The rising of groundwater level in the “metalliferous ring” of Iglesiente Mining District (SW Sardinia – Italy)

Massimo Vincenzo Civita, Adriano Fiorucci and Giovanni Saiu

Abstract: The important mine district of Iglesiente, in the SW of Sardinia Island (Italy) count a number of shafts where lead, zinc and silver ores are mined. The ores occur in a carbonate rock complex of the Lower Cambrian highly folded and faulted with the remobilization of the mineral deposits and the development of various karst cycles. In this highly permeable complex flow large quantities of groundwater that posed serious problems for a modern mining activity since XIX century. Several dewatering plants were realized in time at various levels below the sea level. Being almost exhausted the mineral while working dewatering plant al -100 m below sea level, discharging 1.35 m^3/s of high chlorined water, the hydrogeologic problem was studied at the whole with the economic support of EC. A new dewatering plant at – 200 m bsl was planned and start in 1985.

Unfortunately, the prices of the lead and zinc fell down in the early 2000 and were taken the decision to close all the mine activity. When the dewatering plant was turned off, in all the mining district the groundwater began to rise. A number of electronic gauges putted into several shaft have measured the draw up, together with the main hydrochemical parameters. This paper summarized all the data and observation about the complex phenomena happened during the rise up, with the hope to provide a useful precedent for the number mining activity with the same problems all wide the world.

Riassunto: *L’importante distretto minerario dell’Iglesiente, nella parte sud-occidentale della Sardegna (Italia), è sede di un certo numero di miniere dove si estraggono minerali di piombo, zinco e argento. I minerali si rinvengono in un complesso carbonatico del Cambriano Inferiore intensamente piegato, fagliato e con una vistosa rimobilizzazione dei giacimenti minerari e lo sviluppo di vari cicli carsici. In questo complesso altamente permeabile un consistente flusso di acque sotterranee pone seri problemi all’attività mineraria sin dal XIX secolo. Diversi impianti di drenaggio sono stati realizzati nel tempo a varie quote al di sotto del livello del mare. Durante il drenaggio a -100 m sotto il livello del mare, si è prodotto uno scarico con una portata di 1.35 m^3/s di acqua ad alto contenuto di cloruri, il problema idrogeologico è stato affrontato grazie al sostegno economico della Comunità Europea. Un nuovo impianto di drenaggio a - 200 m sotto il livello del mare è stato realizzato nel 1985. Purtroppo, i prezzi del piombo e zinco sono fortemente diminuiti nei primi anni 2000 e questo ha portato alla chiusura degli impianti estrattivi. Quando l’impianto di drenaggio è stato disattivato si è osservato un generale innalzamento dei livelli idrici sotterranei in tutto il distretto minerario. Un certo numero di acquisitori automatici posizionati nei pozzi hanno misurato in continuo i livelli idrici e alcuni parametri idrochimici. Questo lavoro riassume i dati raccolti e le conseguenti osservazioni fatte durante il complesso fenomeno di risalita dei livelli idrici, con il proposito di fornire un utile precedente per la numerosa attività mineraria con gli stessi problemi in tutto il mondo*

Keywords: Sardinia, mining, hydrogeology, dewatering, sea water, rising groundwater level.

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Introduction

In several parts of the world where mining resources have been strongly exploited by high penetration in the ore deposits deepness, severe problems have been reached when impacting highly productive and strongly feeded aquifers. Here are listed some particular case (Table 1).

When the casting off of those mining operation is indispensable, cause the ore exhaustion, or the digging out is not economically viable also versus the high dewatering costs, here a totally new problem, quite never happened in 20th Century, rise on. The mined district begin more or less quikly to fill in by groundwater. The dynamic level goes to rise up since to rich the original static level, prior the forced dewatering take place. This rise up highly impact the over standing land and environment.

Nowadays an emblematic case has happened: “Within the complex of go DL mines of Witwatersrand (SA), where on 2010 July a strong warning has went up cause the groundwater not more lined uplift. It is forecasted that millions of litres of highly acidic mine water (AMW) is rising up under Johannesburg and, if left unchecked, could spill into the streets some 18 month from now.” The acid water was controlled by dewatering systems currently about 600 m below the city’s surface, but it is rising at a rate of 0.6 ÷ 0.9 m/d. Marius Keet, director of water quality management, has warned that “it can have catastrophic consequences for the Johannesburg central busi-

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Tab. 1:*Daily average dewatering discharge from some mining operations affected by severe problems of groundwater (After Civita, 2005).*

Mine Operation Site	Worked Ore Deposits	Impacted Aquifers	Average Dewatering km^3/d	m^3/s
Jiao Zuo (North China)	Coal	Karstified dolomite	657	7.58
Nyirad (Hungary)	Bauxite	Karstified limestone	400	4.63
Konkola (Zambia)	Pb, Co	Fractured dolomite	400	4.63
Far West Rand (South Africa)	Au	Fractured dolomite	385	4.45
Pine Point (Canada)	Pb, Zn	Dolomite limestone	227	2.63
Tatabanya (Hungary)	Coal	Karstified limestone	215	2.50
Fengfeng (North China)	Coal	Karstified limestone	173	2.00
Megalopolis (Greece)	Coal	Karstified limestone	156	1.80
Monteponi (Italy)	Pb, Zn, Ag	Dolomite & limestone	147	1.70
Friedensville (Pennsylvania)	Zn	Dolomite & limestone	120	1.38
Iszkaszentgyőrgy (Hungary)	Bauxite	Karstified limestone	115	1.30
Nose Rock (New Mexico)	U	Shale & sandstone	110	1.25
Mufulira (Zambia)	Cu, Co	Fractured dolomite	100	1.15
Rokana (Zambia)	Cu, Co	Fractured dolomite	90	1.05

ness district if not stopped in time. Acid mine drainage is affecting western, central and eastern basins in the Witwatersrand gold fields area, which have strongly impacted the Vaal and Crocodile river system."

Several other cases is now verified everywhere. Here the most recent are presented.

