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Storage of Water in the Voids of Abandoned Mines and Fractured Rocks

O. Sammarco

Italian Bureau of Mines, Ministry of Industry

ABSTRACT

This paper describes the characteristics that the abandoned mines and the fractured igneous and metamorphic rocks must have in order to be utilized as water reservoirs.

It is underlined that the geometries of the networks determined by the interconnections of the fractures are irregular and unknown and, by reporting experimental results, that the motion of the water in the same fractures is irregular, as well. For these reasons the behaviour of a hypothesized reservoir cannot be foreseen only by models or tests limited to very narrow portions of the reservoir. The analogy between networks of fractures in hard rocks and mining networks and, by consequence, the possibility of solving problems of storage in the first by results obtained from the latter are point out. Two reservoirs are explained, the one constituted by the fractures of an extinct volcano the other by the voids of an abandoned mine connected, moreover, with the fractures of that volcano. Such examples show the opportunity to deep the knowledges of known reservoirs in order to choose right others.Criteria of valuation that provide specific verifications, expounded at last in this paper, enable, just, such choices.

The usefulness of such storage systems to many countries of the Third World with long dry spells is interesting.

INTRODUCTION

In the hard rocks natural cavities and sometimes voids due to mining activities, which are or could be filled with water, can appear. The natural cavities typical of the plutonic, volcanic and metamorphic rocks are represented by faults, fractures and joints that were generated from tectonic and/or thermal stresses, but can be modified because of successive settlings and exogenous agents among which, however,the dissolution has a negligible role.

This paper discusses the problems related to the storage of water, above all, in the cavities of such rocks and in the voids of abandoned underground mines. But, the karstic cavities cannot be considered on all occasions separated from the others. In fact, the first may be joined at times to the latter and a same fracture may intersect non-subject to karst phenomena rocks and subject rocks. These latter would make systems of conductive openings in basically impermeable rocks more and more various and so still more difficult to schematize with regard to their hydraulics.

The excessive difficulties that one meet in obtaining models and experimental data by which it is possible to know the hydrodynamics in the fractured rocks, the analogies between these rocks

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and the mining networks, analogies that could make it possible to arrive at the behaviour of the first by means of the knowledges on the latter, the experimentally obtained results on the motion of the water in a natural cavity and the examples of reservoirs, are all subjects emphasized in this paper. They can be considered as stages of a deductive reasoning, by which the opportunity to obtain reservoirs on the basis of analogous cases and then to experiment on the reservoirs so obtained in order to improve their efficiency and choose right the places of others is perceived.

The observations and the deductions which are stated in this paper derive mainly from the experimental results of a continuous and prolonged research work carried out, in underground mines of the Southern Tuscany, in order to localize and drain water bodies which could cause inrushes and flooding. It's evident that the knowledges acquired in this way are valid for the water reservoirs at issue, too.

FLOW OF GROUND WATER IN ABANDONED MINES AND IN FRACTURED ROCKS

The motion of water through the fractures of a rock or the voids of a abandoned mine is a determining factor for their utilization as reservoirs. It, in effect, causes either in the fractures or in the voids removal, transport and deposition of material, connections and disconnections of hydraulic circuits. These events can decidely influence the efficiency of the reservoir with regard whether to the water inflows and downflows or to the water quantity accumulable which may be, for example, reduced heavily in consequence of excessive deposition of material in the resorvoir.

It may be possible, at times, to know how the motion of the water occurs in a flooded mining network by the heads in the nodes and by the hydraulic characteristics of the branches of the network. Instead, in order to try to know, even if approximately, how the water moves in a network of fractures one must resort to other methods.

For the fractured rock masses modeling techniques wich enable to obtain the permeability of a fractured rock, when the lenght, width, location and direction of the fractures are known, have been suggested (Witherspoon, 1986). But, since it is not possible to state with reliability the cited parameters and since these are not always sufficient to represent the real fractures, it is little likely to obtain models which are able to yeld acceptable forecasts. Attempts have been made to calculate an expected value for the hydraulic conductivity for statistically homogeneous formations (Dagan, 1979), by finding, however, deviations, as larger so smaller the Representative Element Volume is (Gustafson and others, 1989), due probably to the fact that the hydraulic conductivity is not statistically homogeneous (Gustafson and Krasny, 1994). The hydraulic conductivity of the rock in correspondence with an interval of a borehole, isolated from the rest of the borehole by a straddle packer, evaluated from pressure and flow of the water injected in the packed off interval (Moye, 1967), cannot be considered representative of the conductivity of the surrounding rock because in this latter the geometry of the fractures may vary noticeably. That is indirectly corroborate also by the large skatter of the values of conductivity around the relative regression curves determined in order to find, for particular rocks, the more probable trends of the hydraulic conductivity versus the depth (Ahlbom and others, 1991).

