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WATER STORAGE IN MINING CAVITIES: RESULTS OBTAINED DURING REGULATED FLOODING OF THE GAVORRANO MINE

Onofrio Sammarco

Italian Bureau of Mines, Ministry of Industry
Corpo delle Miniere - Via Goldoni, 6
58100 Grosseto, Italy
Phone: + 39 056420155, Fax: + 39 0564411250

ABSTRACT

In a mine in Southern Tuscany, that will soon have to be definitely abandoned, to avoid the damages that would derive from its uncontrolled flood, the spontaneous inflow of water into it is regulated through a specific program that envisages special procedures, interventions and precautionary measurements. The implementation of this program make it possible to verify whether it is possible to store water in the mine cavity and also to analyse the ways in which water flows into such cavity and correlate rainfall and water flowing into the underground cavity. Among other things through such correlation it is possible to identify: the phase-displacement between rainfall trend and the trend of the rate of flow of water reaching the cavity and that is pumped out. Such phase-displacements have appeared to depend above all on the trend of previous rainfall and in particular on the duration and intensity of the rain; it is also possible to detect that after prolonged and intense periods of rain the water flows into the mine at larger flows than occurred previously for similar levels of rainfall. This latter effect, which is due substantially to the increased permeability of the formations around the mine network, was noticed in the past only after the occurrence of floods in mines, but it has been possible to quantify it only now. With regard to this, it is pointed out on the basis of experimental data that on the occasion of overabundant rain and flooding, rock permeability may increase and hence water and/or gas inflows into the mine may occur or intensify. Hence the results obtained are useful not only for verifying the efficacy of mines as reservoirs and for the management of such reservoirs, but also for predicting intolerable inflows of water and/or gas that may occur when the surrounding formations become more permeable. Finally, the data obtained during the slow rise of the water level in the shafts are used to calculate the capacity of the reservoir and to identify the causes that tend to decrease such capacity.

INTRODUCTION

A mine is an important hydraulic work for intercepting water especially when, being located in an area with superficial and/or deep aquifers, it captures waters that would otherwise be difficult to capture.

Even though intercepting water is not at all desirable during mining, it could prove to be useful once the mine is closed down for storing the intercepted water especially in the case of underground mines excavated in areas characterized by high levels of evaporation and long periods of drought.

To evaluate whether it is possible and convenient to accumulate the waters intercepted during excavation in a mine cavity, it is convenient to gain knowledge about the continuity of the water inflows, the factors influencing them, secure that the capacity of the cavity is sufficiently high, and that the geometry of residual voids making up the mine do not change in time so much so as to prevent the accumulation of usable water.

Action is being taken to collect all the above information for the cavity produced by the exploitation of the Gavorrano mine (Southern Tuscany), during its flooding; flooding which has been regulated so as to avoid damage both during rises in water level in the mine and after its abandonment. The data being recorded and used to control flooding and other data collected during flooding, are used to gain deeper understanding of the behaviour of the mine cavity in relation to the inflow and storage of water.

GAVORRANO MINE: REGULATED FLOODING AND STUDY OF THE MINE CAVITY CHARACTERISTICS AND OF THE INFLOWS OF WATER

From 1898 to 1981, pyrite, located in a Plio-Pleistocene granite intrusion, was extracted from the Gavorrano mine. The intrusion had caused failure and upheaval of the overlying sedimentary formation consisting mainly of Liassic and Triassic limestones and Neogene sediments.

The intense fracturing resulting from this event together with the karst phenomena and the settlements caused by the mining activity have made the formations surrounding the mine extremely conductive (Sammarco, 1993).

The mining method used initially for a short period of time was caving, after which the cut and fill method was adopted. Washery mining wastes were used at first as fill, and then washery mining wastes with clay grout, and then crushed limestone and clay grout and finally cement fills, which at present are located at 73 m, 152 m and 99 m below sea level, in the northern, central and southern parts of the mine respectively.

The waters flowing into the mine are thermomineral waters coming up from the granite fractures present in the bed of the deposit (Vighi, 1964), and meteoric waters conveyed from the karst conduits and from fractures that were at times enlarged as a consequence of the mining activity.

Prior to regulated flooding, the mine was kept completely dry by pumping out the waters. Following flooding the water level rises and submerges both the walls and the fills. In the presence of water and unless cemented, the latter could no longer be capable of sustaining the overlying fills and hence as has already occurred there could be cave ins with violent gushes of water up the shafts.

The layout of the mine network is shown in Figure 1, where besides the geology and morphology also other elements are given so as to highlight the reasons why it is necessary to regulate the flooding of this mine and to explain the criteria used. The figure also shows the Bagno hamlet, the tailings ponds and the site of the thermomineral water springs that became dry during mining because the hot and cold waters were drawn by the mine. Flooding needs to be regulated according to precise provisions (Sammarco, 1998) in order to avoid water re-appearing near the dry springs, that is to say into the zone that is currently covered by the ponds as well as inside the formations underlying the hamlet. Such formations are made of alluvial clayey soils which, if flooded, would lose their resistance and undermine the stability of the overlying buildings.