- On 2009, researchers warned polluted water from the abandoned go DL collieries may render Mpumalanga, in SA Vaal river valley, a wasteland.
- The acid water surging from the SA West Rand mining operation, large amount of acid mine water continue to flow into the surficial water network that feeds the Cradle of Humankind in Sterkfontain where it was discovered in 2008 a skeleton of *Australopithecus sediba*, a humanoid of about two million year old.
- In the Appalachian Region it was pointed out that the seeping or surging from abandoned mines the groundwater often acidic coats streambeds whit orange sediments killing the bottom of the food chain often desolating entire watersheds.
- In the Lake County, Colorado, they are strongly working to reduce the risk of 1.5 billion gallons of acid mine drainage blowing out the walls of the Leadville Mine Drainage Tunnel that drains water from a portion of the underground workings of the Leadville Mining District.

A great number of cases have been collected all wide the word of mine works abandoned or in the way of abandonment where the stop of dewatering will cause large damages to the environment, to surficial water network, to the settlement.

The most number of cases, the highest damage happens unexpected cause the lack of hydrogeologic knowledge, forecasting and prevention previous studies, as the nowadays flooding in the coal mines of Xintai (Shantong) and Wangjialing (Xiongning) in China.

The case history herein presented, previous studies have been performed after the dewatering switch out. An important monitoring system of groundwater quality and rise up was planned and made operative in all the mining plants of the Iglesiente Mining District (IMD),

The District is located in the south-west part of Sardinia island. It was the most important Italian (and one of the main of UE) lead and zinc ore production pole, estimated to contain reserves of 2.5 Mt of metal, i.e. double the quantity as yet extracted. Nevertheless, the Pb and Zn sulphides and oxides orebodies exploitation in this area (Fig. 1) was hindered by serious drainage problems due to groundwater circulation in the carbonate formations, in which the orebodies are contained.

Although the early traces of the exploitation of the ore bodies date back to the Nuragic Civilization (3000 B.C.), during the historical age several peoples had exploited the rich ore bodies, beginning by Phoenicians and going on with Roman Empire, till the Spanish Kingdom, the Pisan Republic and at last the Italian Kingdom. In 1850, new mining works were opened, new mining and mineralurgic techniques were then introduced. But very soon the production was slow down by the presence of groundwater, against which, from 1870 to the recent past, a veritable battle has been fought to enable excavations to be sunk below the groundwater static level. First the construction of a drainage tunnel gives exploitable a good ore body panel, but in 1929 following the Wall Street crash, values of metals

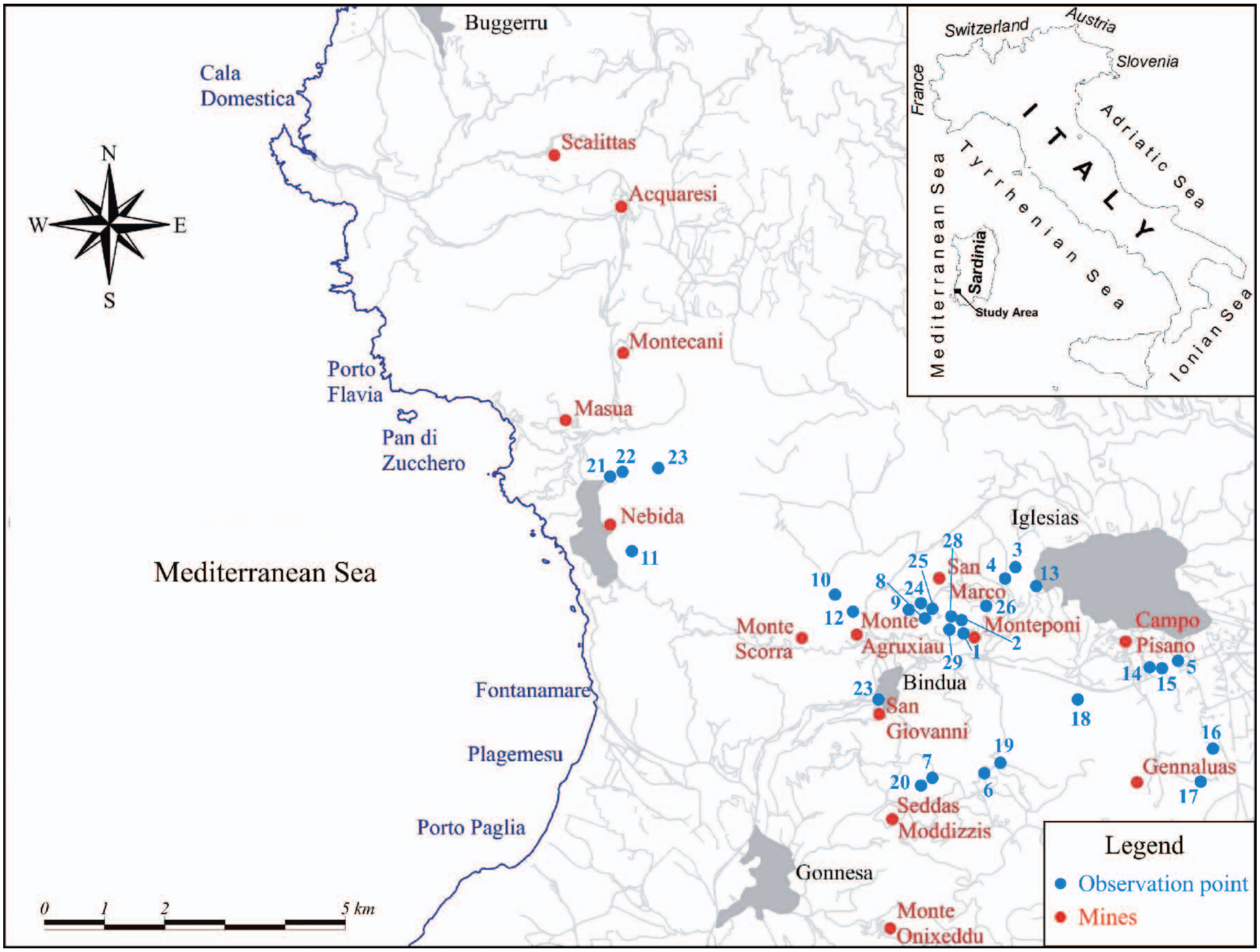

Fig. 1: *The Iglesiente Mining District with the position of the various mining working plants*

dropped drastically on the London stock exchange, causing problems of labour redundancy and reduction in sales throughout the mining sector. During the period between the 2nd World Wars the mine activity recorded fall and rise moments: in a first stage a huge development was experienced, and the Iglesiente mines strongly contributed to post-war reconstruction, by satisfying a great part of the demand for metals. But at the end of century, a slow but relentless process of abandonment due to the drop in economic conditions, exhausting of resources together with the costs involved in the exploitation of metal deposits imposed by the presence of enormous volumes of groundwater needing to be pumped out and the international drop in metal prices, were the recognized causes for the abandonment of the Iglesiente district mines.