In general, it is very hard to identify, a priori, elements from which to deduce the hydrodinamics in a mining network and, most of all, in a system of interconnected fractures of a rock mass.

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Therefore, it is better to take into consideration historical data and experimental results of the same reservoir which has to be estimated and/or of analogous others in order to obtain approximate information about the water quantities accumulable and the water flow-rates that can be drained by gravity or pumped, in various circumstances, without endangering the reliability of the reservoir (Sammarco, 1990, 18).

Solutions for natural reservoirs of water can be also found by experimenting on flooded mines. In reality, the fractures, the faults and, generally, the discontinuities, that are met in the hard rocks, present various and more or less irregular shapes (Burdon and Fuganti, 1973) and may be filled to varying degrees by materials which, even if permeable, considerably increase the resistance to the water flow (Bancks and others, 1994). As a consequence, they by intersecting form more or less complex networks whose isochronous lines of the total head may considerably differ from a downflow path to another. The branches of the mining networks, consisting of galleries, exploitation voids, inclined shafts, shafts and raises, even if at the outset of regular geometric shapes, as time passes and once they are flooded, could vary in their shapes and dimensions in consequence of cave-ins and swellings (Sammarco, 1993, 20) and/or in consequence of removals, transports and depositions of materials on behalf of the flowing waters (Sammarco, 1994, 22). Since these events don't occur uniformly in every branches of the mining networks, these latter can be considered similar, with regard to the geometry, to networks in fractured rocks. This means that the flow and the stagnation of the water which occur in a set of interconnected fractures of a rock can be, even they, considered similar to which in a mining network that has been for some time flooded. For this reason experimental results concerning the latter, easily interpretable for the initial geometry of the network is known, can be valid for a fracture network in a rock mass the behaviour of which is often hard to explain since its configuration is unknown.

But, it's very important to understand, whenever it is possible, how the water moves in the very fractures. In a exceptional case it has been possible to know the speeds of the water along a cavity, attributable either to tectonic events or to karst phenomena, during its emptying. It is a water body detected by means of bereholes in the Campiano mine (Sammarco, 1988). Figure 1 shows: below, the cross-sections of the orebody dyke that is exploited and of the water body tha has been detected, supposed symmetrical about centre line; above, the going down speeds of the water along this cavity at the outset of its emptying, on the left, and in the marked sections of the cavity during the emptying, on the right. It is pointed out that the motion of the water was variable and not permanent: the speed of the water at the outset of the emptying varied greatly along the cavity, since the horizontal section area of this varies as a function of the elevation, and in every its section as time passed, since the water level in the same cavity gradually dropped. It is possible that turbolent conditions there have been in corrispondence to the sections in which greater the speeds were, owing to the irregularities of the walls of the cavity. These conditions undoubtedly would be occurred if the water would have downflowed with greater flow rate as a result, for example, of the interception of the water body with other boreholes.

The cavity examined cannot be considered like a singular case. In fact, the fractures in the rocks have irregular shapes and, when hold water and are superficial, are subject to fillings and emptyings, even if partial; consequently the motion of the water along them is various and not stationary. Such fractures behave such as hydraulic accumulators and/or conductors for which, however, it is not possible, substantially, to find expressions that define the water flow by correlating hydraulic parameters, above all because of the impossibility to quantify these latter.

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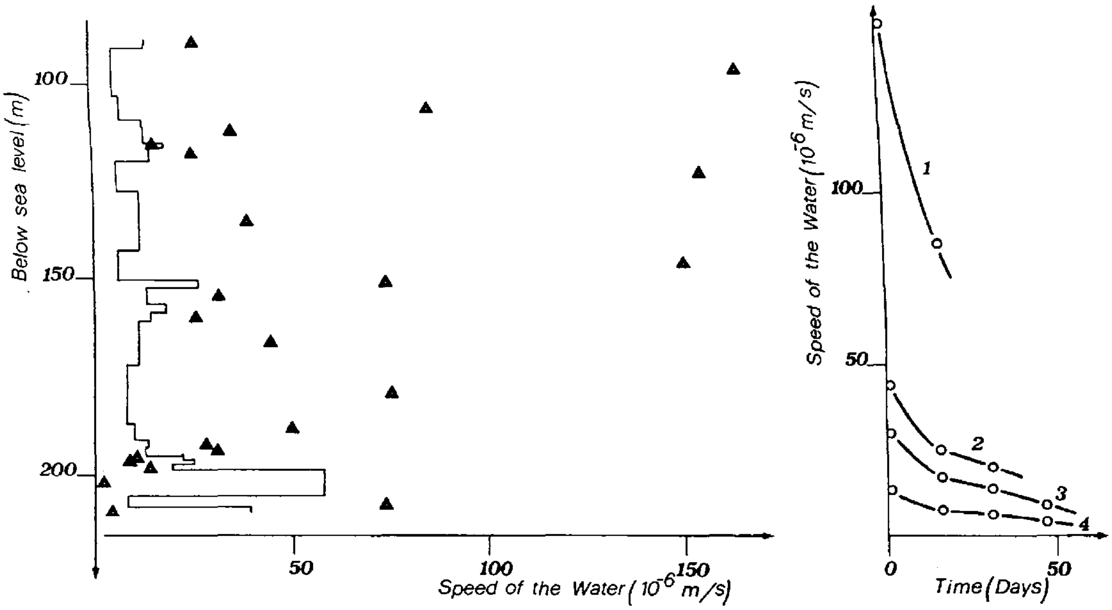

