MINE WATER AND THE ENVIRONMENT, VOL. 14 , ANNUAL ISSUE , 1995, PAPER 5, PP 57-70

STORAGE OF WATER IN THE VOIDS OF ABANDONED MINES AND IN FRACTURED ROCKS

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ABSTRACT

This paper describes the characteristics that abandoned mines and fractured igneous and metamorphic rocks must have before they can be utilized as water reservoirs.

The geometries of the networks produced by the interconnections of the fractures in rock are frequently irregular and unknown and the experimental results reported indicate that the flow of ground water through these fractures is equally unpredictable. The behaviour of water in a hypothetical reservoir cannot be predicted solely by modelling or tests limited to small areas of the reservoir. An analogy is shown to exist between networks of fractures in hard rocks and mining networks and the possibility of solving problems of water storage in fractured rock by the use of results obtained from mining experience is discussed. Two reservoirs are described, one located in rock fractured by the action of an extinct volcano and the other in an abandoned mine in the same rock. The examples show how knowledge of existing reservoirs can be used to aid correct choice of method. Finally, evaluation criteria based on specified factors are presented, allowing informed selection of methods to be made.

These water storage systems have potential application in many Third World countries where long dry spells are encountered.

INTRODUCTION

In hard rock mining, the voids remaining after cessation of activities are sometimes accompanied by the presence of natural cavities, which may or may not be filled with water. The natural cavities typical of plutonic, volcanic and metamorphic rocks usually contain faults, fractures and joints generated by tectonic and/or thermal stresses. These can be modified by successive settlings and exogenous agents among which dissolution of the rock has a negligible role.

This paper contains discussions of the problems related to the storage of water in rock cavities and in the voids of abandoned underground mines. However karstic cavities where they exist, may be connected at times to the mined out voids by the fracture systems which may intersect both karstic rocks and subject rocks. This would result in complicated systems of conductive openings in basically impermeable rocks and accompanying difficulties in the design of underground water storage where these conditions occur.

The difficulties associated with computer modelling and obtaining experimental data related to hydrodynamic behaviour of the fractured and caved rock surrounding the mining excavations, and particularly, to simulate reservoir properties and flow patterns, are high lighted in this paper. These can be considered in stages of deductive reasoning by which the creation of reservoirs on the basis of analogous cases followed by experimentation on the reservoirs to improve their efficiency and choice of location of future reservoirs is studied.

The observations and deductions reported in this paper are derived mainly from continuous and prolonged research investigations carried out in underground mines in Southern Tuscany. The original aim of the project was to locate and drain water bodies which were prone to inrushes and flooding. The knowledge thus acquired is also relevant to water reservoirs.

FLOW OF GROUND WATER IN ABANDONED MINES AND IN FRACTURED ROCKS

Information about the motion of water through rock fractures or the voids in an abandoned mine is an important factor in the creation of reservoirs. Water movement causes transport and deposition of material in the fractures and voids, resulting in changes in connections and disconnections in the hydraulic circuits. These changes can significantly influence the efficiency of the reservoir with regard to water inflow and downflow and further influence the capacity of the reservoir which may be, for example, substantially reduced as a result of excessive deposition of material in the reservoir.

It may be possible to understand the flow of the water in a flooded mining network by measurement of the heads in the nodes and studies of the hydraulic characteristics of the branches of the network. However, to evaluate, even approximately, how the water moves in a network of fractures other methods must be tried.

In the case of fractured rock masses modelling techniques for measuring the permeability of a fractured rock mass based on knowledge of the length, width and location and direction of the fractures have been suggested (Witherspoon, 1986). However, it is generally unlikely that models which are able to yield acceptable forecasts will be obtained since it is not possible to state with confidence the cited parameters and since these are not always accurate representations of the real fractures present. Attempts have been made to calculate an expected value for the hydraulic conductivity in statistically homogeneous formations (Dagan, 1979). However, deviations become larger as the Representative Element Volume is reduced in size (Gustafson et al, 1989). This is probably due to the hydraulic conductivity not being statistically homogeneous (Gustafson and Krasny, 1994) where the hydraulic conductivity of the rock in the borehole interval and isolated from the rest of the boreholes by a straddle packer, being evaluated from the pressure and flow of water injected in the packed off interval (Moye, 1967). The hydraulic conductivity in these circumstances cannot be considered representative of the conductivity of the surrounding rock as the geometry of the fractures may vary significantly. This is indirectly corroborated by the large scatter of conductivity values around the regression curves plotted to estimate, for particular rocks, the probable trends of hydraulic conductivity versus depth (Ahlbom et al, 1991).

