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THE KARST AQUIFERS OF TUSCANY (ITALY)

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ABSTRACT

The overexploitation of the alluvial aquifers in Tuscany and their increasing contamination, especially by chemical agents, has led people to turn to the region's karst aquifers, which are less exploited and contaminated. Hydrogeological studies of the regions containing karst aquifers are necessary to insure their proper exploitation. Such studies have reached different stages in the various areas. Three karst aquifers, chosen both for their importance and because hydrogeological studies of these aquifers have reached different stages, are described. The Apuan Alps, in part because they are the most famous speleological area of Tuscany, have been studied for many years, and their hydrogeology is known in detail. In the Colle Val D'Elsa region the general underground circulation patterns followed by the waters are known, but precise estimates of the groundwater resources and studies for their protection have yet to be made. A karst aquifer discovered under the lagoon in the region of Orbetello was examined for the first time in the course of this study; its catchment area was determined, and a preliminary calculation of its potential was made.

INTRODUCTION

The most heavily exploited aquifers in Tuscany are those in the Quaternary alluvial deposits of the internal and coastal plains. In many areas they are beset by problems of both quality and quantity: overexploitation (exacerbated, over the past three years, by a drastic drop in precipitation) has reduced the reserves, while contamination, both induced (intrusion of salt water into the coastal groundwaters) and direct (pollution by industry and agriculture), has made the water unfit for use. Given this situation, the lightly exploited karst aquifers have become quite important. Clearly, the exploitation of these aquifers must be based on a thorough knowledge of their hydrogeology. Specifically, hydrogeological balances must be made to estimate the exploitable reserves, and, at the same time, to plan the steps necessary to protect them from contamination.

Though carbonate outcrops are not very large in Tuscany, in some areas they contain significant hydrological reserves. The principal areas in which carbonate rocks are exposed, according to the survey of karst areas carried out by the Department of Land Management of the Region of Tuscany (Forti et al., 1989), are shown in Fig. 1. The importance of these areas as aquifers depends upon their surface area, rate of recharge, and, more importantly, degree of karstification.

The most important karst aquifers are in the formations of the Tuscan series with ages ranging from Triassic to Jurassic. In particular, the Triassic Calcare Cavernoso and Liassic Calcare Massiccio Formations are the thickest and most highly karstified. At present, our knowledge of the hydrogeology of these systems varies considerably from area to area. In some areas, detailed studies have been made to estimate both reserves and vulnerability to contamination, while in other areas, the underground hydrogeological

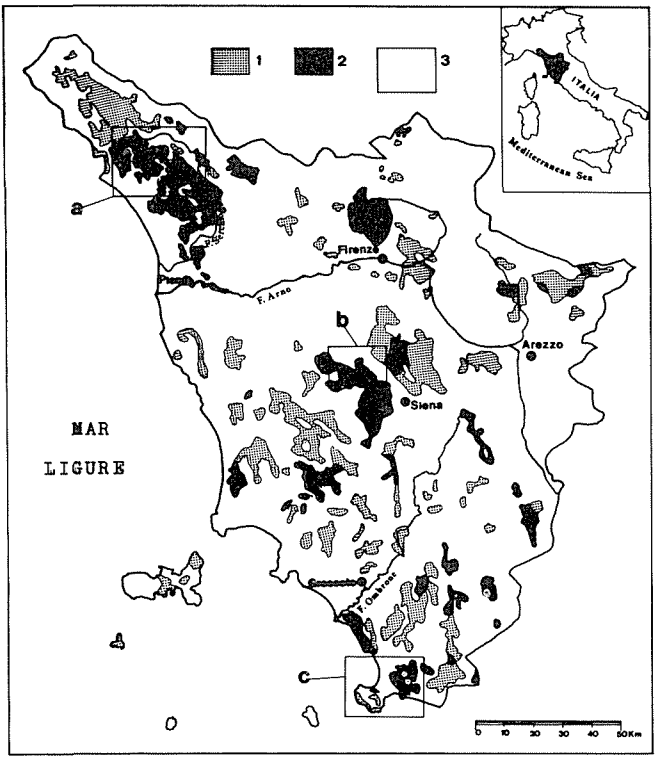

Fig. 1 - Carbonate outcrops in Tuscany. 1: Moderately karstified areas. 2: Heavily karstified areas. 3: Areas discussed in this paper - (a) Apuan Alps; (b) Colle Val d'Elsa area; (c) Orbetello area.

rescurces have yet to be determined. In the following sections, three areas containing karst aquifers that have been studied to differing extents, will be discussed.

