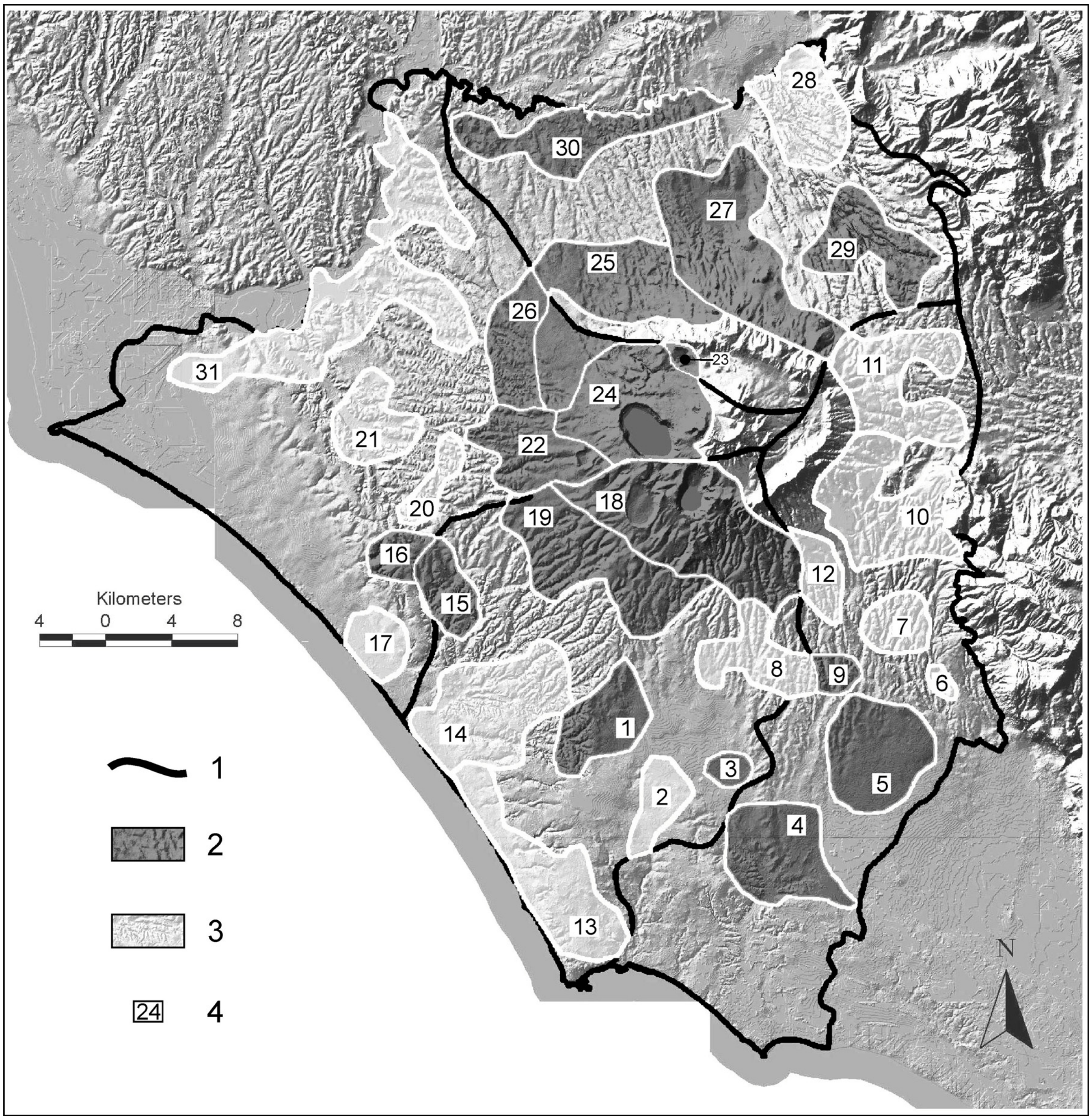

FIG. 8: Balance, critical areas and attention areas in the CAHU. LEGEND: 1) Ground water basin boundary; 2) Critical area; 3) Attention area; 4) Reference number.