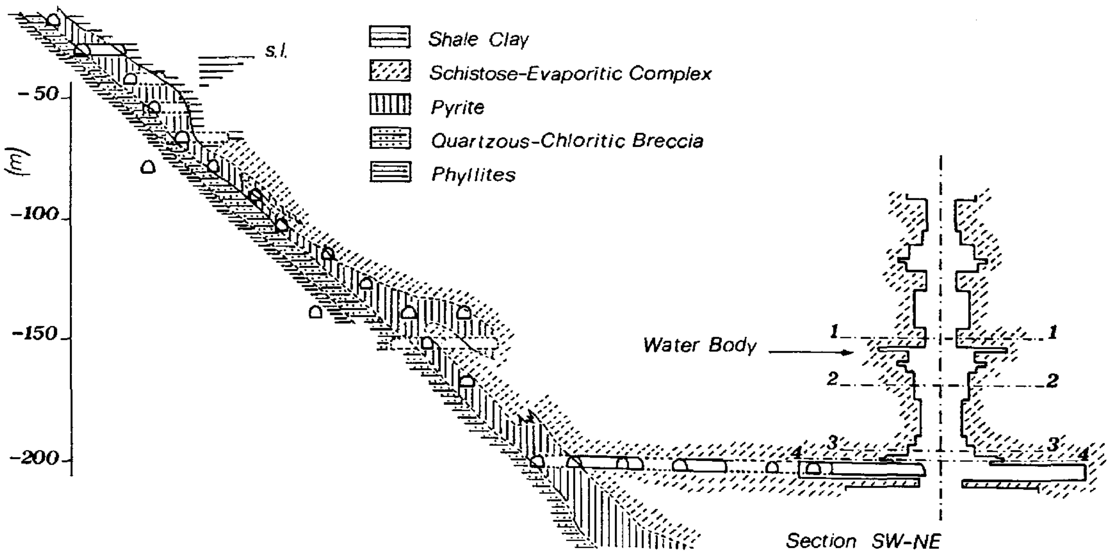

FIGURE 1. Water body detected by means of boreholes in proximity to the hangingwall of the deposit in the Campiano mine. Above: speeds of the water in the body. Below: cross-section of the mine in correspondence to the water body.

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EXAMPLE OF WATER RESERVOIRS

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

The Monte Amiata Volcano is located in Southern Tuscany at 45 km ENE of Grosseto. Its volcanism was still in activity some 400,000 years ago, by producing, according to the succession of the volcanic events: Quartz-Latitic Ignimbrites and Reoignimbrites; Quartz-Latitic Lava Domes; Quartz-Latitic Lava Flows; 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 amd others, 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 Volcanites 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, for even if local variations of the water-table level, activactions and deactivactions of hydraulic circuits that manifest themselves, on the surface and in the underground mine schematized in figure 2, respectively by sudden increases and decreases of flow-rate of water downflows and above all by abrupt appearances and disappearances of usually dry water courses.

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

An example of abandoned mine from which a water reservoir it is possible to obtain 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 (Fig. 2), in an area where there used to be many springs, with a moderate flow, which began to dry up as the mining work proceeded, while 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; the latter when the exploitation determined opening that permitted infiltrations of contact water.