THE APUAN ALPS

The major hydrological reserves associated with karst aquifers in Tuscany are concentrated in the Apuan Alps. For this reason, and because Tuscany's most famous caverns are in the Apuan area, many studies to unravel the area's complex hydrogeology have been carried out over the years; by now the hydrogeology of the Apuans is essentially understood. The Apuan Alps form a large tectonic window in which a metamorphic series outcrops. The rocks ranging from Middle Triassic to early Cretaceous in age are for the most part carbonates (dolomites, marbles, and siliceous limestones), and in some places reach a thickness of 1000 m. The complex tectonic phases that caused the uplift of the Apuan Massif produced intense fracturing, which, combined with the well developed surface and hypogene karst of the carbonates, has produced excellent aquifers with very high permeabilities. The high rainfall in the area, which averages 2500 mm/year, and easily surpasses 3000 mm/year in the higher parts of the chain, contributes to make these aquifers extremely rich. As can be seen in Fig. 2, which shows the springs with the highest discharges, karst springs are numerous, and border the massif. The subsurface catchments of the individual springs were determined through hydrological balances and dye tests. In some cases, the subsurface catchments were found to be considerably larger than the hydrographic basins (Piccini & Pranzini, 1990, Fig. 3). The

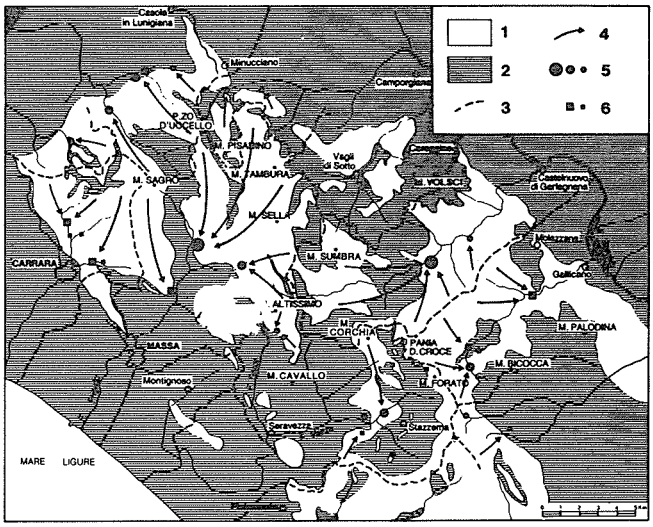

Fig. 2 - Hydrogeological sketch of the karst aquifers of the Apuan Alps. 1: Carbonate rocks, highly permeable due to fracturing and karst. 2: Impermeable or slightly permeable rocks. 3: Hydrogeological divides, determined in part from dye tests. 4: Paths followed by groundwater determined through dye tests. 5: Non exploited karst springs with discharges greater than 1000 l/s, between 1000 and 100 l/s, and between 100 and 10 l/s. 6: Exploited karst springs with discharges between 1000 and 100 l/s, and between 100 and 10 l/s.

largest spring in the Apuan Alps, located inland from the city of Massa, has a discharge of 1500 l/s, and supplies the Frigido River. On the opposite flank of the chain, the largest spring is the Pollaccia, which was a discharge of about 1000 l/s. There are at least 10 springs with discharges between 400 and 100 l/s, and many others have discharges greater than 10 l/s; the total average discharge is therefore about 6 m^3/s. Given that the total area covered by the karst aquifers that supply the above-mentioned springs is 170 km^2, the specific discharge is about 0.035 $m^3/s/km^2$, equivalent to an infiltration of 1100 mm of water per year.

