International Journal of Mine Water, Vol. 5, No. 2, (1986), 29-42
Printed in Madrid, Spain

SPONTANEOUS INRUSHES OF WATER IN UNDERGROUND MINES

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ABSTRACT

Several water inrushes occurring in Italian underground mines were carefully observed in order to study causes and circumstances, of such events and to investigate the possibility of predicting these inrushes.

It turned out that whereas the spontaneous inrushes, ie those determined by natural episodes, are accompanied by clear warning signals linked with changes in the water regime and, possibly, of mine gases. However, the inrushes caused by the mining activities are accompanied by few and indistinct warnings.

With respect to the spontaneous inrushes, the observation of events prior to the occurrence of inrushes suggest that the gas flow rates can be correlated to the hydrodynamics activities around the mine, whereby possible inrushes can be forecasted by means of the gas flow rates.

With respect to mining induced inrushes, however, since clear warning signals are lacking, it is proposed that preventive measures may be used rather than forecasting. It is suggested that in order to avoid such inrushes it is necessary to obtain an exact and up-to-date information of ground water regime around the planned workings. A study was therefore undertaken to back analyse the records of mine inrushes together with parameters and characteristics of individual inflows.

INTRODUCTION

The inundations resulting in mining disasters have almost always been sudden and violent, veritable irruptions. Consequently, these particular inflows of water must be studied in detail, before and during their occurrence, in order to understand the sequence of premonitory events leading to inundations and the preventive measures to be adopted in order to reduce the risks to the minimum.

It is not essential to make clear-cut distinction between spontaneous inrushes of water and inrushes caused by mining operations (blasting, drilling, driving near older workings), because the water inrushes that can be defined as spontaneous would not occur if there were no cavities created by mining allowing the inflow of mine water. In the same way, an inrush of water from old mines would not occur if they were not flooded.

But it is necessary to introduce a classification, defining as spontaneous the inrushes caused mainly by natural episodes and as provoked those brought about as a direct consequence of the mining, especially because the events that foretell the former often differ from those that precede the latter.

FLOODING IN ITALIAN UNDERGROUND MINES.
OBSERVATIONS AND DEDUCTIONS

From 1910 to the present, in the underground mines of southern Tuscany only, the fatalities given in the following list were caused by flooding. It will be noted that 17 persons died due to water inrushes and one due to a slow influx of water:

1914 (24 May)	1 killed by inrush of water from old workings at Ribolla colliery (Grosseto);
1935 (12 August)	14 killed by inrush of water from old workings at Ribolla colliery (Grosseto);
1952 (21 January)	2 killed by inrush of water from old workings at Lilliano colliery (Siena);
1964 (11 March)	1 killed by flooding of a shaft that occurred as a result of plugging of a drainage hole in the Poggio Mortaio pyrite and magnetite mine (Grosseto).

From 1963 to the present, again in Tuscany, there were three floodings, without fatalities, in the underground mines of Selvena, Bagni San Filippo and Campiano-Boccheggiano. Two of the floodings were spontaneous, and the third provoked. These episodes were studied by the author right from the outset in order to gain elements useful for forecasting such events beforehand. The available data related to smaller-scale events, but which were still analogous to the first ones, were also examined. The events that took place in those circumstances are outlined, and those that can be considered premonitory are pointed out.

Selvena Mercury Mine

The Selvena ore body (Grosseto) is of hydrothermal origin and chiefly consists of cinnabar antimonite inbedded in mainly clayey gangue at the contact zone between clayey formations at the roof and Rhaetian limestones (Upper Trias) at the bed. The contact is quite regular in the mineralization zone but often very disturbed around it.

In 1973, an inundation of water and mud occurred at the tunnel face at -200 m level, which is the deepest point in the mine, at 2184 m from the mouth. Since this tunnel emerged directly to the outside, the water did not invade the upper levels, but only the bottom tunnel. In the last section this tunnel had crossed alternations of limestone and clay for 15 m; at the blind end, at the moment of the inrush, there was clay exposed at the face with limestone at the floor.

Before the flooding only the -200 tunnel was subject to continuous emanations of mixed CO_2 and H_2S, almost entirely given off by the water that flowed out of the face at a rate of about 10 l/s. In normal conditions, a total of 15 l/s of water inflowed in the tunnel.