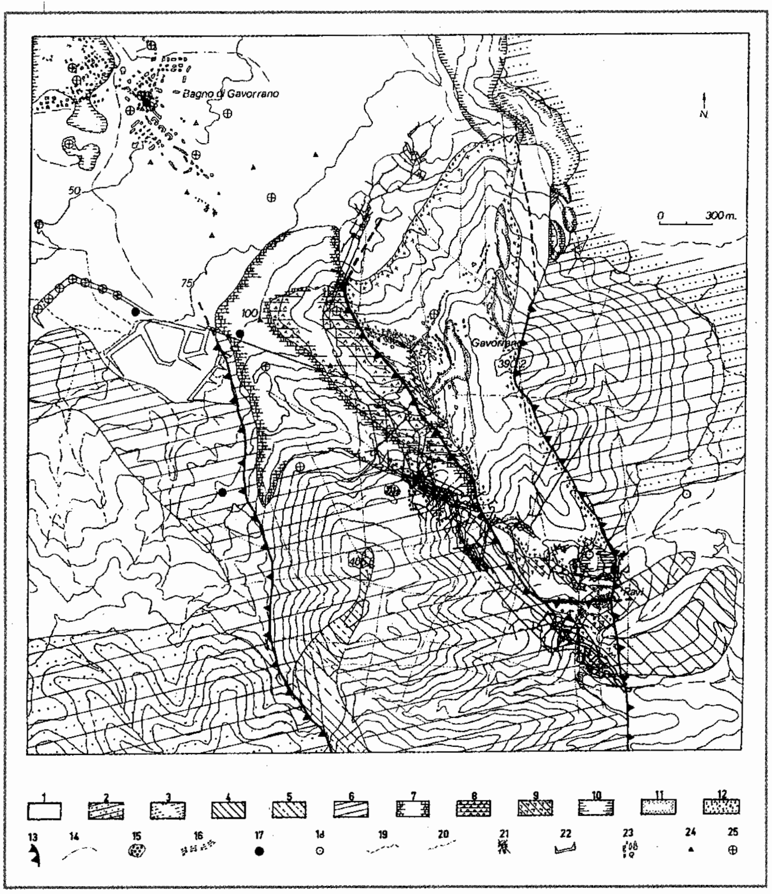

Figure 1. The Gavorrano underground pyrite mine. Outcrops, faults, fractures, morphology of the surface, pre-existing and current situations above and around the mine network, monitoring equipment for regulating flooding.
1 Alluvium. 2 Neo-autocht honous sediments. 3 Allochthonous flysch.
4 Stratified flinty limestones (Lias). 5 Stratified limestones (Lias).
6 Limestones (Lower Lias). 7 Stratified limestones (Upper Trias).
8 Cavernous limestones (Upper Trias). 9 Metamorphosed cavernous limestone.
10 Phyllites (Upper Trias). 11 Microgranitic lode. 12 Quartz monzonite.
13 Faults. 14 Ascertained and probable fractures. 15 Sinkhole.
16 Fractures and faults induced by the mining activity at the natural fractures and/or alignments weakened by karst phenomena. 17 Depleted thermal springs.
18 Depleted water springs. 19 Streams. 20 Dry streams. 21 Mine network.
22 Tailings Ponds. 23 Built-up areas. 24 Piezometric wells.
25 Datum points for measuring soil movements.

The following actions have been taken to regulate flooding and ensure maximum safety:

- there is high redundancy for the underground routes for the transit of personnel, for the electricity and mechanical plants and in particular for the pumps and their automatic and control systems;
- submersible motor pumps, equipped so as to keep the water level in the shafts steady or to increase or lower it according to necessity, are used;
- water level in the mine is constantly monitored and recorded also to detect possible its oscillations, which at times

precede major cave ins; in case of water level oscillations, the personnel must abandon the underground mine and carry out the necessary interventions from the surface;
- rainfall is continuously recorded and the water flow rate pumped out is frequently gauged, and since the water level inside the mine is left constant during this measure, the water pumped out obtained in this way is equal to the amount of water inflow into the mining cavity;
- water levels in piezometric wells, drilled for this purpose, are constantly monitored to keep the swelling of aquifers under control; when the water level inside the mine will have risen to rather high levels, datum point readings will be taken frequently so as to identify any ground movements attributable to such swelling.

The methods adopted and the parameters that are recorded to regulate the rising of the water which spontaneously inflows into the Gavorrano mine, are useful also for investigating the factors that are responsible for the inflows of water into the underground cavity, their influence on such inflows, the amount of water that can be stored and the behaviour of the mining cavity during and after flooding. In particular,
- rainfall and flow rate of water pumped out data are used to correlate these two parameters and to identify the effects of the rainfall on the hydraulic conductivity of the formations overlying the cavity;
- the data concerning flow rate and those on the rising of the water level in the mine are used to gain knowledge about the geometry of the cavity and identify the episodes that may limit or vary its capacity.