Since the average precipitation over this area, which is concentrated in the higher parts of the massif, is about 2500 mm, we can calculate that there is an infiltration rate of about 45%. Considering the steep slopes in this region, this value is quite high, and

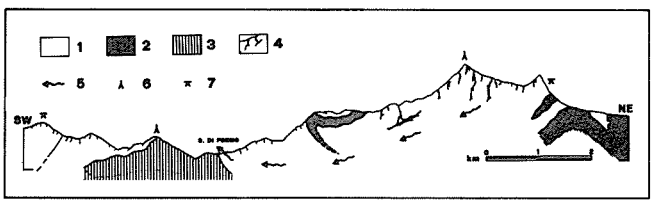

Fig. 3 - Hydrogeological section across the Apuan Alps. 1: Marbles and Dolomites, highly permeable due to fracturing and karst. 2: Calcareous-siliceous rocks, moderately or slightly permeable. 3: Crystalline basement, impermeable. 4: Caves. 5: Karst circulation. 6: Superficial divides. 7: Subsurface divides.

shows how well developed the surface karst features are. Even though there are large amounts of excellent water whose salinity, despite its coming from a carbonate aquifer, is low, little more than 15% of it is put to use. The Apuan Alps is therefore a region whose hydrological resources can be further exploited, even though care must be taken to avoid damaging its delicate fluvial ecosystems, which are important enough for the region to have been declared the Apuan National Park in 1988.

The hydraulic characteristics of these aquifers do, however, limit the degree to which they can be exploited. The well developed hypogene karstification, combined with a phreatic network which is probably well channelled, conspire to make the discharges of the majority of these springs, and in particular the larger ones, quite variable. The minimum discharges are in general about 10% of the average discharges, and about 2-3% of the peak discharges. This results in less water being available in the summer months, just when the demand is highest. Another limitation is the high vulnerability of these springs to contamination, due to the intense karst of the region. The situation is complicated by the extensive quarrying of the renowned Apuan marble, which has been going on for over 2000 years, and which has produced high risk conditions. A map based on a number of parameters including lithology, degree of karstification, slope, etc., has been drawn to show the differing vulnerabilities of the karst aquifers (Civita et al., 1990). Just two classes are shown in Fig. 4, one can see that because the marbles are the most intensely karstified rocks, quarrying is concentrated in the areas at greatest risk. There is therefore a fundamental incompatibility between quarrying and the exploitation of the hydrological resources, which can only be resolved by limiting or rigidly regulating the former, while protecting the environment in the most vulnerable areas.

THE COLLE VAL D'ELSA REGION

There are some important exposures of the carbonates of the Tuscan series in central Tuscany, in structural highs produced by the extensive tectonic phase that began in the

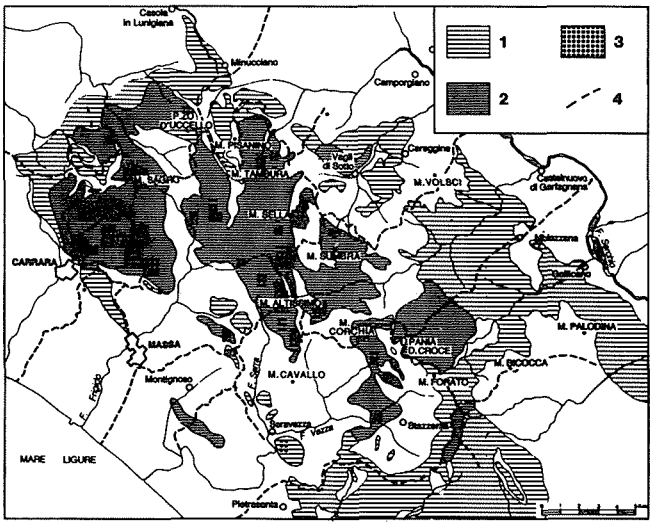

Fig. 4 - Map showing the vulnerability to contamination of the karst aquifers of the Apuan Alps. 1: Moderately vulnerable areas. 2: Highly vulnerable areas. 3: Areas where marble is quarried. 4: Hydrogeological divides.

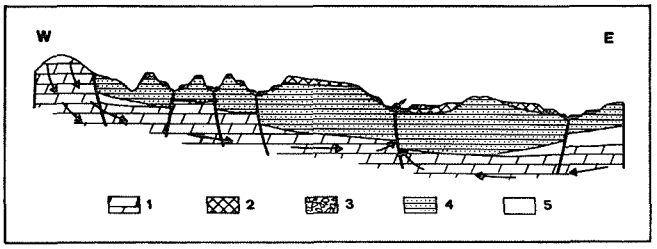

Fig. 5 - Schematic hydrogeological cross section (not to scale) of the Colle Val D'Elsa area (from Casagli et al., 1990). 1: Calcare Cavernoso (Triassic), highly permeable due to fracturing and karstification. 2: Travertine complex (Quaternary), permeable due to primary porosity. 3: Recent alluvial deposits, permeable due to primary porosity. 4: Clays and sands (Pliocene), generally impermeable. 5: Shaly-marly-arenaceous complex (Cretaceous), practically impermeable. The arrows indicate the flow path of the water that feeds the springs of Colle Val D'Elsa (see Fig. 6).