In general, it is difficult to identify, from first principles, factors governing the hydrodynamics in a mining network and, it is even more difficult to similarly treat a system of interconnected fractures of a rock mass. Therefore, it is better to consider historical and experimental data of the reservoir being studied, as well as other similar sites to obtain approximate information about the water quantities capable of being stored and the water flow-rates that can be drained by either gravity or pumping without endangering the reliability of the reservoir (Sammarco, 1990, 18).

Design solutions for natural reservoirs can be also found by experimenting on flooded mines. The discontinuities in the form of fractures and faults that are met with in hard rock projects, are typically of more or less irregular shapes (Burdon and Fuganti, 1973) and may be filled or partially filled by material which, even if permeable, considerably increases the resistance to water flow (Bancks et al, 1994). These form complex intersecting networks whose simultaneous lines of total head may differ considerably from one downflow path to another. The branches of mining networks, consisting as they do of galleries, stopes, inclined shafts, shafts and raises, even if they were initially of regular geometric shapes, after flooding, will vary in their shapes and dimensions due to cave-ins and swellings (Sammarco, 1993, 20) resulting from removal, transport and deposition of materials caused by the water flow (Sammarco, 1994, 22). Since these events will not occur uniformly in every branch of the mining network, the situation is geometrically to fracture networks in rocks. This means that a set of interconnected rock fractures can be considered similar to a mining network that has been flooded for some time. Therefore experimental results obtained from a flooded mine are easily interpretable if the initial geometry of the network is known, and can be used as the basis for analysis of a fracture network in a rock mass of unknown configuration.

However it is very important to understand, where possible, how the water moves through the fractured material. In an exceptional case it was possible to determine the water flows in a cavity, attributable either to tectonic events or to karst phenomena, during its emptying. This was in a water body detected by means of boreholes in the Campiano mine (Sammarco, 1988). The lower part of Figure 1 shows the cross-sections of the orebody being mined with the water body also shown, assumed to be symmetrical about the centre line. The upper part on the left shows the flow rate of the water along this cavity at the commencement of dewatering, and on the right are shown the marked sections of the cavity during the dewatering. It must be pointed out that the rate of the water movement was variable during drainage and that the rate of initial dewatering varied greatly along the cavity, since the horizontal section area of the cavity varies as a function of elevation, and time, since the water level in the same cavity gradually dropped. It is possible that turbulent conditions occur in the sections in which the water flows were greatest owing to the irregularities of the walls of the cavity. This undoubtedly would have occurred if the water flow rate was enhanced as a result of, for example, the interception of the water body with other boreholes.

The cavity examined cannot be considered as a singular case. In fact, fractures in the rocks have irregular shapes and, when used to store water, are subjected to superficial erosion due to the recharging and dewatering, even if partial, which would be expected to occur. Such fractured areas behave as hydraulic accumulators and/or conductors for which it is impossible to obtain expressions that define the water flow by correlating hydraulic parameters, because of the impossibility of quantifying them.