On 16 April 1973, it was found that in the blind end of the tunnel both the values of the CO_2 concentration and the values of the ratio between the concentration of H_2S and that of CO_2 were significantly lower than normal values, without affecting any change in the ventilation. On 18 June it was noted that the flow rate of the water from the -200 tunnel had slightly risen.

On 27 June 1973, at 6.00 pm, it was decided to abandon the working face as it was discovered that the flow rate of the water had more than doubled following a spontaneous inrush of water and mud, fortunately in the absence of personnel. The inflow rate of the water steadily rose, although with slight oscillations around the mean value of each period, reached 100 l/s on 6 July, the maximum of 260 l/s on 25 July and then dropped by 200 l/s in the first days of August and levelled off at some 25 l/s in October. The water in the bottom of the Rocca shaft, 60 m above the -200 tunnel, disappeared two days after the inrush and reappeared on 15 August.

On 2 July the inrush face was inspected, and at equal ventilation, concentrations of CO_2 and H_2S of 6% and 200 ppm respectively were found, almost 10 times higher than the normal values.

After the inrush, while the water inflow rate increased, and before it reached its maximum, in overlying headings which until then had never been affected by gas influxes (Fig 1), concentrations of CO_2 were found whose time trends presented themselves as waves similar to the wave representing the water flow rate, but lagging somewhat behind it.

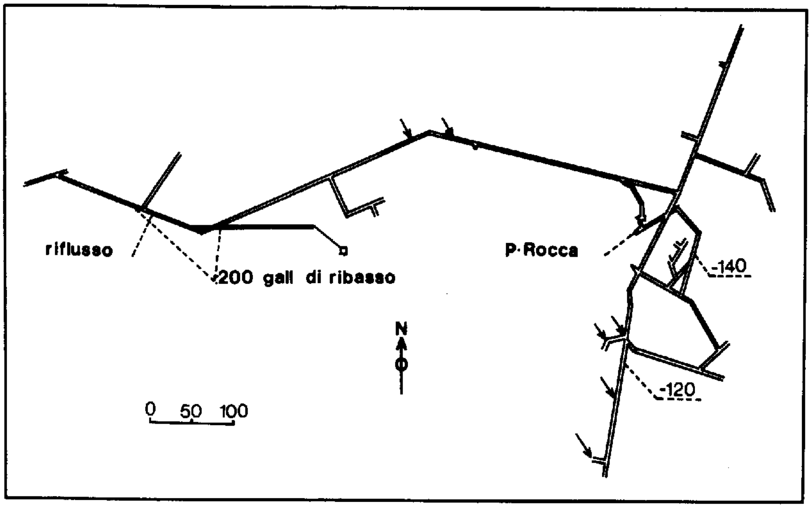

Figure 1: Selvena mine: plan of the southern sector, levels -120 and -200 m. The square indicates the point of the -200 tunnel where the water inrush occurred in 1973; the arrows indicate the points where there were CO_2 emanations.

After the inrush, 1,400,000 m^3 of water discharged from the tunnel, transporting, in successive stages, a total of 1500 m^3 of silts and coarse materials.

Other inrushes similar to the one described, but characterized by considerably smaller volumes of water, occurred on 17 April 1963, 27 March 1969, 24 April 1974 and 6 January 1976, always on the working face of the -200 tunnel. The inrush of 1963 was particularly violent. It occurred at the face in clayey formations 3 m above the contact zone with limestones, and the water partly projected and partly entrained a total of 1400 m^3 of mainly coarse material, which made the last 300 m of the tunnel inaccessible. The water flowed at high rates (close to 100 l/s) only for 4 days. On that occasion the pressure of the water at the face (normally 9 atm) rose to 13 atm for a few months before the inrush, 9 atm one day before it, and 1 atm six days after. The mining of the tunnel was suspended a few days before the inrush as it was noted that the water influx had increased and also the gas concentration in the tunnel had risen.

Thus, for cases analogous to those of Selvena, there is a risk of water inrush in a zone of a tunnel when the following is registered in it:

- increases of the piezometric load;
- variations in the mine atmosphere of the concentrations of the gas that is given off by the water and, in the case of several gaseous components, variations in the ratios of the concentration of each component with respect to that of each of the others;
- intensifications, detectable shortly before the inrush, of the water influx and the gaseous emanations.