Miocene and is still under way; the structural lows contain Miocene lacustrine or Pliocene marine sediments. Figure 5 is a schematic cross section of the region, in which the highs are formed by carbonate rocks rendered permeable by fracturing and karst, while the basins are filled with unconsolidated sediments (clays and sands) whose permeabilities are generally low. The highs are therefore source regions for deep aquifers, whose waters rise along faults, producing springs whose discharges can be quite high. In many cases the circulation is very deep and the waters become highly saline and quite thermal (reaching temperatures of 70°C); one must keep in mind that the thermal gradient in central and southern Tuscany is high because there are granitic stocks at shallow depths. Indeed, Tuscany was the first place in which geothermal energy was used to produce electricity. In other cases, the waters have low temperatures and salinities, and can therefore be used as drinking water and for industrial and agricultural needs.

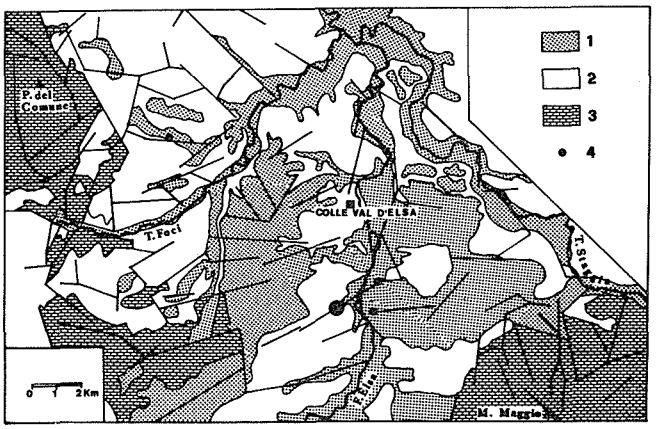

Fig. 6 - Hydrogeological map of the Colle Val D'Elsa region. 1: Travertines and alluvial deposits (Quaternary), permeable due to primary porosity. 2: Clays and sands (Pliocene), generally impermeable. 3: Calcare Cavernoso (Triassic) and Conglomerates derived from the Calcare Cavernoso (Miocene), highly permeable due to fracturing and karst. 4: Hypothermal springs (20-22°C); the larger dot indicates the Vene degli Onci, a spring with an average discharge of 1.5 m^3/s.

There are some large springs in the Colle Val D'Elsa area (Fig. 6) whose hydrologic reservoir is in the Calcare Cavernoso. This formation outcrops as a breccia, consisting of limestone and dolomitic fragments cemented by a calcite cement, whose origin is controversial. However the Calcare Cavernoso formed, its very high permeability has allowed intense groundwater circulation, which has produced karst that is deep and well developed, even though it is only rarely traceable. Rain water infiltrates the elevated regions of Monte Maggio and Poggio del Comune, and rises along faults. During the Quaternary, the waters from the carbonate rocks produced significant travertine deposits. The studies carried out in this area have shown that the average infiltration in the carbonate terrains is equivalent to about 45% of the annual precipitation. Because of the high permeability of the Calcare Cavernoso, the underground circulation is well channelled, and almost all of the water flows from a few springs. In addition, the elevation of the mouths of the springs is constant, indicating that the carbonates form a continuous aquifer with a single piezometric surface. Not all the water rising from the carbonate reservoir reaches the surface; in some cases there are local thermal and salinity anomalies in the superficial aquifers, which indicate that significant amounts of thermo-mineral water are dispersed into these aquifers (Casagli et al., 1990, Fig. 7). Some thermo-mineral springs are used as spas, while many other low temperature thermal springs could be used as low enthalpy geothermal resources, for example, to heat houses or greenhouses.