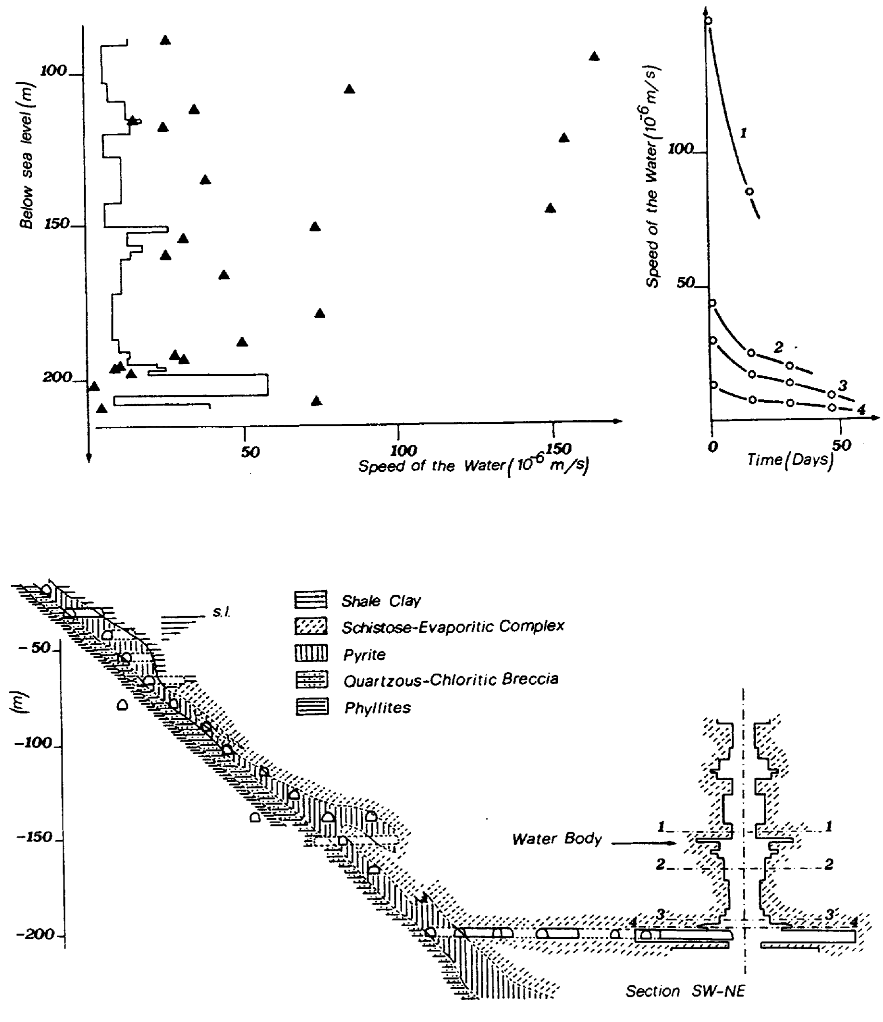


Figure 1 Detection of aquifer by means of boreholes in proximity of the hangingwall of the at Campiano orebody (a) Rate of dewatering with time (b) cross-section of the mine in relation to aquifer (water body) .

EXAMPLE OF WATER RESERVOIRS

The phreatic ground water in the volcanites of the Monte Amiata, shown in Figure 2, is an example of natural water reservoirs in fractured rocks.

The Monte Amiata Volcano is located in Southern Tuscany 45 km ENE of Grosseto. Its volcanism was still active some 400,000 years ago, producing, according to the observed succession of the volcanic events: quartz-latitic ignimbrites and reoignimbrites, quartz-latitic lava domes, quartz-latitic lava flows and trachytic lava flows. The volcanites are based on an impermeable sedimentary substratum made up largely by shales and marls. The materials of the volcanic eruption, which took place mainly along approximately SW-NE fractures, filled the existing depressions of the substratum and produced the morphologic inversion of the landscape (Jacobacci and others, 1967). Following the eruption, the central part of the volcanic body collapsed, as evidenced by volcanic-tectonic faults, newly formed or rejuvenated from old fracture lines (Calamai et al, 1970).