After the inrush, there is a risk of flooding of the levels situated above when the following is registered in it:

- reduction of the water influx;
- new gaseous emanations and (or) increases in the flow rates of those already present.

Sudden breakage of the rock at the point of the water inrush, in events similar to those just cited, may depend on the following causes, which may also occur simultaneously:

- gradual weakening of the "natural barrier" due to erosive action of the water;
- uplifting, even if slow, of the piezometric surface until it produces pressures sufficient to make the rock collapse;
- abrupt increase of the piezometric head as a result of the rejoining of perched waters (due, for example, to the priming of natural siphons or the giving way of impermeable diaphragms).

Furthermore, the gas itself, whose emanations seemed to depend on the hydrodynamics, could cause an inrush of water:

- because it could, for example, connect up a tunnel with a natural reservoir located at a sufficiently high level; or because, having accumulated in the reservoir, it compresses the water until it makes it overflow or because it acts as vector fluid entraining the water directly, April 1975 [1];

- because if it comes into proximity with a mine with water under pressure, it could suddenly expand, supplying its elastic energy to fracture and project the rock.

Bagni San Filippo Mercury Mine

The ore bodies of Bagni San Filippo (Siena), composed of little mineralized columnar clusters - mainly cinnabar in clayey-calcareous gangue - is also of hydrothermal origin, but unlike the one at Selvena it is irregular, at places it is dislocated, and is rarely clearly delimited by the contacts with the banks.

The mine which was formerly exploited, divided into three levels, was essentially comprised of two shafts, one for air intake and one for return, connected by tunnels and passes. With the exception of the downcast, dug in compact Rhaetian limestone, all the other passages had been dug in very altered Rhaetian limestone beneath a clayey cover, not always of low permeability, which often penetrated into the cavities of the limestones themselves.

Hydrothermal manifestations were present both outside and inside the mine, but in spite of the mining operations they had never undergone significant variations of position, nor irregular flow rate variations: underground a mixture of CO_2 and H_2S emanated directly from the rock and bubbled through the water that had percolated into the mine, whose overall flow rate had normally ranged between 12 and 30 l/s.

In March of 1976, the mine was flooded for the first time. This first flooding was followed by others which gradually became more violent because the circulating water continued to increase the permeability of the terrains. At 6.15 am on 10 March, in proximity to a raise, at a depth of 140 m from the surface, at the face of a short tunnel, water coming in at a rate of 2 - 3 l/s was noted for the first time. After 8 hours this became 12 l/s. Subsequently, an increase in the rate of the water influx from a fracture at the base of the upcast was registered. On the 11th the overall flow rate stayed constant, on the 12th a reduction was observed, probably on account of the ground settlement and resulting reduction in the ground permeability, Brown 1982 [2]. On the 13th both the flow rates cited and that of the water influx in an exploratory tunnel on the middle level started to increase steadily again and the deeper tunnels were gradually invaded, despite the perfect efficiency of the pumping plants (Fig 2).

On 17 March the water level reached a height of 20 m above the deepest tunnel and then began to descend.

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[1] - An example of dependence of the flow of the water on that of the gas is found at Terme di Montepulciano (Siena), where the water flows in only if the outflow of CO_2 is permitted from a well in a nearby gas field and where the flow rate of the water, as that of the gas increases, first increases and then decreases until it cancels itself out.

[2] - Concomitantly, at 6 m below the base plane of the intermediate level, in a zone near the upcast, there had been a subsidence of the terrains, with the formation of a chasm 4 - 5 m in diameter.

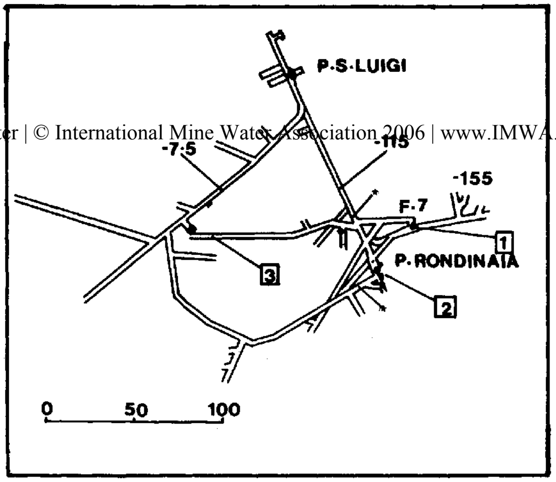

Figure 2: Bagni San Filippo mine: plan. The squares and the numbers inside indicate, respectively, the points of the water influshes that flooded the underground and the order in which they occurred; the stars indicate the measuring stations for the gas flow rates.