The results obtained so far are described in the following.

RAINFALL AND WATER INFLOWS

It is difficult to infer the influence of rainfall on the waters flowing into a mine cavity because usually it is impossible to gain knowledge, not even rough knowledge, of the geometry of the system and in particular of the permeability characteristics of the rock around the cavity, as well as of the space-time trends of rainfall in the basins feeding the cavity.

Moreover, in the specific case of the Gavorrano mine, the hydraulic conductivity of the rock between surface and mine cavity varies considerably round the cavity. This fact, which appears quite clearly from Figure 1 observing both the variety of the formations located above the mine network and the variability of their state of fissuring along the network, was noticed clearly during the exploitation of the mine; rainwater would flow into the northernmost sites which were in contact with loosened granites, immediately after the rain, whereas in the southern sites, excavated in compact rocks, the water would arrive only a few months later.

For this mine it is easy to identify the hydrological basins, but not the hydrogeological basins feeding the former. Therefore, even though there is information about the trend of rainfall in time for the various hydrological basins, one cannot have knowledge about all those that actually flow into the mine cavity, because it is impossible to identify all of them.

Furthermore, since this mine is fed by both rain waters and thermomineral waters, the difficulty in gaining knowledge of the space-time trends of the rainwater directly flowing into the mine is compounded by the difficulty in knowing exactly what route is followed by such rain waters underground to get to the mine after having mixed with thermomineral waters. Indeed, the latter could reach the mine after having mixed with large amounts of rainwater which in turn could refer to different periods of time because they come from different sites and flow along routes that are totally distinct of one another.

To avoid all these difficulties, correlation have been found between rainfall and water inflow into the mine by using schemes and simplifications and by using experimental data.

In general, the permeability situations of the formations lying between ground surface and the mining cavity can be schematized as follows.

- Compact formations with "hydraulic conductors" consisting of fracture or karst conduits that directly connect the surface with the mine cavity. In each fracture or conduit the water outflow may occur either in the manner of a canal or at pressure:
  a) in the former case, when this type of flow occurs throughout all the length of the fracture the flow rate of the water entering the underground cavity via the fracture is equal to the flow rate of the water entering the fracture from the surface, will depend not only on rainfall, but also on the situation at the surface, and will have a lag with respect to the flow rates measured at the mouth of the fracture that will depend on the geometry of the latter;
  b) in the latter case, the flow rate of water at the mouth of the fracture is almost always different from the flow rate of the water that reaches the mine; the latter will increase or decrease depending on whether the flow rate at the mouth of the fracture is greater or smaller than the flow rate at its outlet; as a consequence, since the geometries of the fractures and the flow rates of water at their mouths vary, the amount of water flowing into the mine from one fracture may increase or decrease, while at the same time the opposite may be true from another fracture;
- loose formations, characterized by primary permeability and hence by slow outflows typical of porous formations. Meteoric waters may very well appear in the cavities a long time after the rain;
- formations characterized by secondary permeability that provide hydraulic connection between the surface and the cavity by means of formations characterized by primary permeability. All the cases in which the former formations are in contact with the latter are included in this case, whatever the geometries and their reciprocal positions are. In particular, completely or partially filled fractures are one such case. It is obvious that in such cir-

cumstances the modes of outflow may be various and extremely complex.

All these conductivity situations, that occur around the cavity, can help explain the influences of the rainfall trends on the trends of inflows into the mine.

Since the time trend of rainfall does not vary excessively from one zone to another of the territory acting as catchment basin of rainwater for the Gavorrano mine, rainfall is recorded only at the centre of the plan of the mine network. Such recording is correlated with the trend of water inflow rate into the mining cavity so as to identify the influence of rain on such flow and to know how and why such influence may vary in time.

The most significant data observed during our 43-month experience are discussed in the following.

Figure 2 shows the daily rainfall values and the trend of the water flow rate pumped out of the mine. The values of this flow rate, measured to establish its trend, are determined by keeping the water level inside the shafts constant and hence they also represent the values of the flow rate of the water inflow into the mine. Figure 2 shows that this flow rate depends appreciably on rainfall.