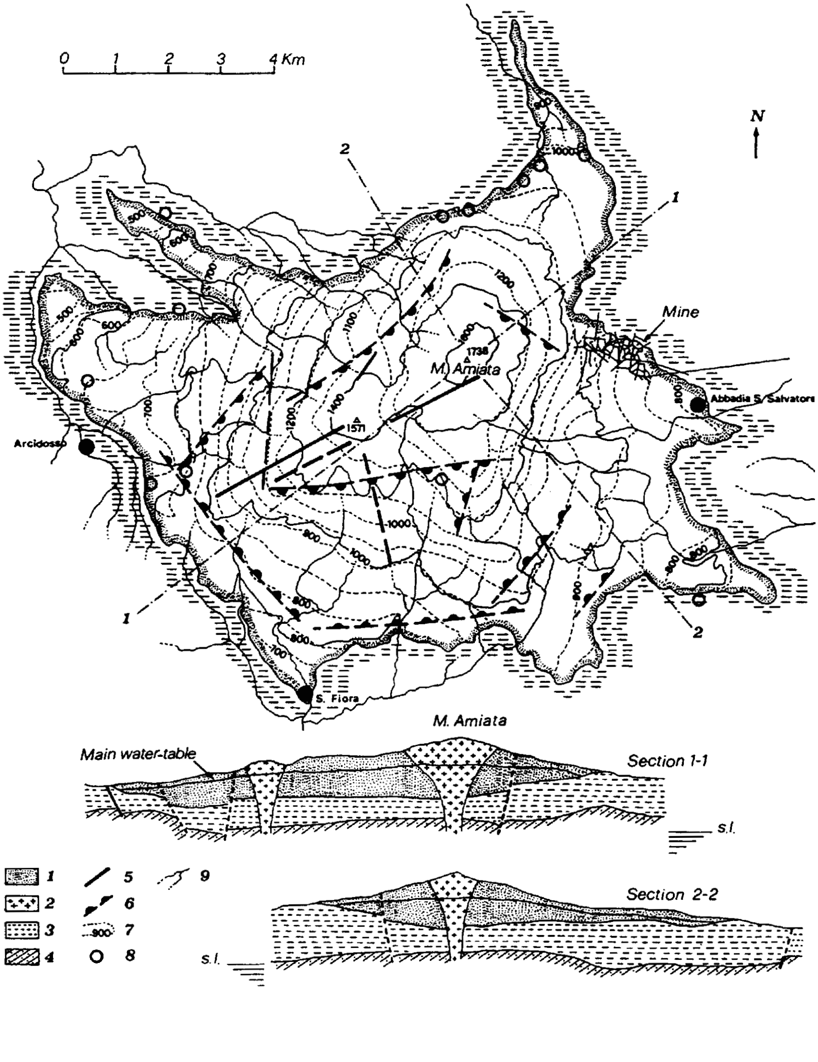
The bowl shape of the sedimentary substratum underlying the volcanites and the marked and closely-located fractures represent the most favourable conditions for a large storage of fresh water in the highly permeable volcanic complex.

Figure 2 shows the isopiestic lines of the main water-table in the volcanites. These lines have been individualized through static level measurements in the boreholes and depression springs and by localizing the marked geoelectric resistivity contrast existing between aerated or moist Vulcanites and water-saturated volcanites. The phreatic surface lies at elevations generally higher than those of the rims of the internal basin ; the water can thus overflow outside such a basin giving birth to a great number of perennial springs. In the area within the internal basin there are only a few springs which originate from water bodies suspended above the main water-table (Calamai and others, 1970). The connection system of the faults, fractures and joints in the volcanites is such as to produce activations and deactivations of hydraulic circuits for even local variations of the water-table level on the surface and in the underground mine are schematized respectively in Figure 2. Sudden increases and decreases in flow-rate of water downflows occur and above all abrupt appearances and disappearances of usually dry water courses.

The main water body contained in the volcanic complex is connected hydrogeologically via volcanic chimneys, fractures and volcano-tectonic faults with confined aquifers underlying the substratum of the vulcanites. These aquifers form geothermal fields (Atkinson et al, 1978), the steam from which is utilized for electricity generation. The acquifers deepen beyond 2,000 m below sea level in the Southern part of the Monte Amiata (Latino and Sammarco, 1981).

An example of an abandoned mine in which a water reservoir could be established is the Abbadia S. Salvatore mine.

This is an underground mercury mine, near the built-up area of Abbadia S. Salvatore, on the eastern slopes of the same extinct volcano Monte Amiata (Figure 2). The area contained many springs of moderate flow, which began to dry up as the mining work proceeded, while at the same time in the mine water emergences occurred in concentrated and diffused form. The former appeared in the high parts when water bodies in the trachyte fractures were intercepted by the galleries and the latter when the mine openings permitted infiltrations of contact water.