The concentrated water emergences, are already almost all introduced into the aqueduct of the nearby village and used as drinkable water; the seepage water are, instead, directed towards the

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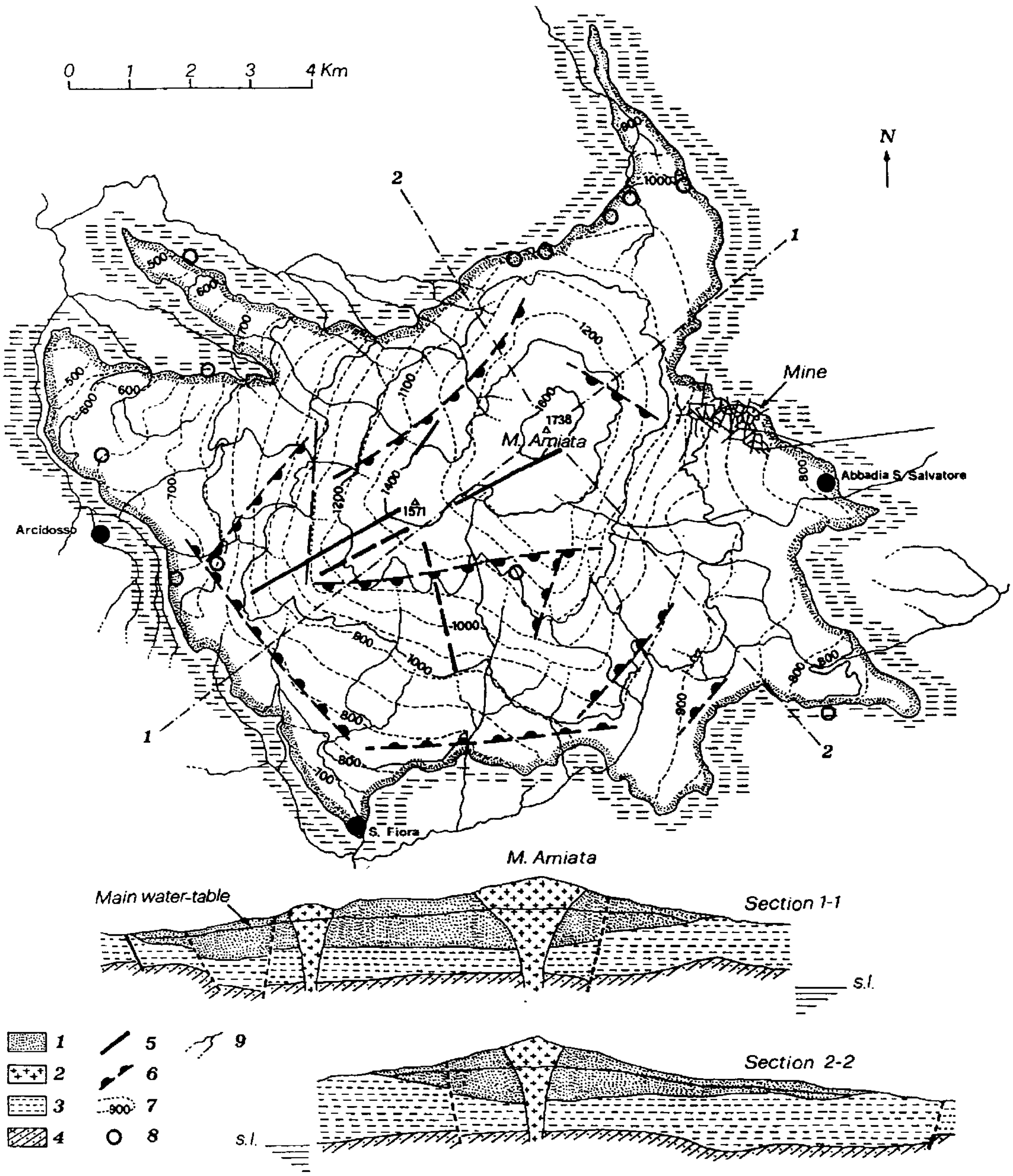

FIGURE 2. Hydrogeological and Tectonic Map of the Monte Amiata Volcano.

1. Volcanites (Ignimbrites, Trachytes) 2. Volcanic Conduits 3. Impermeable Sedimentary Substratum (Shales, Marls, etc.) 4. Mesozoic Rocks of the Tuscan Formations 5. Eruption Faults 6. Volcano-Tectonic Faults 7. Isopiestic Lines of the main water-table in the Volcanites 8. Springs 9. Rivers and Streams

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bottom gallery and, above all, the Italia gallery, at 511 and 786 m above sea level respectively, from which they are drained out (Sammarco, 1990, 17).

In figure 3 the Abbadia S. Salvatore mine schematized by its galleries and its exploitation zones, represented by black areas, and the built-up area of Abbadia S. Salvatore are shown in plan and in correspondence with two particular vertical sections.