The waters of other springs that are normal, though fairly hard, are used for municipal supplies, and, more rarely for agriculture. Since the demand for water for these uses increases yearly, while the reduction in rainfall that has occurred in the past years has reduced the amount of water available, new sources of water must be found. In the Colle Val D'Elsa area, these sources essentially lie in the aquifers of the Calcare Cavernoso. A well 180 m deep has already been drilled in the vicinity of Monteriggioni (7 km

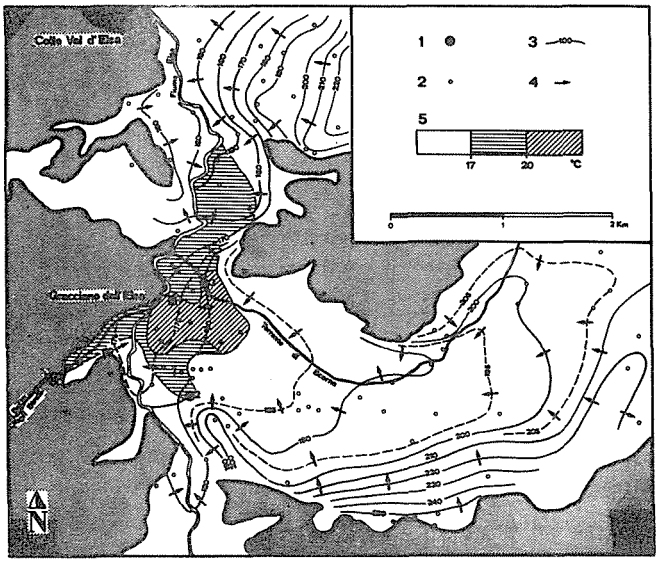

Fig. 7 - Thermal anomaly in the groundwater in the travertines and alluvial deposits, due to the intrusion of thermo-mineral water rising from the Calcare Cavernoso. 1: Springs. 2: Wells for measuring the temperature and chemistry of the superficial waters. 3: Isophreatic contours. 4: Flow lines of the superficial groundwater. 5: Temperatures of the water in the wells.

southeast of Colle Val D'Elsa). It produces 30 l/s, which demonstrates the aquifer is fairly rich. However, before planning to exploit the aquifer more intensely, one must examine the hydrological balance of the entire system to avoid overexploiting it. It is in fact clear that, since the aquifer is supplied exclusively through rain water infiltration, one cannot pump more than the average yearly supply. Overexploitation through wells would, in the long run, reduce the discharges of the springs.

Another problem that must be examined is the vulnerability to contamination of this groundwater; indeed, the high circulation rates and small capacity of the carbonates for purifying the water makes these wells and springs vulnerable to pollution sources at considerable distances. With regards to possible pollution sources, there are few potentially dangerous industries in the area. The greatest danger is posed by agriculture, from the fertilizers and herbicides used. An example of this problem can be seen in the area of Rosia, near Siena, where considerable amounts of herbicides are used in the cultivation of a small alluvial plain. In some areas, the alluvial aquifer already contains concentrations of atrazine in excess of those allowed by law for drinking waters. Since there are three wells at the edge of the plain that draw water from the Calcare Cavernoso of Monte Maggio for Siena's municipal aqueduct, there is a real danger that the contamination of the superficial aquifer will spread to the deeper aquifer, rendering its water unfit to drink.

THE REGION OF ORBETELLO

This part of the Tyrrhenian coast has an intense seasonal tourist trade; the considerable increase in the population during the summer creates serious water supply problems. A significant confined aquifer has been found below the Orbetello Lagoon (Fig. 8). Its piezometric surface is above sea level, and, as the low salinity of the water in the lagoon indicates, it in part supplies the lagoon. The extreme hardness of the water renders it