In order to face these uneconomical conditions which were made even worse by the depressed metal ratings on International Stock Exchanges (Table 2), a rationalization process of all the specific sector was started.

A tentative to re-vitalize the mining works was then made with economic support from the EEC, the implementation of a new system for pumping out water was studied: this was to be 200 m below sea level to allow deposits, which otherwise could not be exploited, to be mined, and came into operation during the Nineties.

Despite this latter attempt at re-launching the sector, the financial statements clearly showed the non-viability of activities, "artificially" kept alive by government grants for purely occupational purposes.

Metal	1988	1989	1990	1991	1992	1993
Zinc	1540	2350	1820	1386	1596	1651
Lead	852	926	977	690	760	802

Tab. 2: *International Pb and Zn quotations expressed in Italian Lires/kg*

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In 1993, *ENI* announced a programme for the total shut-down of mining activities on the Island, at least as far as metalliferous ores were concerned. Among the most important decisions in recent history was that of closing the Monteponi *–200 pumping plant*, owing to the excessive cost (approx 3.5 M€/year for electrical power). The motor units were gradually switched off to implement a gradual process reducing the pumped capacities, thus causing "controlled" uplift of the dynamic level throughout the whole basin. Great attention was paid to studying the uplifting, equipping several mines with multi-parametric probes, and to collecting significant data.

This work summarizes all the hydrogeological observations, the forecasting mathematical models used in the analyses and monitoring elements produced during the uplifting, to be used as examples in case of similar situations that might be present in many other parts of the word (Civita 2005)

Geologic outline

1978; Cocozza 1979; Civita *et al*. 1983 for in-depth details. The IMD area is characterised by the presence of *Cambrian* and *Ordovician* structures involved by the action of different tectonic phases attributable to the *Caledonian Orogeny* (known as the *Sardinian Phase*) and the *Hercynian Orogeny*.

As summarized in Fig. 2, the oldest Palaeozoic sequence crops up in the IMD. It begins with a thick (about 3000 m) epicontinental Cambrian succession consisting of three formations: *Nebida Formation (Fm)*, turbiditic sandstone with limestone lenses; *Gonnesa Fm*. (the so-called «Metalliferous», as most ore bodies are located herein - Fig. 3), dolomite and limestone; *Cabitza Fm*. nodular limestone and rhythmic varicoloured shale.

The Cambrian sediments were exposed to external agents up to a transgression. In this way the trasgressive conglomerate ("Puddinga") rests in unconformity on all the 3 above mentioned Cambrian formations. All described sediments were deformed and metamorphosed during the Carboniferous phase by the Hercynian Orogeny.

Because of the intense deforming Palaeozoic phase (*Hercynian and Caledonian Orogeny*), the most evident and important structures are therefore synclines and anticlines with prevailing N-S and E-W trending axes. The largest is the Monteponi N-S axis close to the vertical syncline, with the varicoloured shale (*Cabitza Fm*.) in the core. Another syncline, the Nebida E-W axis, intersects the first, generating a complex scythe shaped structure.

Post-Hercynian epeirogenetic phases have sectioned the previous structures into a number of fault blocks. Those phases (*Alpine Orogeny*) might have been relevant to hydrogeological problems in the area of Monteponi by reactivating o DL faults. This was confirmed by accurate studies within the mines and by remote sensing surveys, both aircraft and satellite–vectored (Civita *et al*. 1983).