In expectation of the abandonment of this mine, interventions have been carried out in order to keep invariable in time the hydrodynamics inside and round the mine. Even though these interventions, consisted principally in consolidating galleries and shafts by very permeable structures, are part of those planed out in order to prevent that the water, rising in level, could pollute the drinkable waters and could reappear on the surface in zones to be protected, favour the preservation in time of the mining voids and the possibility of utilizing efficaciously the mine for storing up water in it. This latter goal can be easily attained by Laying hermetic and sufficiently resisting seals to the outlets of the two mentioned above drainage galleries.

In order to estimate approximately the water quantity accumulable in the mine during determinate periods, the flow-rates and the cumulative quantities of the water drained during the 1994 have been represented in figure 3: in one year almost 106 m3 of water can be stored, because only the minor inflows will be covered with water while the mine is flooding. 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, certainly emptied in part during the mining activity, one deduces that it is possible, having sealed the downflows, to store up very high water quantity, but in periods of long duration.

VALUATIONS AND INTERVENTIONS

In order to decide whether to utilize a fractured rock mass or an abandoned mine as water reservoir or not, also on the basis of the possible interventions necessary for realizing the reservoir or for improving its efficaciousness, it is opportune:

- To make sure that the network of the fractures in the rock or the mining netwok is watertight to the highest hydrostatic pressure foreseen in course of operation, checking also experimentally its watertightness by filling trials. If leakages will be picked out or foreseen, to value the opportunity of eliminating them by specific interventions that consist, mainly, in groutings inside the zones that are to seal.

- To determine the total available volume and if possible the configuration of the network. The configuration of a mine should be known, while by determining its volume on the basis of the historical data (Tab. 1) either fractures in the rock communicating with the mining network, directly or through fractures produced by the same mining activity, or clayey formations, that swelling reduce the total volume, are not considered. 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 calculed by carrying out, during the emptying of the network, very frequent surveys determining flow-rates of water leaving the network and hydrostatic pressures: the more frequent

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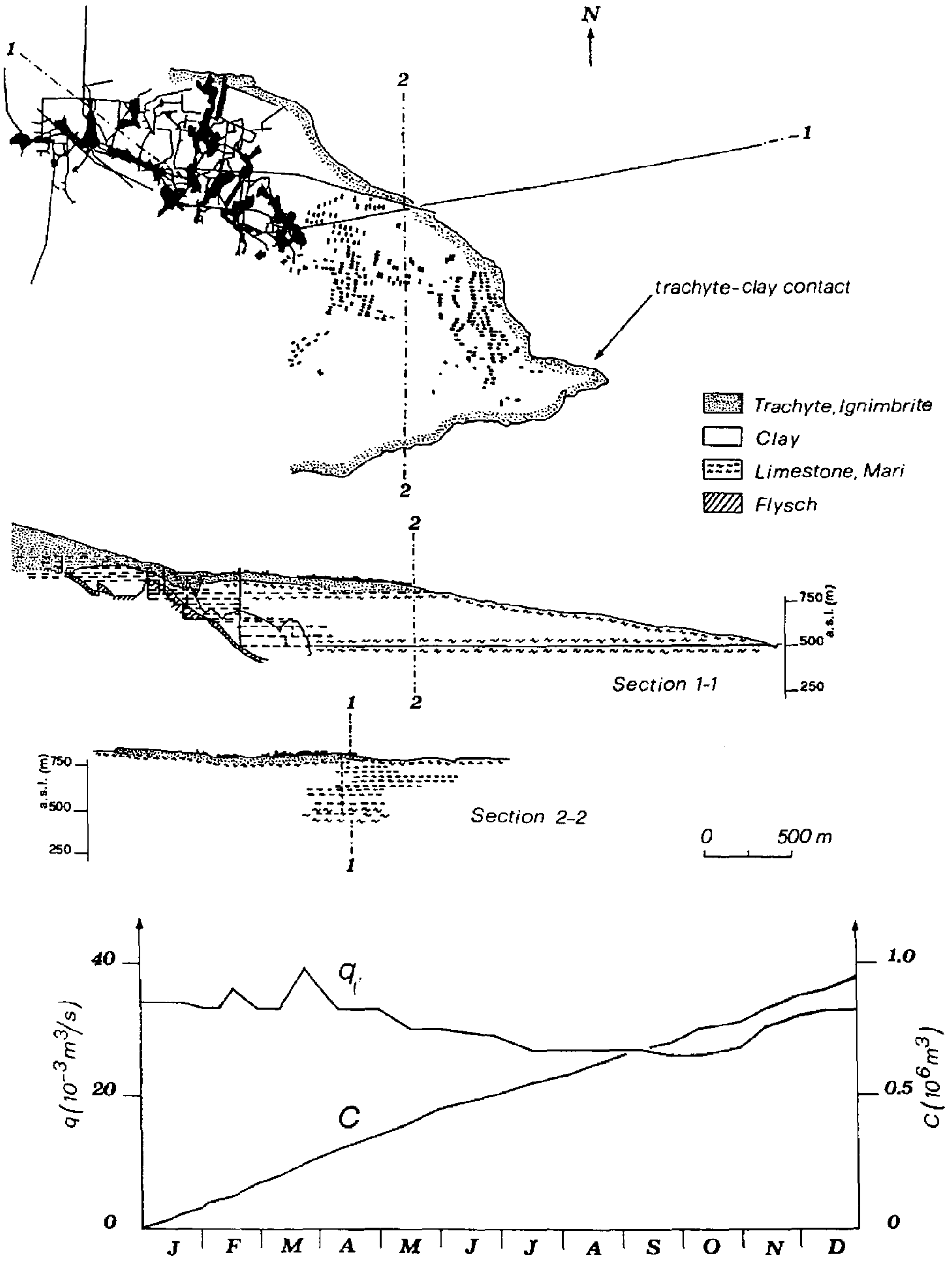