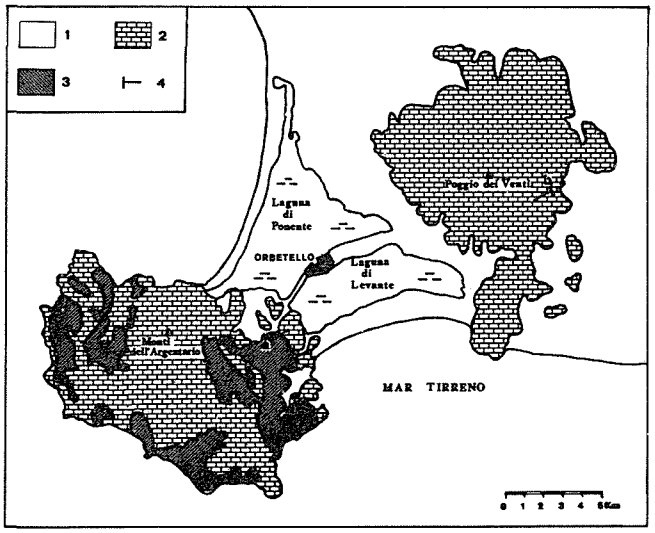

Fig. 8 - Geological map of the Orbetello area. 1: Pliocene and Quaternary deposits: clays and sands. 2: Calcare Cavernoso Formation (Triassic): dolomitic limestones brecciated and karstified. 3: Verrucano Formation (Triassic): phyllites and quartz-rich conglomerates. 4: Cross section shown in Fig. 9.

unfit for drinking without treatment. It does however appear suitable for irrigation, fish breeding (its temperature, close to 20°C, favours this activity), and for use in the lavatories of the many resorts along the coast. As drinking water presently serves these needs, this would considerably reduce the strain on the drinking water supply. In order to manage this aquifer correctly, without creating problems such as salt water intrusion or subsidence, a careful hydrological study of the region must be made.

Tectonically, the area consists of a depression, that contains the Orbetello Lagoon, between two structural highs, M. Argentario and Poggio dei Venti. These highs are almost entirely made up of Calcare Cavernoso, which is more than 400 m thick here, and is exposed over an area of more than 67 km^2. The Calcare Cavernoso is intensely karstified in these mountains (Mori, 1923; 1932), and there are many dolines, some with diameters greater than 500 m. At M. Argentario, the Verrucano, a formation underlying the Calcare Cavernoso that consists of impermeable phyllites and quartz-rich conglomerates, is also exposed.

The sediments of the Orbetello Lagoon, which date to the Middle Pleistocene, are over 100 m thick, and consist of alternating fine sands and clays. Because of the presence of significant superficial ore deposits, whose genesis is related to the uprising of granitic stocks, the area has been thoroughly explored (RIMIN, 1980), and a precise geological cross section can be drawn (Fig. 9).

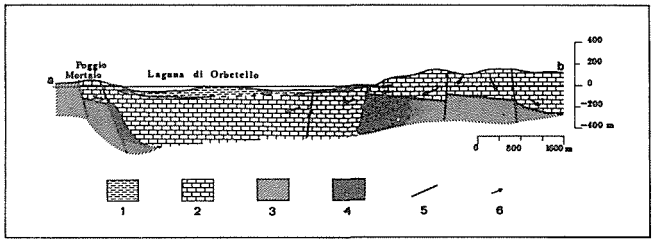

Fig. 9 - Hydrogeological cross section of the Orbetello area. 1: Lagoonal deposits: clays and fine sands, slightly permeable. 2: Calcare Cavernoso Formation: dolomitic limestones, extremely permeable due to karstification. 3: Verrucano Formation: phyllites and quartz-rich conglomerates, practically impermeable. 4: Pyrite ore deposit. 5: Faults. 6: Water flow.

A sizable pyrite deposit has been found under Poggio Mortaio. Mining it has proven difficult because of the large amounts of water that filter into the shafts. Water under pressure has also been found in the lagoonal sands on the eastern side of the depression. Below the Orbetello Lagoon there are, therefore, sizable aquifers; the most important lies within the Calcare Cavernoso, which is isolated from the sands by an impermeable reddish brown clay layer. The water comes from the karstified carbonates of Poggio dei Venti, where the Verrucano serves as the impermeable base of the aquifer. The lack of significant springs around Poggio dei Venti indicates that most of the infiltrating water goes to feed the aquifer below the lagoon. It is also possible that some of the water feeds the deep circulation that emerges as a copious thermal spring 15 km southwest of the hills.

An initial analysis of the hydrogeological basin leads to the calculation that the Calcare Cavernoso exposed at Poggio dei Venti covers an area of 35 km^2. The records taken at the Orbetello meteorological station over the past 20 years indicate the average annual precipitation is 716 mm; with an infiltration coefficient of 40%, 10 million m^3 of water

would go to supply the aquifer below the Orbetello Lagoon each year. The area, because of its high degree of karstification, appears vulnerable to contamination. However, because the karst area is wooded and there are no potential sources of contamination, it is not presently endangered.

ACKNOWLEDGEMENT

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