Analysis of Hydrogeological

The study involved detailed computations of the hydrogeological balance, requiring highly accurate data concerning the distribution of recharge and withdrawals in time and space. To analyze the relationships between recharge and withdrawals, the hydrogeological balance is built is such a way as to highlight a deficit, i.e. the difference between inflows and total outflows.

To estimate the terms of the balance in the CAHU, resort was made to a specific methodology taking into account: i) physical factors affecting aquifer recharge; ii) anthropogenic disturbances due to withdrawals and diversions of surface and underground water bodies; iii) variation (in time and space) of non-structural limits of hydrogeological basins (recharge areas), which change with inflows and intensity of withdrawals.

The hydrogeological balance methodology used in this study has the following features:

- it analyses the variability (in time and space) of rainfall and climate on a monthly basis, dividing the investigated area into 250 m-side cells;
- it takes into account the impact of morphology, lithology, pedology, vegetation and land use on runoff and evapotranspiration, with a high level of spatial detail;
- it permits us to compare the distribution and extent of withdrawal with the distribution of net recharge;

- it allows data to be updated with respect to the reference period and aggregate them by individual hydrogeological basin.

The analysis of Table 1 suggests the following major considerations.

The comparison of precipitation in the period from 1997 to 2001 with precipitation in the period from 1981 to 1985 indicates a decrease of about 180 mm/yr and a corresponding decline in net recharge from 351 mm/yr to 242 mm/yr.

This situation is compounded by the fact that total withdrawal (for drinking, irrigation and industrial uses) has an impact on net recharge. In effect, throughout the CAHU, groundwater withdrawal accounts for 74% of the recharge volume.

TABLE. 1: Hydrogeological balances of the CAHU

ANNUAL VALUES – 1997-2001	**Area 1,982 km^2**			
Hydrogeological balance parameters	**mm/year**	**l/s**	**Mm^3/year**	**% P**
Precipitation	731	45,925	1,448	100.0
Runoff	138	8,610	272	18.7
Evapotraspiration	346	21,659	683	47.2
Net recharge (Effective Infiltration)	245	15,364	485	33.5
Withdrawals by use				**% di EI**
Farming	46	2,900	91	18.9
Drinking	53	3,347	108	21.8
Industry, trade and services	75	4,696	148	30.6
Total Withdrawals	175	10,943	345	**71.2**
Untapped water resources (EI - Withdrawals)	70	4,421	140	28.8
Discharge				**% P**
low water flow	62	3,893	123	8.5
MEAN ANNUAL VALUES – 1981-1985	**Area 1,982 km^2**			
Hydrogeological balance parameters	**mm/year**	**l/s**	**Mm^3/year**	**% P**
Precipitation	907	57,004	1,798	100.0
Runoff	183	11,501	363	20.2
Evapotraspiration	375	23,568	743	41.4
Net recharge (Effective Infiltration)	351	22,060	696	38.7

TABLE 2: Hydrogeological balance of groundwater basin 1 – Cisterna-Velletri.

MEAN ANNUAL VALUES – 1997-2001	**Area 487 km^2**			
Hydrogeological balance parameters	**mm/year**	**l/s**	**Mm^3/year**	**% P**
Precipitation	805	12,423	391.8	100.0
Runoff	95	1,452	45.8	12.0
Evapotraspiration	406	6,215	196.0	50.0
Net recharge (Effective Infiltration)	307	4,686	147.8	38.0
Withdrawals by use				**% di EI**
Farming	79	1,215	38.3	25.9
Drinking	26	394	12.4	8.4
Industry, trade and services	31	475	15.0	10.2
Total Withdrawals	135	2,084	65.7	**44.5**
Untapped water resources (EI - Withdrawals)	172	2,602	82.1	55.5
Discharge				**% P**
low water flow	87	1,339	42.2	10.8

TABLE 3: Hydrogeological balance of groundwater basin 2 – Aprilia-Pomezia.