FIGURE 3. Abbadia S. Salvatore Mine. Above: plane and sections of the mine. Below: flow-rate, q, and cumulative quantity, C, of water drained from the mine.

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these surveys are, the closer the reconstructed network will be to the real one (Sammarco, 1988).

- To value the stability of the reservoir also further to the highest oscillation foreseen of the water level (Sammarco, 1993) and to make sure about the possibility of removing sediments that could compromise the functionality of the system. The Campiano mine, for example, seemed stable: in this mine neither significant landslides nor swellings at the contour of the voids occurred in consequence of its flooding that lasted eight months and was characterized by high oscillations of level during the emptying of the mine (Sammarco, 1986).
- To value, 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 the dry spells.
- In the case of a fed network, to value if the flow-rates of the water inflows into the network decrease as time passes. Figure 4 shows, above, the case of the Campiano mine into which water coming from the old Merse mine inflows by gravity through boreholes expressly carried out: on account of the obstructions of these latter the water stopped inflowing into the Campiano mine till the boreholes were cleared. Same figure shows, below, the case of the Niccioleta mine with regard to which it has been noticed, by considering the ratio between the cumulative quantity of the drainage water and the cumulative rainfall during two periods, that the conductivity of the inflows decreased remarkably as time passed from the end of the first period to the beginning of the second, because of huge landslides occurred in the stopes of the mine (De Col and Sammarco, 1982), and on the average increased slightly during this latter period. At any rate it is useful to know the historical data of the rainfall and of the flow rate of the drainage water and, in the case of mines subject to floodings, how this latter decreased in the course of the floods, when the hydrostatic pressures downstream from the inflows increased (Sammarco, 1993, 21).
- When a reservoir cannot feed by gravity the area where the water has to be utilized, to value the convenience of the pumping, by computing the necessary power for pumping from the foreseen elevation of the water level.

CONCLUSIONS

The great difficulties that appear when one means to know the hydrodynamics of a water reservoir in fractured rocks by models or by trial on very narrow parts of the reservoir have been shown. These difficulties are due in substance to the impossibility to know the geometry of the fractures and to the irregularities in them of the motion of the water that, according to the experimental results quoted is, as a rule, neither uniform nor permanent.

Owing to such difficulties and as it is possible to get information from existing reservoirs, such as it is inferable from the described ezamples, one deduces that are above all the well-known facts on the hydrodynamics of the natural reservoirs in fractured rocks and of the flooded mine that can make it possible to forecast the behaviour of a hypothesized reservoir. Such behaviour will be

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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

TABLE 1. Vacant volumes in abandoned mines obtained by subtracting from the total volume of the extracted material the volume of the introduced material.