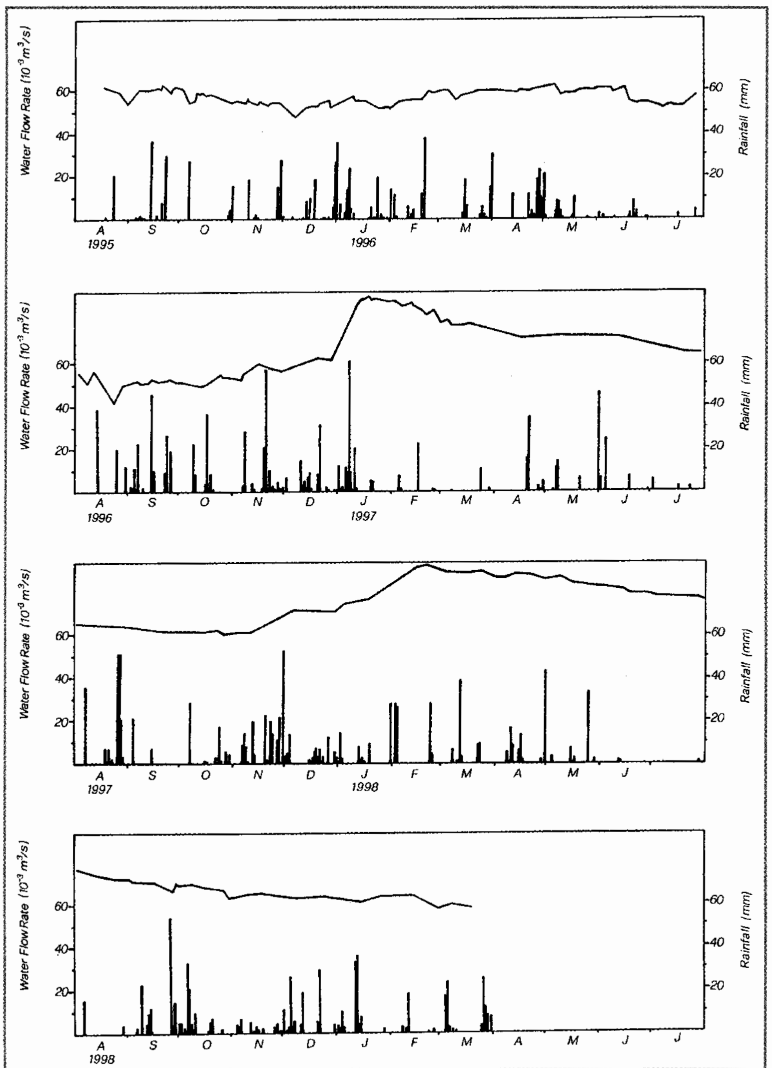

Figure 2. Daily rainfall and overall rate of water flowing into the underground mine.

The same figure shows that fluctuations in the flow rate are less marked than rainfall variations. This is so because:

- the mine also collects deep thermomineral water whose flow rate is virtually constant;
- during the rain, meteoric inflow into the fractures that make up the aquifer in the mine area, would be greater than the outflow of water flowing into the mine, so much so that the water accumulating in the fractures would be large enough to attenuate the repercussions of the range of rainfall on the flow rate of the water flowing into the mine.

From this latter reason there ensues that the larger the aquifer communicating with the mine the greater the amount of water that it can hold and hence the smaller the ranges of values of the water flowing into the mine as the latter is less affected by rainfall trends. This emerges clearly by comparing the water rate flowing into the mine at different depths: usually, the deeper the mines the smaller the influence of rainfall on the water rate (Sammarco, 1994).

In order to better established the dependency of the water flowing into the mine on rainfall, Figure 3a shows monthly rainfall values, r, and monthly flow-rate, d_0. Even though, because of irregular rainfall, precise correlation cannot be found in this figure, it can however be noticed that on average the wave of the flow rate show an approximately four-month delay with respect to the wave of the rainfall.

As it is possible to better highlight the influence of rainfall on flow rate by taking into account only the part of the latter due to rainwater, and considering that thermomineral waters are the main component feeding the mine, of the overall monthly rate of flow, d_0 only the amount d is considered which is obtained by adding to the difference between monthly flow and minimum monthly flow over the period being considered, the average of such difference for the same time period.

Figure 3b shows the monthly rainfall, r, and the partial monthly flow rate, d, thus obtained. Figures 3c and 3d, the bimonthly and four-monthly rainfalls, as well as the respective bimonthly and four-monthly partial flow rates inferred from the partial monthly flow rates, d.

The influence of rainfall on flow rate appears more clearly in figure 3b than in the previous figure. In Figure 3c and in particular in Figure 3d the delay appears clearly as does the consequentially of the flow wave with respect to the rainfall wave. In this latter figure, where the values shown refer to four-month periods, which are equal to the duration of the above prevailing lag-time, the opposition between flow wave and rainfall wave is quite marked, except for the December 1996-July 1997 period.