(1) Volcanites (Ignimbrites, Trachytes) (2) Volcanic conduits (3) Impermeable Sedimentary stratum (Shale, marl etc.) (4) Mesozoic rocks of the Tuscan Formations (5) Erruption faults (6) Volcanic , Tectonic faults (7) Isopiestic lines of the main water table in volcanites. (8) Spring (9) River and streams

Figure 2 Hydrological and Tectonic map of the Mount Amita Volcano

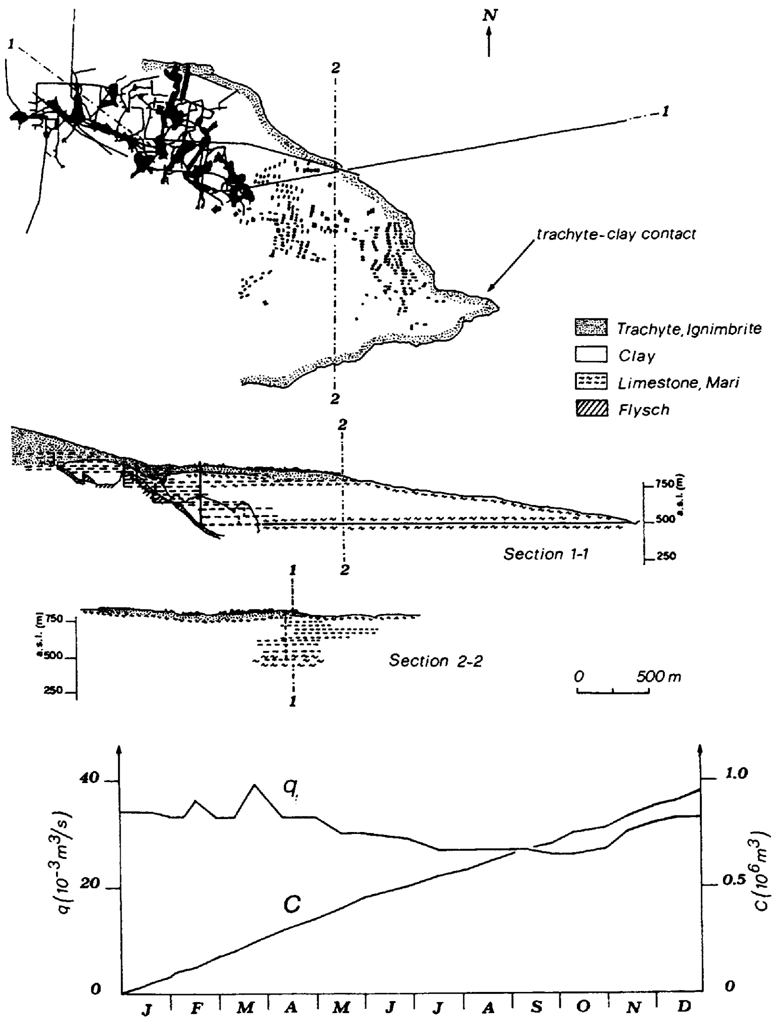


Figure 3 Abbadia S. Salvatore Mine. Above; Plan and section of the mine Below: Flow rate q, and cumulative flow of water 'C' drained from the mine.

The emergent water is at present almost all introduced into the aquaduct of the nearby village and used as drinkable water. The seepage water is directed towards the bottom gallery, principally the Italia gallery, at 511 and 786 m above sea level respectively, from which the water is drained out (Sammarco, 1990, 17).

Figure 3, schematically shows the development and mining zones in the Abbadia S. Salvatore mine represented by black areas, and the built-up area of Abbadia S. Salvatore is shown in plan and in two vertical sections.

In anticipation of the abandonment of the mine, work has been carried out in order to preserve the hydrodynamics regime within and surrounding the mine. The work consists principally in consolidating galleries and shafts with highly permeable structures, part of these are planned to prevent rising water levels from resulting in pollution of the drinkable waters and reappearance on the surface in environmentally sensitive zones. The work will allow preservation of the mine openings for storage of water in it. This goal can be easily attained by use of airtight and watertight seals to the outlets of the two above mentioned drainage galleries.

In order to estimate the storage capacity of the mine the flow-rates and the cumulative quantities of the water drained during 1994 are presented in Figure 3. In one year almost 10^6 m^3 of water can be stored, because while the mine is flooding only minor inflows will be covered with water. Since the total volume of the residual mining voids, calculated by subtracting the total volume of the material introduced into the mine from that of the material extracted, is about three times bigger than the volume of the water storable in one year and since the mining voids are connected with fractures in the trachytic rock, which will certainly have been emptied in part during the mining activity, it can be deduced that it is possible after sealing of the downflows to store very large volumes of water for very long periods using the above methods.