Following the main flooding, the subsequent inundation followed - each usually with higher inflow rates (due to the increased permeability of the terrains) and a shorter duration (because of the increased power used for the education) with respect to the preceding floodings. It was possible to investigate the influence of the hydrodynamics in the surrounding area underground on the influxes of gases in the mine and to relate the variation of the flow rate of the gas mixture getting into the mine and the variation of the ratio between the concentrations of the two components with the sense, speed and extent of the shift of the level of the water in the shafts, Anon [3]. Mainly, the effects that appeared most important were: the increase of the gas flow rate and the increase in the ratio between the CO_2 and H_2S contents, in the case of a rise of the piezometric suface; the decrease, in the case of its lowering. Effects that seemed, however, also to be influenced by the preceding oscillations of the peizometric surface.

On the basis of the correlations cited here, in the same mine, in the years 1977 and 1978, it was possible to use the values of the gas flow rates, measured in the ventilation air, to arrive at the shifts of the piezometric surface, indicating risks of impending floodings which sometimes actually occurred in the deepest level. The validity of the method

[3] - From these factors depended the variations of the pressure gradient between cavities filled by the gases and tunnels, of the pressure of the water on the gas influxes, and of the mass of gas that could be dissolved.

was continuously confirmed by the trend of the flow rate of the water pumped out and by the trend of the water level in a shaft.

Consequently, since the spontaneous inrushes of water in mines are usually caused and preceded by the rise of the piezometric surface around the underground area, in the case of the presence or appearance of gases in the mine, [illegible] cited here and of others that are analogous and always specific for the underground area they refer to, represents another means of forecasting, in addition to the ones mentioned previously.

As far as the causes are concerned, among those already listed with regard to Selvena, for Bagni San Filippo, the possibility of an abstraction towards the underground area of part of the water of a stream located above is to be included. The flow rate of the stream dropped simultaneously with the flooding episodes and with the appearance on the outside of two new sulphureous exhalations, formed either due to veritable explosions caused by the rapid expansion of gas compressed by underlying water or, more likely, due to splitting of the ground, eroded below by the water. By seeping in, the stream water could have brought about the swell of nappes around the workings and consequently the formation in the mine of new influxes and the intensification of those already existing. This hypothesis is strengthened by the subsequent disappearance at the surface of the stream water, which had seeped into the sink that had formed in correspondence with one of the two sulphureous exhalations. Hence, variations of surface watercourses could also give warning of possible water inrushes underground.

Campiano-Boccheggiano Pyrite Mine

In the Campiano mine (Grosseto), the downward continuation of a vein of ore bodies at a depth greater than 500 m from the surface mainly composed of pyrite formed by substitution of buhrstones and evaporites (Upper Trias) is exploited. The vein runs along a large fault trending NW-SE, having a throw of over 1000 m and an average dip of 45°.

This fault brings Permo-Triassic phyllitic schists, at times intercalated by evaporites, into contact with schistose-clayey flysch formations. The latter outcrop at the top of the fault and make up a substantially impermeable complex. At the bottom of the fault, on the other hand, the phyllitic schists outcrop, permeable only in correspondence with fractures and surrounded to the S and W by outcrops of buhrstone, characterized by a high capacity of absorption and entrainment due to karst phenomena and fractures. Both the phyllites and the buhrstones seem to be affected by secondary faults, outcropping or laid bare by the mining.

The topmost part of the vein mentioned above was exploited in the past, in successive stages, down to 200 m above the site of the Campiano mine now under exploitation. The mine, moreover, is located 8 km S of the stream-dominated geothermal fields of Travale and Monte Gabbro, in which the stream is encountered at depths of 100, 700 and more than 2000 m. The mine is thus characterized by geothermal gradients nearly three times higher than the average ones of the earth's crust. It follows that in the Campiano mine the water may come from above, from the permeable structures and from the voids of the old mining working and from below, from deep natural reservoirs connected or not with the steam ones, containing remote meteoric waters and, probably, juvenile fluids. The mine essentially consists of two twin shafts and a helicoidal ramp that winds around them, to provide access to the ore bodies, exploited by sublevel stoping and subsequent back filling. The mine network extends into the roof terrains, which were always found to be dry, up to 450 m from the surface, and in the bed terrains, where a depth of 740 m was reached. The vein had just been intersected when, in January 1977, during penetration at the bed, a violent inrush of water occurred by a plughole and the mine was flooded.