In any case, taking into account shorter time intervals, it can be noticed that rainfall peaks are detected in the mine with different time lags and in different ways (Figure 2). Such delays and different patterns depend in particular on:

- the rainfall trend prior to and after reaching its maximum and minimum values: the persistence of heavy rainfall after having reached a maximum in rainfall may extend the period during which the rate of inflows into the mine increa-

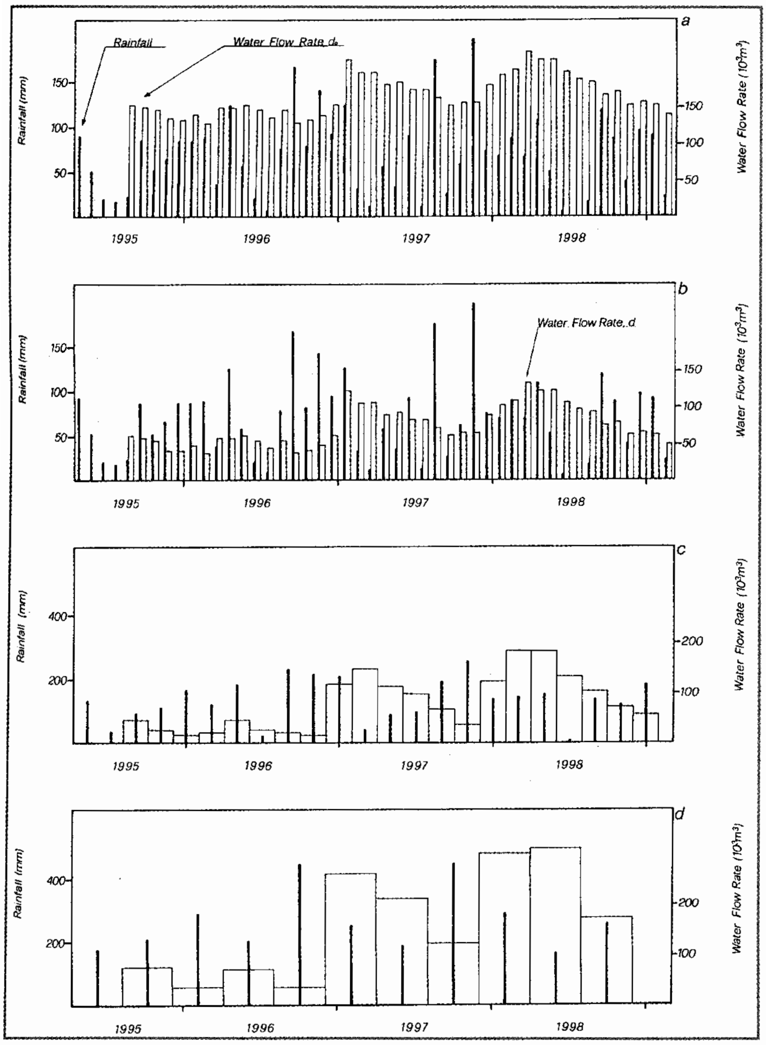

Figure 3. Monthly rainfall and flow rate. (a), monthly; (b), bi-monthly (c), and four-monthly (d) rainfall and partial flow rate.

ses, a period which will end when the hydrostatic pressure feeding such inflows will have reached a maximum;

- the permeability of the formations around the mine voids, namely on the time that the water takes to transit from the surface down to the mine; such time varies considerably along the network of the Gavorrano mine.

Since the permeability of the formations may vary in time especially as an effect of the circulating waters, the delays and the ways in which the rainfall produce their effects in the mine may appreciably change in time also as a result of the changes resulting from the effects of previous rainfall on that permeability. Such changes, that have been clearly observed, are discussed in the following.

PREVIOUS RAINFALL AND PERMEABILITY OF THE FORMATIONS SURROUNDING THE MINE CAVITY

By using $k_{(ti-j-ti-j-1)} r_{(ti-j-ti-j-1)}$, where j<1, to indicate the aliquot of meteoric water that have fallen over the time interval $t_{i-i} - t_{i-j-1}$ and that have flown into the mine over the $t_i - t_{i-1}$, $d_{(ti-ti-1)}$, time, the following approximate expression indicating the hydraulic conductivity of the system can be written

$$\frac{d_{(ti-ti-1)}}{k_{(ti-j-ti-j-1)}\, r_{(ti-j-ti-j-1)} + \ldots\ k_{(ti-ti-1)}\, r_{(ti-ti-1)}} \qquad (1)$$

where

$$\ldots k_{(ti-j-ti-j-1)} + \ldots k_{(ti-ti-1)} = 1$$

This quantity, that has the dimensions of a surface, derives from the hydrological balance relationship, and represents the aliquot of meteoric water that reach the cavity.

It is self-evident that the higher the permeability of the rock between the surface and the mine cavity, the greater the amount of meteoric waters that will reach the cavity and the lesser the amount of waters flowing on the surface and the amount that is subtracted as a result of evapotranspiration.

Expression (1) may be considered as the empirical expression of the "apparent permeability" of the whole of the formations surrounding the mine cavity, "apparent permeability" which takes into account not only the effective hydraulic conductivity of those formations, but also the influence of siphons, of the joining of hanging water-bearing strata as a result of the rise of their isopiestic lines, of the contributions by water bodies that may be connected with or disconnected from hydraulic circuits flowing into the cavity, as a result of resumed circulation or obstruction.