EVALUATIONS AND MODIFICATIONS

To decide whether a fractured rock mass or an abandoned mine is usable as a water reservoir, and to determine the modifications which may be necessary to create a reservoir of the type described above, the following factors should be considered:

- It is necessary to ensure that the network of fractures in the rock or the mining network will remain watertight when subjected to the highest hydrostatic pressure foreseen in the course of the operation, experimentally checking its water tightness by filling trials. If leakages are discovered or expected, they must be eliminated using specific techniques consisting mainly in the use of grouting inside the zones to be sealed.

- It is also necessary to determine the total available volume and if possible the configuration of the network. The configuration of a mine should be known, and its volume determined on the basis of the historical data (Table 1). Factors which may be present and not considered at this stage include fractures in the rock which communicate with the mining network, direct or through fractures produced by the same mining activity, or the presence of clayey formations which by swelling will reduce the total volume. The surface of the horizontal cross-sections at various elevations and the volume of a network of a mine or of a fractured rock can be calculated by carrying out, during the emptying of the network, very frequent surveys to determine flow-rates of the draining water and associated hydrostatic pressures. The more frequently these surveys are carried out, the closer the reconstructed network will be to the real one (Sammarco, 1988).

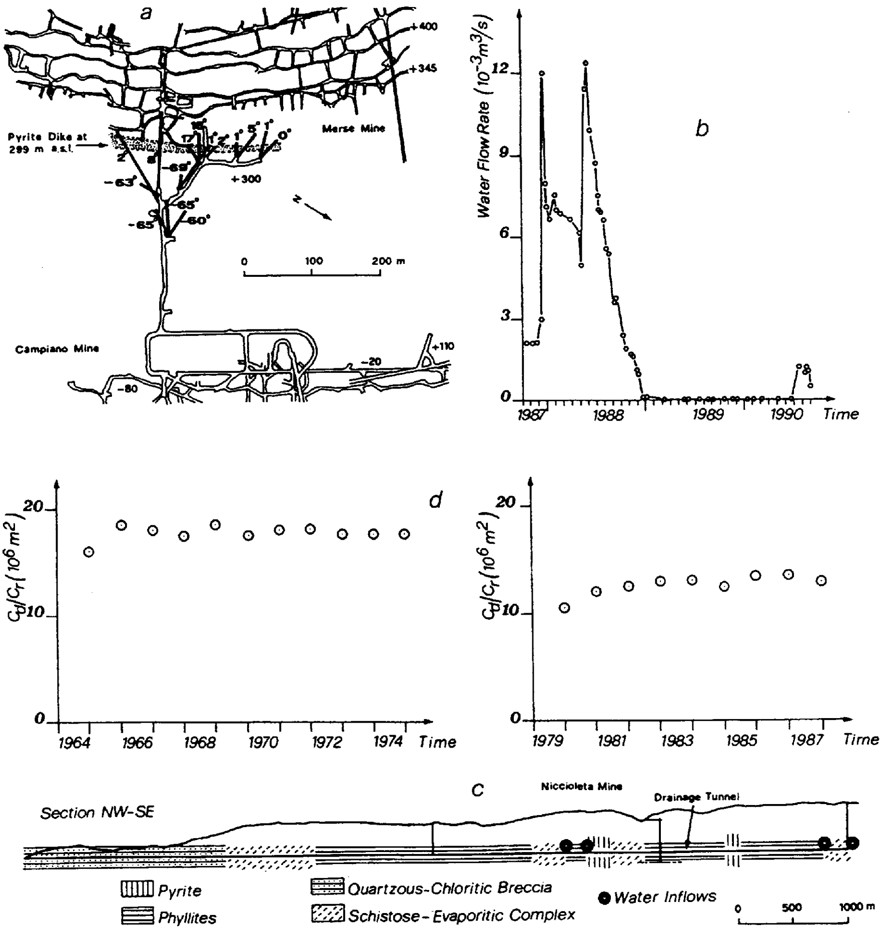


Figure 4 . Irregularities of water flows from the mine. (a) Plan of the Companio Mine (b) Water flow rate with time (c) Section through Niccioleta mine (d) Ratio of cumulative drainage and cumulative drainage in Niccioleta Mine

Table 1. Vacant volume of the abandoned mines obtained by substracting the volume of backfill from the total volume of the extracted mineral and the rock.