Before this event there had been water influxes from the bed and from the vein, both in the old mine located above the Campiano mine as described earlier and in the Campiano mine itself.

Hot Water Inundation:- On several occasions, in the old mine, the excavation resulted in influxes of hot water from the lowest level reached. In 1901 an influx of 20 l/s of water at 45°C brought about partial flooding of the mine and the disappearance at the surface of a few springs.

In the Campiano mine, a first influx of 0.8 l/s of water at 52°C was found while reaching the vein at an elevation of 75 m above sea level with a test hole. In December 1976, a second occurred when the vein was reached by another test hole exactly at sea level. This was an intermittent influx, occurring at two minute intervals, of water at 58°C and of gas; the average flow rate of the water was just over 0.04 l/s. A third influx occurred on 27 December 1976 at 33 asl from the face of the ramp, with which the vein had to be crossed in descent and which had just made contact with the roof. As the 41st plughole was being drilled, the water had flowed out at a rate of 9 l/s and a temperature of 53°C. Both the central informer hole and the previous 40 plugholes had appeared dry.

To pump out the water of the third influx and any which would might be met in crossing the vein, a basin and a pumping plant were prepared at 33 m asl. Then the crossing of the vein was resumed with a rising tunnel alongside that of the third influx. After the mineralized vein and a few metres of phyllites at the bottom had been crossed and after the central informer hole and no less than 26 plugholes had been drilled without encountering water, at 3.00 pm on 26 January 1977, from the 27th plughole, just completed on the wall nearest the tunnel of the third influx, there was a sudden and violent influx of water that caused part of the wall and the face to collapse and, projecting coarse material for some distance, enlarged the hole, quickly reaching a flow rate of approximately 150 l/s.

The mine was flooded. Nine days later, when the water level, continuing to rise, had reached the elevation of +328 (100 m below the presumed local groundwater level), eduction from the ramp was begun with raft-mounted pumps.

During the eduction the flow rate of the water running into the mine, although tending to fall, oscillated considerably on account of the varying speed at which the level of the water downstream side of influxes reduced. The flow rate gradually increased after sudden drops of that level and slowly decreased after halts or slow declines.

On 2 October 1977, when the dewatering of the mine had been completed after pumping out over one million m^3 of water, it was noted that the ingress of water from the borehole at +33 m, stopped completely and that 31 l/s of water at 46°C inflowed from the borehole at +38 m, and that the flow rates of the water of the vein at 0 m and at +75 m had fallen off to 0 and 0.2 l/s respectively. (The gas influxes had greatly diminished as well.)

Neither in the stage in which the water rose in the ramp nor during the pumping were flow rate variations observed in the springs outside the mine. However, while the water level fell in the ramp, the levels in the old mining recesses above and in a few wells drilled from the exterior which crossed the vein descended, although more slowly.

As subsequent episodes, but linked with the one described and are therefore useful for formulating hypotheses on the causes and the dynamics of the event, the following are reported: the discovery in the bed of the vein of two gas pockets at a pressure of 9 and 20 atm respectively with a hole vertical towards the bottom 150 m long and with a hole slanting 45° towards the bottom 140 m long, both drilled from the face of the last influx at +38 m; and the instantaneous liberation of CO_2, which occurred following a volley at -170 m (170 m below sea level) that resulted in the blasting and crushing of 160 m^3 of phyllites. The CO_2 continued to come out of a fracture, in 15 days dropping off, in hyperbolic decline, from 0.6 to 0.05 Nm^3/s.

Ground Water Investigations around the Campiano Mine

From observation it seems that the water arrives in the mine through fractures located in the mineralized vein and in the bed evaporites and phyllites near the contact. But it may also happen that the phyllites far away from the contacts, contrarily to what was noted in workings close to Campiano, Anon [4], are not dry. Indeed, deep into the quartzose-phyllitic basement, steam in sufficient amounts for electric power generation was encountered by advance boreholes even at depths of over 3000 m. Thus, the probability of water inrushes is higher in proximity to the deposit, it cannot be ruled out that inrushes also may occur in the bed at a considerable distance from the vein.