To express (1) for this case, reference is made to the trends of monthly rainfall and of the monthly flow rate shown in Figure 3 and it is observed that since the monthly rainfall trend, r, is in general, ahead of the monthly rate of flow, d_0, and of the partial rate of flow, d, by four months, the latter may be considered to depend mainly on the rainfall that occurred four months previously. Knowing that rainfall produces its effects in the mine also with differing delays, and shorter than four months and even without significant delays, the partial monthly rate of flow, d, of the water flowing into the mine cavity has been expressed not only as a function of the rainfall of the fourth month, but also as a function of the rainfall of the three previous months and of the rainfall of the same month to which the flow rate refers, by using the following approximate expression

$$k_{i-4} r_{i-4} + k_{i-3} r_{i-3} + k_{i-2} r_{i-2} + k_{i-1} r_{i-1} + k_i r_i = \frac{d_i}{K^1_i} \qquad (2)$$

where r_i, K^1_i and d_i are respectively the rainfall, "apparent permeability" and the -ieth partial monthly flow rate.

The coefficients k_{i-4}, ... k_i were determined by searching for the set of values of k_i and hence the trend of "apparent permeability" in time that could be justified by the trend of previous rainfall.

Figure 4b shows a trend of K^1 which respects such conditions and that is obtained for

$$k_{i-j-1} = 1{,}5\, k_{i-j}.$$

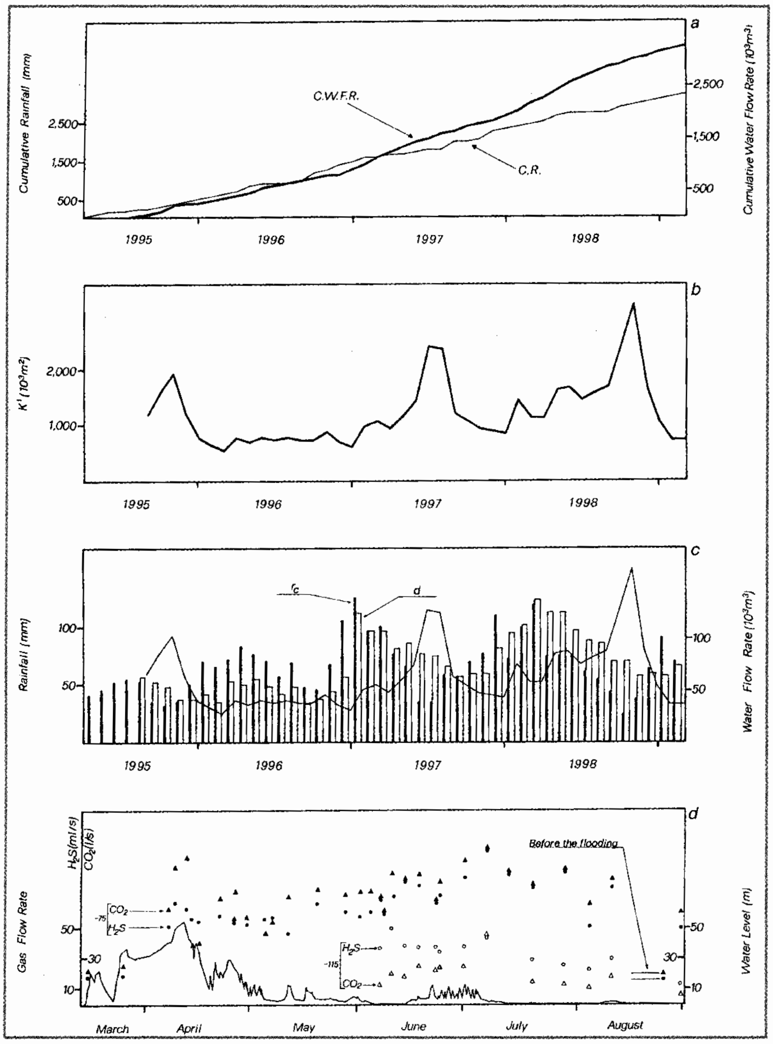

Figure 4. Cumulative rainfall and partial flow rate (a). Apparent permeability (b). Gavorrano mine: Apparent permeability, K', monthly partial flow rate, d, and relative rainfall, r_c (c). Bagni S. Filippo mine: water level in the mine and CO_2 and H_2S flow-rates in the refluxes at the -75 and -115 levels (d).