Five karst cycles were identified in the lengthy span ranging from

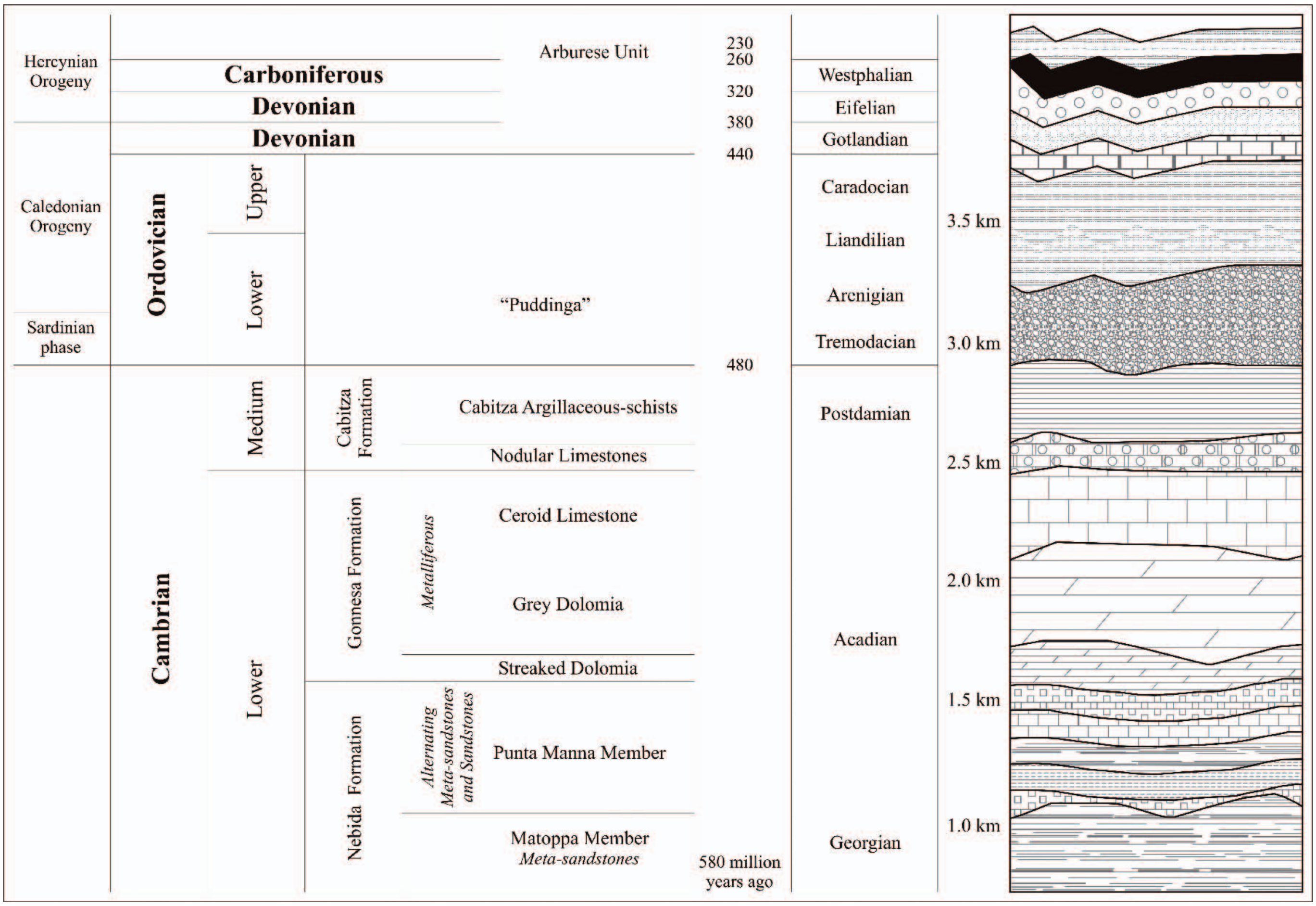

Fig. 2: *Scheme of the stratigraphic subdivision and of the orogenetic phases that have characterised the Sulcis – Iglesiente area (After Cocozza 1979)*

Fig. 3: *On the left - The Porto Flavia mooring: the mined mineral was brought to the surface through a series of shafts tunnelling the mountain and was loaded directly onto large-tonnage ships. On the right: the Masua mining plant.*

the Lower Cambrian-Middle Cambrian up to the Quaternary (Civita *et al.* 1978). The most important cycle is connected with a long Permian-Triassic emersion period, which gave rise to galena and barite accumulations in the karst depressions and caves. The circulation of acid waters, linked to the alteration of the sulphide ores, meteoric waters, deep chloride and thermal waters, produced an extremely varied and complex hyperkarst (Civita *et al.* 1986).

The Zn-Pb-Hg-Ag mineralization of IMD displays a variety of style, paragenesis, size and occurrence compared with host rocks. The ore deposits were initially considered genetically linked to the area's Hercynian granite intrusions. More recent studies, however, suggest that the ore bodies within the Cambrian carbonates are of synsedimentary origin.

Hydrogeological setting

The geologic formations previously described have been grouped in hydrogeological complexes, the salient characteristics of which are listed in Table 3, sorted in reverse stratigraphic order.

The hydro-structures resulting from the whole area's intensive tectonic history are extremely complex: the folds caused by the Sardic phase are crossed by successive folds and faults that are almost orthogonal, and whose geometry frequently causes impermeable schist limbs to be wedged deeply into the karst aquifer, characterised by its rigidity. Thus several quite impermeable structures have been formed, partially in sequence and partially in parallel (the term SERSEM means semi-dependent reservoirs – Civita, 1980), each of them being characterised by diversified piezometric heads. These are in turn divided into smaller sub-basins by smaller limbs, sedimentary dikes, karst fractures and caves filled by calcite sinters or other minerals, quartz veins etc. (Fig. 4)

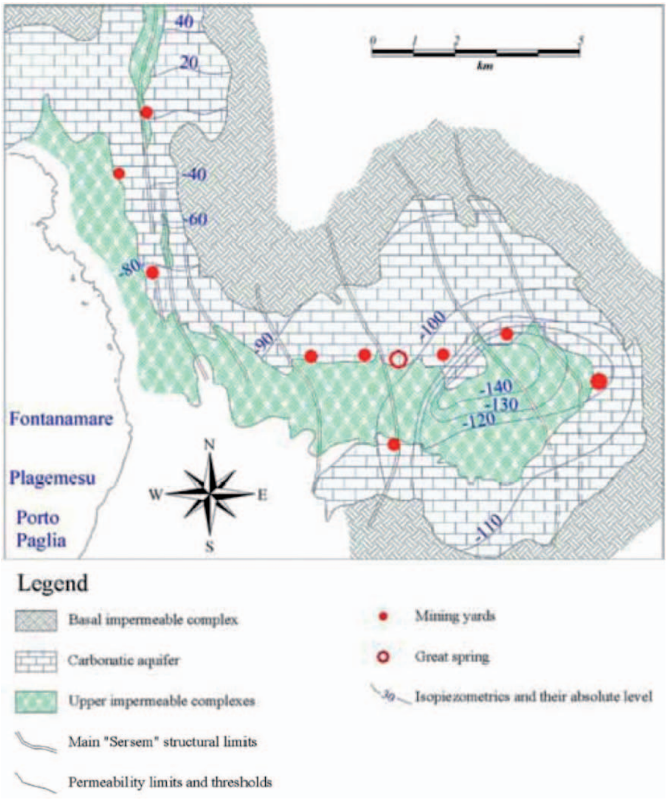

Fig. 4: *Structure of the "Metalliferous Ring" with structural limits that highlight various "SERSEM" – the flow field refers to December 1996, before the exclusion of the –200 dewatering plant*

Groundwater flow in the karst complex is due to different waters from the geochemical and thermal point of view: coDL fresh water with normal chemical composition and several, sometimes large hot springs along the coast and in the deepest levels of the mines with high chloride content (Fig. 5).

Tab. 3: *Schematic hydrogeological characteristics of the main IMD formation*

Formation	Complex	Lithology	Relative Permeability	Hydrostructural Role
"Puddinga"	Upper terrigenous	Arenaceous shale, argillite, siltstones and cemented conglomerate	Poor to nil, in general	Aquiclude
Cabitza	Intermediate schistose	Calceschists, shale and siltstones	Poor to nil, in general	Aquiclude, permeability sills & boundary
Gonnesa	Old Carbonate	Limestone and dolomite	Very high, by fracturing & karst (various cycles)	Main aquifer
Nebida	Lower terrigenous	Sandstones, siltstones and argillite	Poor to nil, in general	Aquiclude, permeability sills & boundary

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Dewatering systems

The identification of the «main aquifer system», drained by the dewatering plants in Monteponi, Campo Pisano, San Giovanni and Nebida mines, was controlled by an inverse balance numeric model. The ratio between the average annual infiltration and the average dewatering discharge is 0.23. This proves the presence of a conspicuous base flow from another influent high chloride-content hydrogeological system: the average chloride content of the water dewatered by the Monteponi mine gradually increased from 1.7 g/l in 1929 to 9.6 g/l at the end of Nineties. Isotopic analyses have enabled the chlorine groundwater to be connected to the sea via a complicated hydrothermal mechanism (Civita *et al*. 1983; 1986).