Mine and mineral extracted	Mining method	Ore and rock extracted (volume before mining) (m^3)	Filling introduced (m^3)	Theoretical total volume of the residual mining voids (m^3)
Abbadia San Salvatore Cinnabar	Horizontal cut-and-fill stopes	6,056,136	3,176,874	2,879,262
Gavorrano Pyrite	Horizontal cut-and-fill stopes	10,120,000	6,500,000	3,620,000
Niccioleta Pyrite	Sub-level stoping	5,060,000		5,060,000
Campiano Pyrite	Filled sub-level stoping	1,471,837	640,736	831,100

- Evaluation of the stability of the reservoir taking into account the largest variation in anticipated water level should be undertaken (Sammarco, 1993). Provision should be made to allow removal of sediments that could compromise he functionality of the system. The Campiano mine, for example, appeared stable: in this mine neither significant landslides nor swellings at the contour of the voids occurred in consequence of its flooding for a period of eight months and was characterized by large variations of level during the emptying of the mine (Sammarco, 1986).

- To evaluate, on the basis of the circumstances, if it is convenient to flood a network deprived of water inflows in order to utilize it as water reservoir for use during dry spells.

- In the case of a fed network, to evaluate whether the flow rates of the water inflows into the network decrease as time passes. The upper part of Figure 4 shows the case of the Campiano mine into which water coming from the old Merse mine inflows by gravity through boreholes purposely drilled. These suffered obstruction which resulted in the water flowing into the Campiano mine stopping until the boreholes were cleared. The lower part of the same figure shows the case of the Niccioleta mine where, by consideration of the ratio between the quantity of the drainage water and the total rainfall during two periods, that the conductivity of the inflows decreased remarkably from the end of the first period to the beginning of the second, brought about by huge landslides which occurred in the stopes of the mine (De Col and Sammarco, 1982), and on the average increased slightly during the latter period. It is useful to know the historical data for rainfall and the flow rate of the drainage water and, in the case of mines subject to flooding, how the latter decreased during he course of the floods when the hydrostatic pressures downstream from the inflows increased (Sammarco, 1993, 21).

- When a reservoir cannot gravity feed water to the area where the water has to be utilized, evaluation of pumping power consumption should be done by computing the necessary power for pumping from the predicted water levels.

CONCLUSIONS

The difficulty of evaluating the hydrodynamics of a water reservoir in fractured rocks by use of models or by trial on very narrow parts of the reservoir have been shown. These difficulties are due in substance to the impossibility of knowing the exact geometry of the fractures and irregularities and as a consequence the motion of the water within them. According to the experimental results quoted this flow pattern is, as a rule, neither uniform nor permanent.

To deal with the above difficulties, deductions can be made based on information obtained from existing reservoirs, shown in the examples, relating to the hydrodynamics of natural reservoirs in fractured rocks and flooded mines and which can be used to forecast the behaviour of a hypothetical reservoir. The resulting data will be augmented during the operation of the reservoir and will be continually modified during the period.

Water reservoirs like those described in this paper can become indispensable for many of the countries in the Third World which experience long dry spells and located far from any surface water courses, lakes or seas where not even desalination is a possibility. In reality, outcrops of plutonic, metamorphic and/or volcanic rocks characterized by the fracturing considered here are an infrequent occurrence in such zones (Sammarco, 1994, 23). The networks formed by these fractures are not suitably supplied with water naturally, they can receive water from far-off rivers by long ducts (Deana, 1990), or directly from the local rains during the rainy seasons (Sammarco, 1992) by utilizing structures that can divert the flooded water courses (Ferioli, 1994) towards the more fractured rocks making possible the immediate penetration into subsoil of the excess of water and this, at same time, avoiding disastrous inundation.

ACKNOWLEDGEMENTS

The author expresses his gratitude to Mr F. Bini, Mr M Costabile and Mrs M. R. Ciardo of this Department for their kind and careful collaboration.

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