MEAN ANNUAL VALUES – 1997-2001 **Area 509 km²**

Hydrogeological balance parameters	**mm/year**	**l/s**	**Mm³/year**	**% P**
Precipitation	750	12,109	381.9	100.0
Runoff	135	2,166	68.3	18.0
Evapotraspiration	366	5,880	185.4	49.0
Net recharge (Effective Infiltration)	253	4,062	128.1	34.0
Withdrawals by use				**% di EI**
Farming	52	840	26.5	20.7
Drinking	90	1,452	45.8	35.8
Industry, trade and services	91	1,473	46.5	36.3
Total Withdrawals	233	3,765	118.7	**92.7**
Untapped water resources (EI - Withdrawals)	20	297	9.4	7.3
Discharge				**% P**
low water flow	62	1,006	31.7	8.3

TABLE 4: Hydrogeological balance/budget of the ground water basin 3 – S. Cesareo-Colonna.

MEAN ANNUAL VALUES – 1997-2001 **Area 409 km²**

Hydrogeological balance parameters	**mm/year**	**l/s**	**Mm³/year**	**% P**
Precipitation	716	9,289	292.9	100.0
Runoff	163	2,089	65.9	22.0
Evapotraspiration	322	4,147	130.8	45.0
Net recharge (Effective Infiltration)	233	2,995	94.4	32.0
Withdrawals by use				**% di EI**
Farming	27	344	10.9	11.6
Drinking	91	1,181	37.2	39.4
Industry, trade and services	132	1,712	54.0	57.2
Total Withdrawals	250	3,237	102.1	**108.2**
Untapped water resources (EI - Withdrawals)	-17	-242	-7.7	-8.2
Discharge				**% P**
low water flow	35	451	14.2	4.9

TABLE 5: Hydrogeological balance of groundwater basin 4 – Marino-Castel Porziano

MEAN ANNUAL VALUES – 1997-2001 **Area 577 km²**

Hydrogeological balance parameters	**mm/year**	**l/s**	**Mm³/year**	**% P**
Precipitation	662	12,104	381.7	100.0
Runoff	182	2,903	91.5	24.0
Evapotraspiration	301	5,417	170.9	45.0
Net recharge (Effective Infiltration)	202	3,621	114.2	30.0
Withdrawals by use				**% di EI**
Farming	27	501	15.8	13.8
Drinking	17	320	10.1	8.8
Industry, trade and services	57	1,036	32.7	28.6
Total Withdrawals	101	1,857	58.6	**51.3**
Untapped water resources (EI - Withdrawals)	101	1,764	55.6	48.7
Discharge				**% P**
low water flow	60	1,097	34.6	9.1

Balance computations infer that withdrawal in the Aprilia – Pomezia (TABLE 3) and S. Cesareo – Colonna (TABLE 4) basins vs. withdrawal in the four investigated hydrogeological basins (TABLES 2, 3, 4 and 5), exceeds the volume of recharge and is around 110%.

In the remaining Cisterna – Velletri (TABLE 2) and Marino – Castel Porziano (TABLE 5) basins, withdrawal accounts for about half of recharge.

Conclusions

The Colli Albani volcano is a complex hydrogeological unit, which hosts an important regional aquifer, as well as perched aquifers. The regional aquifer is sustained by a clayey aquiclude. This is cut by extensional faults, which favor the upwelling of deep-seated fluids, giving rise to gas emission points and to mineralized, thermal and cold water springs. The regional aquifer feeds the radially configured river network of the CAHU, as well as point springs.

In the past two decades, the equilibrium of the regional water resources in the CAHU area broke down, resulting in the following evidence:

- 3-m drawdown of the water level at the top of the volcano (Lake Albano);
- heavy decrease in river discharge (about 50%);
- generalized drawdown of groundwater level in wells (locally up to 100 m);
- drawdown of groundwater level below sea level near the coast.

Water withdrawal proved to decrease the calculated value of net recharge by 74% throughout the CAHU.

Taking into account the extent of withdrawal and the hydrogeological aspects, the study identified areas where the equilibrium between recharge and exploitation has become unsustainable (critical areas). This situation is rapidly depleting the regional aquifers and, with decreasing precipitation, is triggering an irreversible process.

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