By comparing the trend of "apparent permeability" thus obtained, K' (Figure 4b) with that of rainfall (Figure 3), and taking into account the delays with which the rains reach the mine, considerable rises in K' are realized after intense and prolonged rains. This can be explained by the fact that abundant rainfalls, besides intense erosion of non obstructed conduits, produce high hydrostatic pressures in the rock mass and in particular in obstructed fractures, high pressures that are likely to cause obstructions in those fractures to yield (Sammarco, 1994), and once they have yielded, high speed water inflows occur (Hanzlík and Vydra, 1985) which are endowed with high load taking power and high transporting power (Panizza, 1973; Scheidegger, 1961; Thornbury, 1958). This mechanism is confirmed when episodes of intrusions into mines of mud coming from karst cavities (Fernández Rubio and others, 1998) and of fill materials from mine cavities (Jinkai, 1985) are analysed.

On the contrary, reduced values of K' observed after periods of low rainfall, must be attributed to the obstruction of outflow paths especially as a result of sedimentation that occurs when the speed of circulating water slows down.

Even though it is not possible to establish an exact correspondence between rainfall and "apparent permeability" it is evident that rainfall has an impact on permeability and that the marked irregularity of K^1 is to be attributed to rainfall; in the time period considered here, K^1 reached a maximum value equal to 5.5 times the minimum value reached for the same time period (Figure 4b).

The mean value of K^1 prior to 1997 is much lower than the average value of K^1 after 1996. This can be inferred by observing the rainfall and rate of flow trends and above all the cumulative values of these two quantities: in Figure 4a it is clearly seen that up to 1996, cumulative rainfall shows approximately the same average slope as the cumulative partial flow rate, whereas afterwards its average slope is decidedly lower.

Substantially, there have been marked variations in permeability due to rainfall. Since the permeability of the formations around a mine network regulates the inflow into mine of water and/or of gas, such variations need to be taken into account. A few examples may serve to demonstrate this need.

Figure 4c, relative to the case at hand, shows the "apparent permeability" K', monthly partial flow rate, d, and the combination of monthly rainfalls, r_c, that would have contributed to determining the flow rate, d, there shows up that by taking also r_c into account, the largest inflows of water into the mine are obtained for the higher values of K'.

Figure 4d, which refers to a small mercury mine subject to continuous inflows consisting of a mix of CO_2 and H_2S, presents the levels that water reached inside the mine during the very first flood and during subsequent floods, as well as the gas flow rates measured in the refluxes of two levels. After the first flood the following observations were made: a remarkable decrease in the lag time between rain and increase in the water filtering into the mine; subsequent floods, limited by increasing the amounts of water pumped out, were becoming more and more violent, because the circulating waters were continuing to increasing the permeability of the surrounding soils (Sammarco, 1986); and finally, the gas inflows, that had been found to vary immediately prior and after the floods and hence could be taken to be a warning signal (Sammarco 1981), then became stable around values that were more than three times higher those recorded prior to the first flood in the mine.

Even in the Selvena mine similar events were noticed after a flood which occurred in the deepest gallery that communicated directly with the ground surface. On that occasion, gas, consisting mainly of CO_2 was found quite abundant even in zones that had hitherto never been involved by gas emissions; and the flow rate of the water that was educted became stabilized after a few months around values that were twice the previous values. In this circumstance, the increase in permeability was clearly demonstrated by 1,500 m^3 of mainly silty materials that had been transported and sedimented by 1,400,000 m^3 of water.

CHARACTERISTICS AND BEHAVIOUR OF THE MINE CAVITY

The regulated flooding of the Gavorrano mine cavity serves the purpose of studying its characteristics and of understanding its behaviour.

The pumping system and the measurement and recording system are schematized in the upper part of Figure 5. These systems, that have been installed to regulate the flooding, are used to know the geometry of the cavity and how it behaves as the water level rises, too.