What made the described inrush very violent is the probable outburst of gas under pressure with the water behind the workings. The nearness of water in fractures could be indicated by the time dependent emanaties of gas, and higher temperature of the rock.

In any case, since the forewarning elements are few and not very evident, it is necessary to know in advance the actual circulation network of the water, in the immediate vicinity of the mine workings, in order to provide adequate protective barriers and also to determine the sources of the inflows.

For the Campiano mine a study was undertaken to obtain an equivalent circulation network for the given positions of the present water influxes in the mine (Fig 3), inflow rates, static head (height of the groundwater level before the outflow), and the existing correlations existing between influx and the rainfall (Fig 4).

The actual spatial distribution of the network must be predicted taking into consideration the geological and structural situations, the presence of situations analogous to some that are already known, the dimensions of the aquifers (which can sometimes be determined by making use of any transients available, such as, for example, those connected with the dewatering of the

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4 - In the nearby Niccioleta pyrite mine the exploitation continued, without problems of educations, for over three kilometres, among phyllites below a tunnel from which almost 500 l/s of water coming from overlying limestones is pumped.

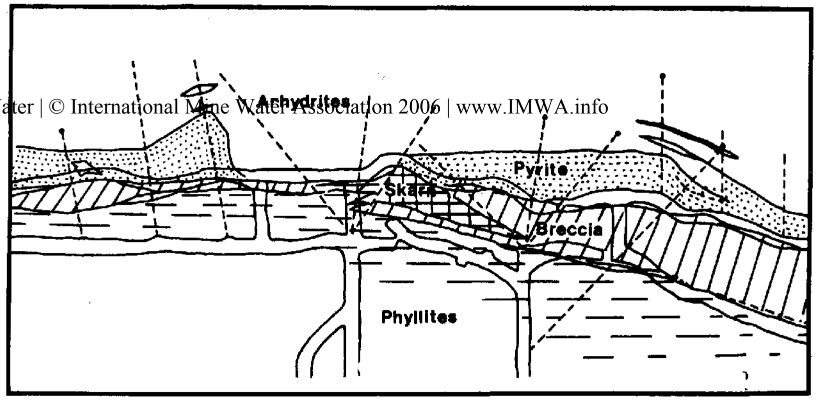

Figure 3: Campiano mine: location map of water inrushes (filled circles) encountered by the test holes (broken lines) drilled, to define the ore body, from the base tunnels of the -80 level.

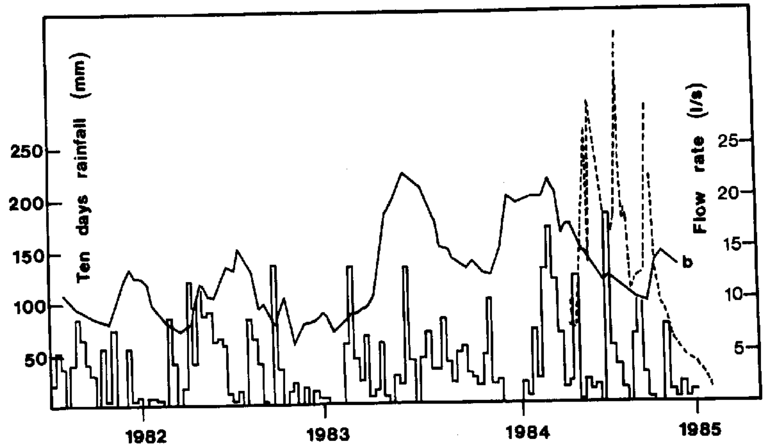

Figure 4: Campiano mine: ten days' rainfall (a), overall flow rate of the water influshes in the Campiano mine (b), and overall flow rate of the water from test boreholes from the old mine (c) as a function of time; the marked and immediate influence of the rainfall on the flow rate of the water from the old mine stands out clearly.

flooded mine), water chemistry, temperature, and the geological origin.

The circulation network relating to a given situation must be kept updated as the mine is developed since the structure of the network is modified not only by the action of the waters, which sometimes plugs (Fig 5) and sometimes erodes, but also due to the succession of static and dynamic stresses transmitted to the rocks around the workings as a consequence of extension.