The first attempt to drawdown the aquifer below the groundwater static level (71 m a.s.l.) took place in 1873 by means of 2 steam-powered pumps ("Sella pumps"). From then until 1993, five other dewatering plants were installed. Data relating to the dewatering plants are presented in Table 4. The first important action taken to dewater the whole mining district was the implementation of a drainage tunnel from the Monteponi mine to the Sa Masa swamp (near the sea) 2.7 m a.s.l., slope 0.5‰, 5874 m long, of which 4344 m in the compact and impermeable schist and 1530 m in the aquifer carbonate complex. When the excavation reached a large karst cavity within the dolomite layers (the so called Great Spring), about 3.6 m^3/s of sandy high content groundwater flowed into the gallery. After 5 months it was reduced to a stable yield of about 1.4 m^3/s. The piezometric level dropped rapidly in the whole mining district.

In the period that followed 1928, 4 different pumping stations had to be installed in succession, located on the vertical in a very compact limestone column. These were increasingly powerful plants which occupied very large underground spaces (Fig. 6), with pump units expressly constructed for this need.

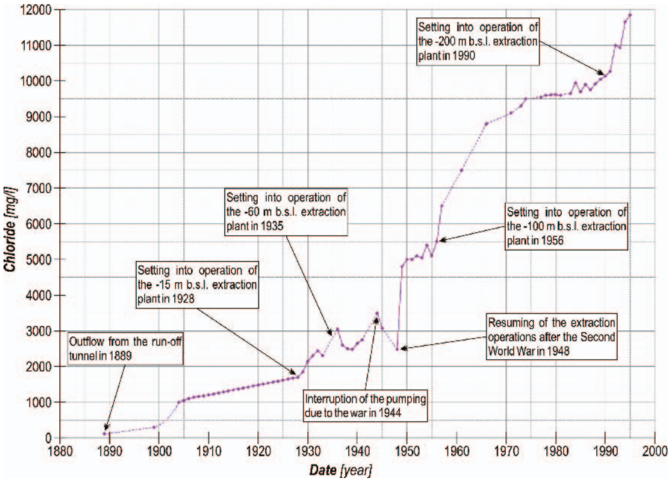

Fig. 5: *Variation of Cl content through time, according to the drawdown induced by the different dewatering plants*

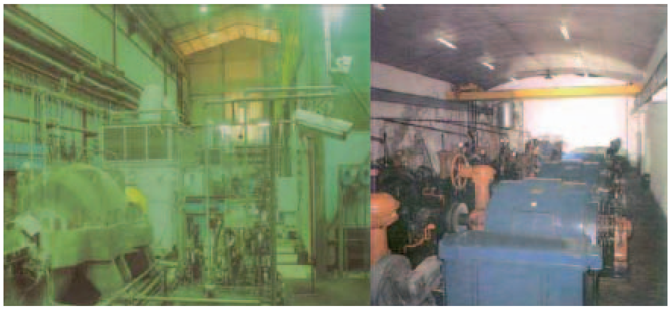

Fig. 6: *On the right, the area of the –100 plant pumping station; on the left, the –200 plant pumping station.*

Tab. 4: *Dewatering plants main data. The groundwater DLs are referred to the centre of the dewatering systems (Monteponi mine)*

Dewatering Plant	Type	Period Of Duty	GW Dynamic Level (m a.s.l.)	Average Discharge (m^3/s)	Gw Average Cl Content (g/l)
"Sella pumps"	Pump groups	1875-1880	61.5	0.30	---
Umberto I	Drainage gallery	1885-1928	13.5	0.12	0.113
-15 plant	Pumping station	1928-1935	-15	0.81	1.7-3.0
-60 plant	Pumping station	1935-1956	- 60	1.02	3.0-5.0
-100 plant	Pumping station	1956-1990	-100	1.55	5.0-9.5
-200 plant	Pumping station	1990-1996	-170	1.65	9.5-12.0

Methodology for groundwater uplift forecasting

As mentioned, the termination of mining activities in the IMD has forced the dismantling of the -200 pumping plant, the cultivation being not economically viable.

This situation led to other issues concerning the hydrogeological aspect: in fact, interrupting the pumping would have allowed the groundwater's uplifting in the carbonate aquifer, so that the most efficient procedure for stopping the plant with maximum safety had to be assessed.

To forecast the timing relative to the DL's uplifting (Dynamic Level), various sets of data were taken into account, basically divided into two data collecting base:

The first is relative to the stoppage of the –60 plant, following the 1943 wartime events.

The second concerns various total stoppages of the –200 plant due to power blackouts, maintenance works, breakdowns, etc.

Using the data produced by the previous complete hydrogeological study (Civita 1986), mathematical models were built up to forecast the groundwater level rise in each mine.

As above named point 1), the information on which the forecasting methodology has pointed up lies on the timing needed for the groundwater DL uplifting to the Great Spring (+ 6.5 m a.s.l.) quantifiable in approximate. 19 months: in fact, at the time of the interruption caused by the Second World War, the DL took approximate 14 months to rise from – 60 and to outflow naturally from the drainage gallery. The dewatering plant stopping on Oct. 08 1943 at 08:00 a.m., the mine works technicians were prepared to survey in continuous the groundwater uplift in several shafts of the IMD. The DL recovery is then accurately analysed since 900 hours from the dewatering stop (Fig. 7). The uplift went regularly increasing till Feb. 1st 1944, when the discharge via drainage gallery has reopened.