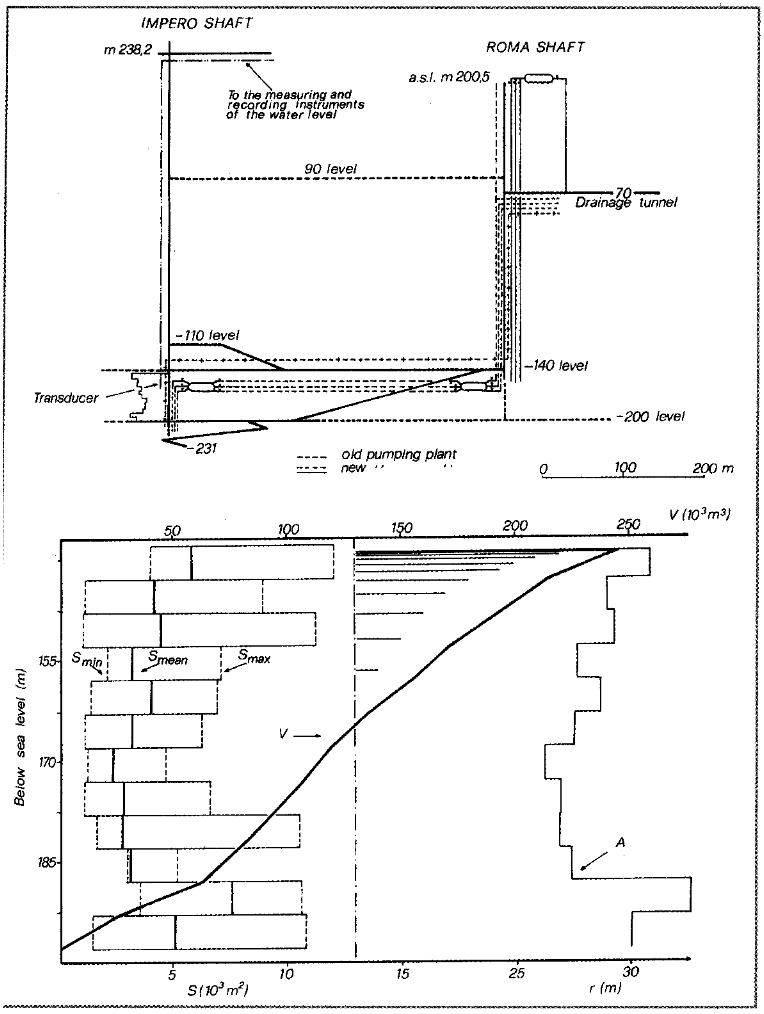

Figure 5. Above. Scheme of the pumping and measurement systems that have been installed for regulating the flooding of the mine cavity and used in order to establish its characteristics. Below. Cavity portion flooded up to now: mean (S_{mean}), maximum (S_{max}) and minimum (S_{min}) horizontal surfaces; vertical cross section of a cavity symmetrical about centre line that is equivalent to that flooded: volume of the cavity (V).

From the recorded measurements of the water level in time inside the shafts and of the overall flow rate of the water flowing into the mine, obtained by measuring the flow rate of the water to be pumped out in order to keep the underground level constant, is inferred the cross-section of the cavity and hence the volume as a function of height.

The lower part of Figure 5 shows, for the cavity portion flooded so far, the mean, maximum and minimum horizontal surfaces (S) and the vertical cross-section of a cavity symmetrical about centre line that is equivalent to that measured (A) for the successive sections of cavity, each being 5 m deep; also the volume of the cavity is given.

The considerable and abrupt horizontal cross-sectional variations of the cavity with height found within each section do not appear to be attributable to cross-section variations of the ore body, which in the flooded part was quite regular, nor to variations in the geometry of the mining works, but rather to cave ins that had either occurred previously or when the cavity was flooded, cave ins signalled at times by violent swings of the water level in the shafts. It is not by chance that the maximum horizontal cross-sectional variation was found in the stretch corresponding to 153 m below sea level, where, at the centre of the mine, the fill consisting of crushed stone and clay grout is in contact with the underlying-reinforced concrete fill. The water by reaching the former would have caused plasticity and liquefaction of the clay contained in the fill, weakening it to the point that it was no longer capable of supporting the overlying fill and/or the side walls.

There may however be other dynamics at play, determined or facilitated by the flooding, that will modify size and shape of the mine voids and that can be grouped as follows:

- Swelling of the clays in both fill and/or walls, that could eliminate voids or isolate them from the cavity.
- Cave ins of cemented fills and/or of compact rock, that could propagate until the collapsed blocks do not offset the loads and thrusts coming respectively from the new vaults and new walls. In such case the cavity would be made more irregular and hence would cause greater variations in the speed of outflow water and consequently a more marked erosion, transportation and sedimentation processes.
- Disintegration and ensuing yielding of the fills consisting of washery waste, placed on top of all the other fills, and sedimentation on the bottom of desegregated material that the pumping fails to remove.
- Gradual silting up of the cavity as a result of sedimentation of the material coming from cave ins or transported by the waters that inflow into the cavity. In this specific case, except for local and transient events, the amount of material that is sedimented should not be too much because the suspended material, found in concentrations equivalent to 2,500:3,000 mg/l and virtually constant with depth, is almost entirely educted with the water pumped out.

Given the nearly total inaccessibility of the underground mine, the effects of all these factors may be determined indirectly during regulated flooding.

CONCLUSIONS

Before using an underground mine subject to water inflows as fed water reservoir, it is worthwhile making sure that in time feeding waters will continue to flow into the mining cavity at sufficient flow rates and that the volume of the cavity will not be reduced excessively. In order to monitor such aspects the procedures set forth here can be adopted, taking into account the results obtained thus far and described here.

In particular, the results on the variations of permeability of the formations surrounding the cavity caused by rainfall readily apply to mines that are still active; permeability increases may intensify gas emissions in the mines where gas leakage occur and may cause increases in water inflows, hence facilitating cave ins and floods.

In all the cases where intolerable inflows of gas and/or water are envisaged, as described in this paper, the lag time with which abundant rainfall affects permeability needs to be among other things identified. If this were not possible, after periods of heavy rains the quantities that one wants to limit are to be kept under control more often.

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