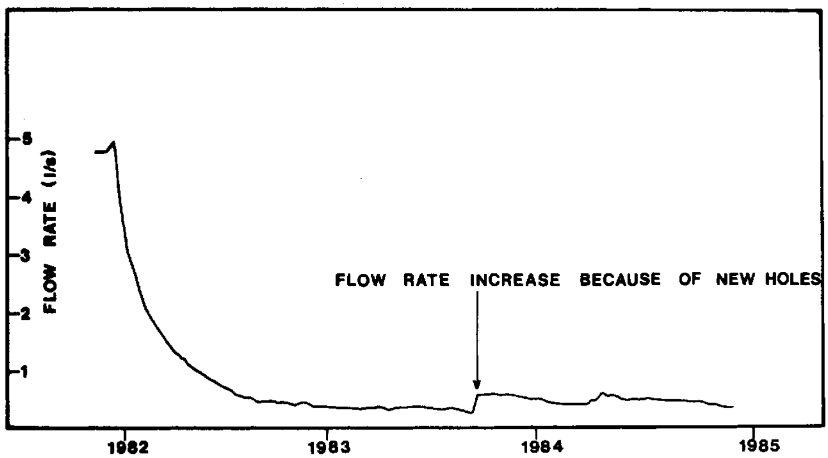

Figure 5: Campiano mine: Example of reduction of flow rate due to gradual plugging of the outflow routes: time trend of the flow rate of the water coming from the vein (+75 m).

From Fig 6, where the time trend of the cumulative amount of pumped water and of the cumulative rainfall is shown, it can be seen how the flow rate of the water coming into the mine gradually increases as the mine is extended. From the end of 1983, ie from when the exploitation was intensified, a greater slope of the curve related to the pumped water with respect to the curve of the rainfall is noted, with the exception of the last period of registration corresponding to the drainage of the mine located above, which significantly influenced the inrushes in the Campiano mine.

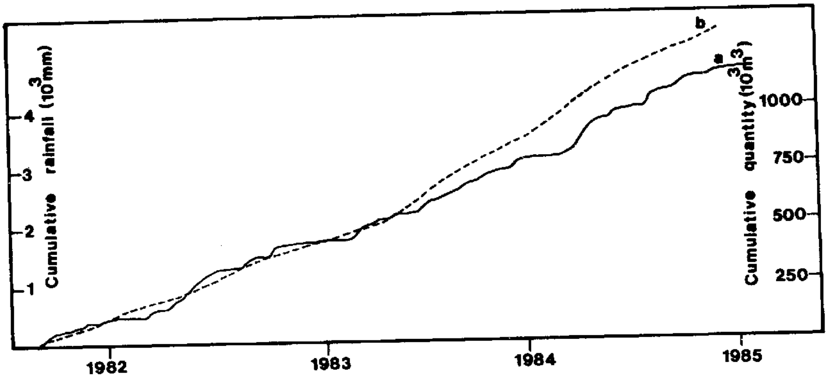

Figure 6: Time trend of the cumulative rainfall (a) and of the cumulative quantity of water pumped from the Campiano mine (b).

CONCLUSIONS

The spontaneous inrushes examined in this paper occurred in terrains that were substantially permeable due to porosity, with the permeability in an unpredictable way on account of the circulating waters. Since it is difficult to adapt mathematical or analogue models to the flow of fluids inhomogeneous and anisotropic media with the permeability varying with space and time, it is difficult to forecast inflows by means of models. Therefore, in cases similar to those examined, the forecasts must rely on the observation and correct interpretation of all the phenomena that precede inrushes, whether they be new events or alterations of ones alreadv existing.

To avoid induced inrushes, analogous to the one described, typical of rocks that are almost exclusively permeable due to jointing, it is necessary to concentrate on the preventive measures rather than on prediction, as the events that can give advance warning of them are very rare. The more exact the knowledge of the actual circulation network around the underground area already developed and in the whole zone that might possibly be affected by mining, and the deeper the understanding of the effects that might occur due to the reciprocal influences between aquifers and workings, the surer the prevention will be.

ACKNOWLEDGEMENTS

The author thanks the managements of the cited mines and that of the ENEL National Geothermal Unit of Pisa for their kind and active collaboration.

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