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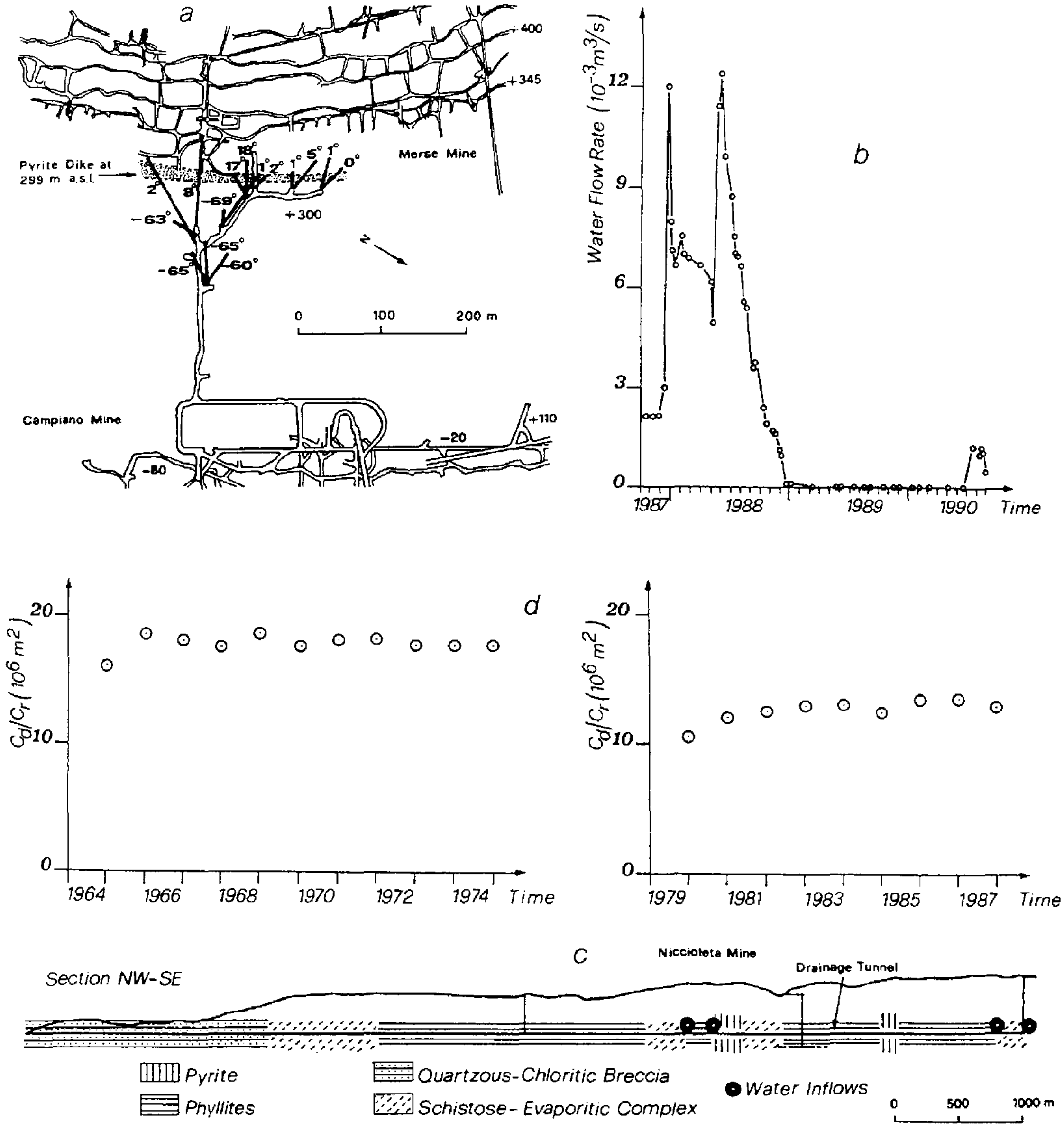

FIGURE 4. Irregularities of water flows drained from mines. Above: drainage system of the Merse mine (a) and flow-rate of the drained water (b). Below: Niccioleta mine (c) and ratio between cumulative quantity of the drainage water and cumulative rainfall (d).

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deepened in the course of the operating in order to modify it adequately by specific interventions, if necessary.

Water reservoirs like those pointed out in this paper can become indispensable for many countries in the Third World with long dry spells and far from superficial water courses, lakes an seas and that, therefore, not even by desalters can be fed. In reality, outcrops of plutonic, metamorphic and/or volcanic rocks characterized by the fractures here considered are very frequent in such zones (Sammarco, 1994, 23). The networks formed by these fractures, if not or not enough naturally supplied, 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 structures that can divert the swollen waves of water courses (Ferioli, 1994) towards the more fractured rocks in order to make it possible the immediate penetration into subsoil of the excess of water and this, at same time, would avoid disastrous inundations.

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REFERENCES

Ahlbom K., Andersson J. E., Nordqvist R., Ljunggren C., Tirn S. and Voss C. 1991. Fjallveden study site. Scope of activities and main results. SKB Technical Report TR 91-52, Stockholm.

Atkinson P., Celati R., Corsi R., Kucuk F. and Romey H. J.. Thermodynamic behaviour of the Bagnore geothermal field. Geothermics, Vol. 7, No. 2-4, Pisa, Italy, pp. 185-208.

Banks D., Rohr-Torp E. and Skarphagen H. 1994. Ground water resources in hard rock; experiences from the Hvaler study, Southeastern Norway. Applied Hidrogeology, 2, pp. 33-42.