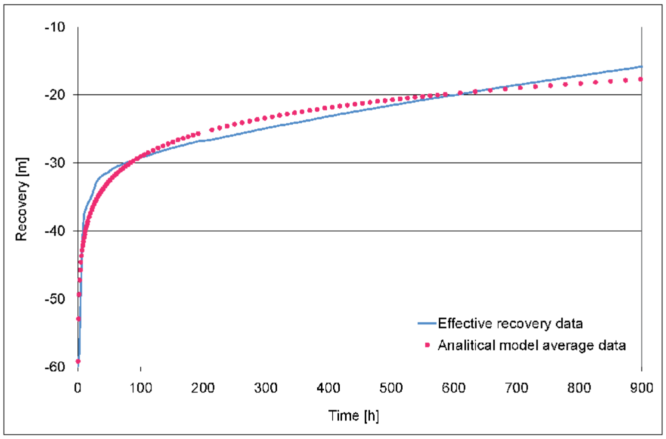

Fig. 7: *Rising of groundwater DL in the central mine works of IMD after the switch-off of the dewatering system -60 (08/101943 – 15/11/1943)*

From the data series of uplift as a function of time take place the analytical expression to model the space-time variations of DL uplifting in the whole IMD.

The diffusion equation that describe the groundwater flow in transient condition, may be well approximated by the exponential equation based on the recovery model stated by Theis (1935) according to Neuman's theory of delayed water table response having well in mind the assumption of Boulton & Streltsova for the unconfined fissured and karstic media. Of course, some simplifications have been introduced cause the scarce hydraulic conductivity data and the spatial high variation of discontinuities in the tridimesional space. So, the entire aquifer must be considered as a equivalent porous medium (Dershowitz & Fidelibus 1998; Zhang *et al.* 1996)

The Theis equation may be simplified by the logarithmic approximation model (Jacob 1950).

The hydrodynamic parameters requested by the analytical model (transmissivity [T], storativity [S]) come from the number of hydrogeologic studies on IMD (see the Reference list). By this way, the consistence between the Jacob's model and the measured data has released having in account of the groundwater basin geometry and its internal boundaries.

Following the effects superposition principle, the aquifer DL variation (referred to H_0) is defined by the relation:

$$h(r,t) = H_0 - H(r,t) \tag{1}$$

The solution of the diffusion equation, using the Jacob's simplification is noted:

$$h(r,t) = \frac{Q}{T} 0{,}183 \log\left[\frac{2{,}25T}{Sr^2} t\right] \tag{2}$$

Where Q is the dewatering discharge, r is the distance of surveyed point from the pumping centre, t the time elapsed.The analytical model allows calculate the water table elevation difference of a point versus whatever other point of the same domain. This difference, in regime condition, is time independent:

$$h(r_1) - h(r_2) = 2A\left[\frac{\frac{\log r_2}{r_1} + \log r_2'}{r_1'}\right] \tag{3}$$

where A incorporate all the constant values in the (2).

The Theis – Jacob relation may be used to interpret the groundwater recovery when a dewatering discharge reduction take place by inserting in (1) a negative flux of the same intensity. This set against to the flux discharged till the stop instant following the relation:

$$h(r,t) = \frac{Q}{T} 0{,}183 \log\left[\frac{\log 2{,}25T}{Sr^2} + \log(t_0 - t) - \frac{2{,}25T}{Sr^2} + \log t\right] \tag{4}$$

where t is the time elapsed from the instant of the Q variation. So, the negative component (recovery) overcame the positive component (drawdown) quantified by the first part of equation. Le DL variations are approximate by the relation:

$$h(r,t) = -\frac{Q}{T} 0{,}183 \log\left[\frac{\log 2{,}25T}{Sr^2} + \log t\right] \tag{5}$$

The mathematic model has been validated by using some stops of -200 dewatering plant caused by blackouts or planned maintenance. In that cases the GW uplift has been observed at several mine shafts as a recovery test.

Fig. 8 shows the Dec. 12 1990 observed at P5 piezometer with in superposition the model isochronal data. Of particular importance the - 200 plant stop on Feb. 13-14 1991, when the discharge was put from 1.65 to 1.00 m^3/s. In this period the DL uplift. During this time interval the DL uplift has been monitored at 8 points of IMD. When the previous discharge rate has been restored, the basic hydrogeologic parameters of the aquifer (T, S) were calculated (Table 5) via equation (3). The first parameter is included within the interval value 2.5E-02 ÷ 4.8E-02. The calculated for the storage coefficient values are included in the interval 4.1E-03 ÷ 1.3E-02 (average 3.0E-03).

During the stop, a double dye tracer test was performer starting from the two extreme observation wells of the mine works (P5 e P10) where two different tracers were injected. The average velocity was monitored and the values of the hydraulic conductivity (K) were assessed (Table 5).

A list of surveyed data seems unnecessary. The gained results are here illustrated via graphic representations here: is possible to observe the good coincidence between the surveyed data and calculated ones (Figs. 9, 10, 11, 12). The correlation index is always included within 0.96 ÷ 0.99 interval.

A first important result gained by the model is the average time interval (hydrodynamic steady flow) within which the discharge variations effect from the centre of the basin (Monteponi dewatering plant) are observed at the periphery of IMD. This time interval is 20 d average on 6 ÷ 7 km distance.

A second result gained is the forecast of flooding times of the mining work levels.

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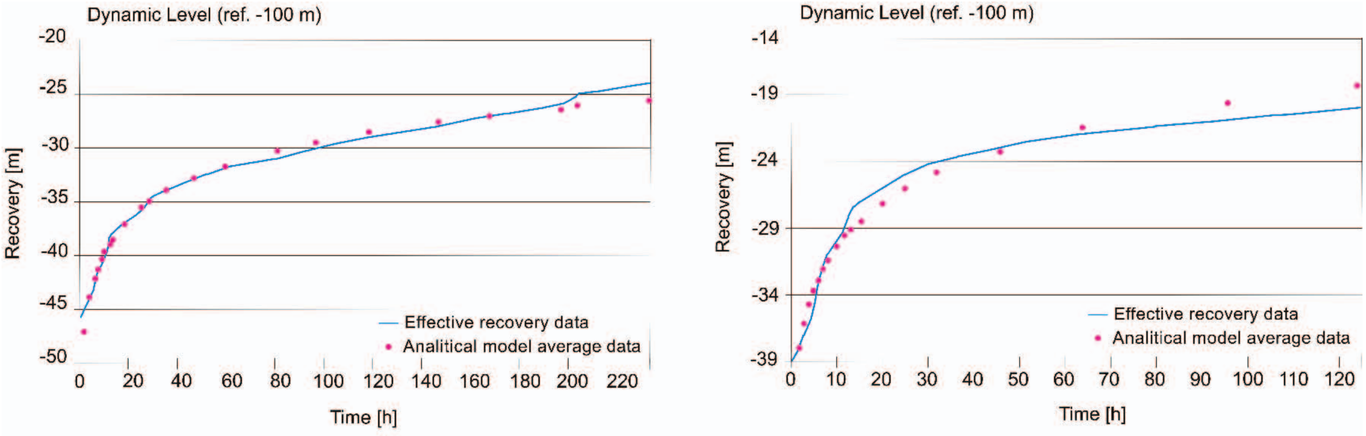