Burdon D. J. and Fuganti A. 1973. Some general characteristics of ground water movement in plutonic, metamorphic and volcanic rock formation. Atti del 2 Convegno Internazionale sulle Acque Sotterranee, Palermo, Italy.

Calamai A., Cataldi R., Squarci P. and Taffi L. 1970. Geology, geophysics and hydrogeology of the Monte Amiata geothermal fields. Geothermics, special issue 1, Pisa, Italy, pp. 1-9.

Dagan G. 1979. Models of groundwater flow in statistically homogeneous formations. Water Resources Research, Vol. 17, No. 1.

Deana F. 1990. La desertificazione del Sahel: una tragedia evitabile? L'ingegnere italiano, Anno XXII, N. 211, pp. 18-24. In Italian.

De Col F. and Sammarco O. 1982. Le frane di Niccioleta: circostanze ed effetti prodotti. Internal Report I. BuMines 112-82, Corpo delle Miniere, Distretto di Grosseto, p. 15. In Italian.

Ferioli F. and Ferioli G. 1994. Le alluvioni, veramente impossibile prevenirle? Quarry and Construction, Anno XXXII , N.12. pp. 55-56. In Italian.

Gustafson G., Stanfors R. and Wikberg P. 1989. Swedish Hard Rock Laboratory. Evaluation of 1988 year pre-investigations and description of the target area, the island of Aspo. SKB Technical Report 89-16, Stockholm.

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Gustafson G. and Krasny J. 1994. Crystalline rock aquifers: their occurrence, use and importance. Applied Hydrogeology, 2, pp 64-75.

Jacobacci A., Martelli G. and Nappi G. 1967. Note Illustrative della Carta Geologica d'Italia: Foglio 129, S. Fiora. Ministero dell'Industria, Direzione Generale delle Miniere, Servizio Geologico d'Italia, Roma, p. 61. In Italian.

Moye D. G. 1967. Diamond drilling for foundation exploration. Civ. Eng. Trans. Inst. of Engineers, Australia, April, pp. 95-100.

Latino C. and Sammarco O. Thermodynamic characteristics of endogenous fluids in relation to their utilization on a wider scale in electricity generation. 1981. Proc. Third International Conference on Energy Use Management: Beyond the Energy Crisis, Opportunity and Cahallange. Bergamon Press, Berlin (West), Germany, Vol. 2, pp. 913-921.

Sammarco O. 1986. Spontaneous inrushes of water in underground mines. International Journal of Mine Water, Vol. 5, N0 2, pp. 29-42.

Sammarco O. 1988. Inrush prevention in an underground mine. International Journal of Mine Water. Vol. 7, No. 4, pp. 43-52.

Sammarco O. 1990. Abandoning mines: Hydrodynamic evolution controlled in order to avoid surface damage. Proc. Acid Mine Water in Pyritic Environments, Lisboa, Portugal, pp. 277-289.

Sammarco O. 1990. Sull'utilizzazione di miniere in sotterraneo abbandonate per stoccaggio d'acqua. Proc. Problemi di Geo-Ingegneria: Ingegneria degli Acquiferi, Geofluid, Piacenza, Italy, pp. 19-27. In Italian.

Sammarco O. 1992. Alimentazione idrica per la regione di Dodoma, Tanzania. Riflessioni prelimi-nari. Proc. Problemi di Geo-Ingegneria: Ingegneria degli Scavi Sotto Falda, Geofluid, Piacenza, Italy, pp. 3-9. In Italian.

Sammarco O. 1993. Delayed water irruptions: events and circumstances. Proc. Environmental Management Geo-Water and Engineering Aspects, A. A. Balkema, Wollongong, Australia, pp. 651-656.

Sammarco O. 1993. Karst and thermal water in an underground mine during and after exploitation. Proc. The First African Symposium on Mine Drainage and Environment Protection from Mine Waste Water Disposal, Konkola Division, Chililabombwe, Zambia, pp. 671-682.

Sammarco O. 1994. Irregularities in mine drainage: causes and consequences. Proc. 5th Interna-tional Mine Water Congress: Mine Water and the Environment, Nottingham, United Kingdom, Vol. 1, pp. 171-181.

Sammarco O. 1994. Criteri di scelta e fattori determinanti per la realizzazione dell'acquedotto di Kinusi, regione di Dodoma, Tanzania. Proc. Giornate di Studio: Problemi di Geo-Ingegneria: Ingegneria degli Scavi Sotto Falda, Geofluid, Piacenza, Italy. pp. 3-15. In Italian.

Witherspoon P. a: 1986. Flow of groundwater in fractured rocks. Bulletin of the International Association of Engineering Geology, No. 34, pp. 103-115.

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