Fig. 8: *Left: DL uplift on Dec. 12 '90 at P5 (-93); Right: DL uplift on Jul.07 '90 at P3 (Monsignore)*

Tab. 5: *Hydrodynamic data from specific aquifer tests obtained using several stops of dewatering*

Monitoring Point	Test Type	Date	T (m^2/s)	K (m/s)	S
Monteponi P5	Marking (Li cloruro)	14/02/91		8,8E-03	---
Monteponi P5	Marking (K bicromato)	14/02/91		8,6E-03	---
Monteponi P2	Aquifer test '91	14/02/91	5,80E-02		1,8E-02
Monteponi P3	Aquifer test '91	14/02/91	5,04E-02		5,6E-02
Monteponi P4	Aquifer test '91	14/02/91	4,58E-02		1,2E-01
Monteponi P5	Aquifer test '91	14/02/91	3,04E-02		9,2E-02
Monteponi P7	Aquifer test '91	14/02/91	7,03E-01		9,8E-02
Monteponi P10	Aquifer test '91	14/02/91	2,11E-01		2,4E-02
Monteponi P4	Dewatering reactivation '48	01/07/48	4,70E-02		7,8E-02
Monteponi Tanas	Dewatering reactivation '48	01/07/48	6,30E-02		---
Campo Pisano P13	Dewatering reactivation '48	01/07/48	3,30E-02		---
Campo Pisano PA4	Aquifer test '95		7,48E-02		6,5E-02
San Marco P8	Dewatering reactivation '48	01/07/48	6.00E-01		---

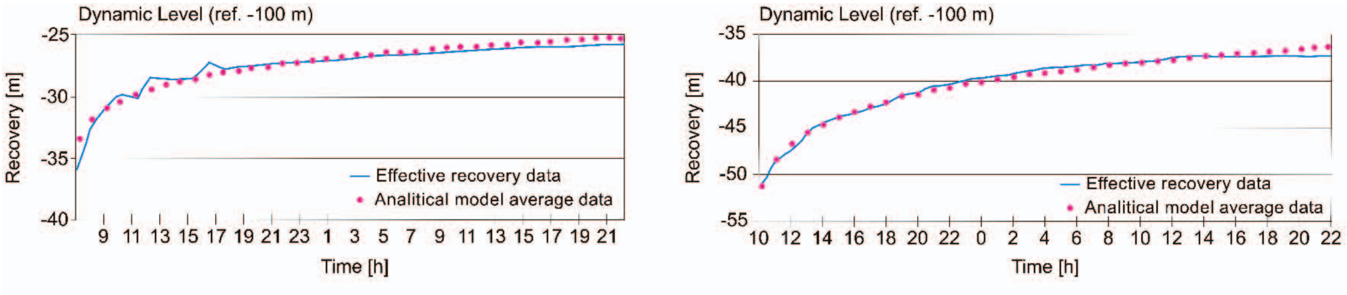

Fig. 9: *Left: DL uplift on Feb. 13 '91 at P2 (Sella); Right: DL uplift on Feb .13 '91 at P3 (Monsignore)*

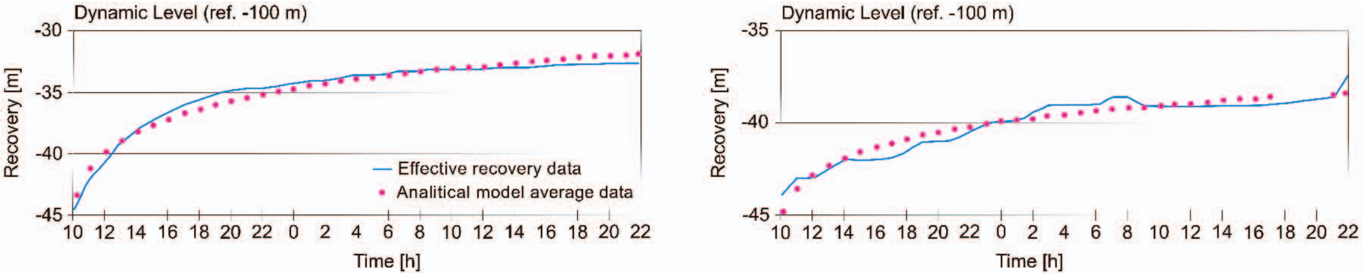

Fig. 10: *Left: DL uplift on Feb. 13 '91 at P4 (Meloni); Right: DL uplift on Feb .13 '91 at P3 (-93)*

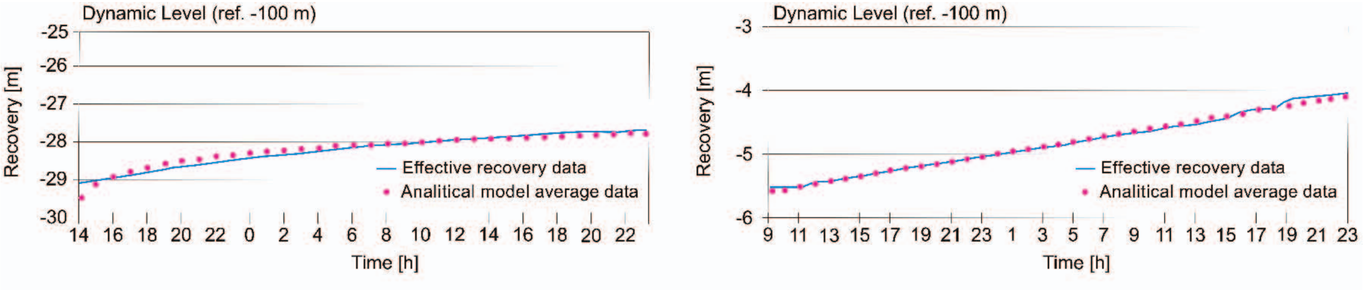

Fig. 11: *Left: DL uplift on Feb. 13 '91 at P4 (Albasini); Right: DL uplift on Feb .13 '91 at P10 (S. Marco)*

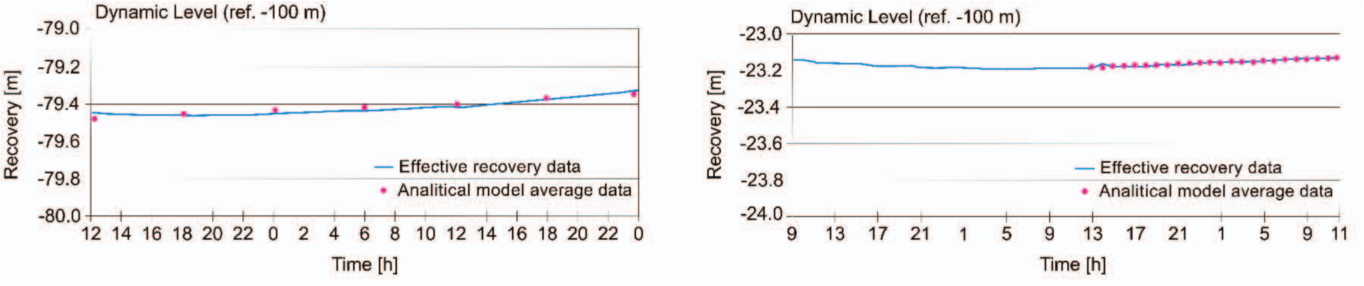

Fig. 12: *Left: DL uplift on Feb. 13 '91 at P14 (Nebida); Right: DL uplift on Feb . 13 '91 at P3 (Campo Pisano)*

Furthermore, the main forecasting study had to take into account a series of aspects too:

- effects on the underground mining structure's geotechnical stability;
- effects on the stability of surface structures;

The selection of the method to be used in outwork the – 200 pumping plant was made from a series of alternatives which, among other aspects, called for the setting up of a hydrogeologic and hydrogeochemical monitoring survey, articulated over multiple points of observation in the entire basin, in order to measure:

- changes in the physical-chemical characteristics of the water no longer pumped;
- dynamic piezometry of the uplifting groundwater.
- effects on the groundwater resources.

The main results of the study for the deactivation of the –200 plant envisaged the implementation of three stages:

1) In the first instance (January 1997), the values of the capacities pumped had to be halved (from 1.7 m^3/s to 0.85 m^3/s) and the construction of structures for the isolation of the mining pits had to be carried out, to ensure a controlled uplifting velocity of the dynamic level, and to guarantee safe access to the plant.

2) In the second stage it was necessary to wait for the dynamic level to reach the -100 m b.s.l. (July 1997), maintaining the reduced pumping rate (0.85 m^3/s), so that the residual mining works could be filled to the above-mentioned level. Should the need for intervention have arisen with the capacity rate having to be modified, accessibility to the plant was considered fundamental. Completely stopping the reduced pumping was subsequently envisaged once that level was reached in Monteponi, in order to allow, at full regime (in the long term), the *natural* outflow of the water through the drainage tunnel. Under these conditions, safe access to the plant was not deemed possible.

3) The third stage consisted of keeping up the installations of the waters' chemical and piezometric monitoring in the maximum deepness available in each mine work.

The purpose of this procedure's implementation was to avoid the formation of turbulence during filling of the residual drawdown cone, since the uplifting velocity would have been considerable. In fact, the strong turbulence could have caused the mud and filler material to be washed away from the empty spaces (mining and karst voids) resulting in their emptying: this was a condition to be absolutely avoided, both for the subsoil geotechnical stability and for the deterioration of the waters' physical-chemical characteristics. Furthermore the elevated uplifting velocity and the turbulence that it caused would have stirred-up the waters resulting in the loss of the qualitative characteristics that, over a period, had been created in the upper levels of the aquifer. In fact, the continued in-depth pumping, allowed a qualitative stratification of underground waters which, despite the increase in the pumped water's salinity, made it possible to carry on with the pumping of groundwater volumes from the higher level of the aquifer itself for civil purposes.

Observation of groundwater DL actual uplift

The analysis of the uplifting of the Iglesiente hydrogeological basin's dynamic level is conducted on the basis of data supplied by the *IGEA S.p.A.'s Groundwater Monitoring Service*, from 1996 onwards, carried out at several former mining sites. In these automatic and/or manual timed detecting sensors are positioned, suitably placed in selected mine shafts:

Campo Pisano - *Shafts 1 and 2*
Monteponi - *Vittorio shaft and T shaft*
San Marco site
Mount Agruxiau - *Vittoria shaft*
San Giovanni
Nebida *Santa - Margherita shaft*
Masua - *Calligaris shaft*
Scalittas - *GaribaDLi shaft*

Table 6 summarizes the essential data pertaining to the aquifer's dynamic level evolution according to the data collected between 1996 (dewatering system interruption) and 2004, by which time the uplifting had become asymptotic in all mines.

As can be observed from the values listed in the above-mentioned Table 6 and from the Fig. 13 diagrams, the uplifting of the piezometric level in the Campo Pisano site basically assumes a logarithmic type trend.

Through a more accurate analysis, at least two stages can be identified in the uplifting's trend:

The first extended during the pumping reduction stage from January to June 1997, in other words when a capacity of 0.85 m^3/s was pumped from Monteponi; during those months the *trend* was approximately of the exponential type.

The second developed after the pumping interruption (July 1997); the piezometric level continued to rise, but with an inverse curve compared to the previous and the inflection point's timing coinciding with the moment of the total interruption of pumping.

The rising of the groundwater deviates from the *trend* exclusively characterizing it between the end of 2002 and the beginning of 2003 when the pumping of 1.3 Mm^3 of groundwater for civil purposes from the Campo Pisano and Monteponi sites for the Municipality of Cagliari was carried out. This drawing of water resources generated a lowering of the groundwater's dynamic level, highlighted by the area's piezometric maps, to which followed the rising once the pumping itself had ceased.

In the same period, in Monteponi (Vittorio shaft and T shaft), the rising of the dynamic level shows a logarithmic trend similar to that of the Campo Pisano shaft. The rising, which was initially much more abrupt than in other shafts under observation, became approximately asymptotic.

In 2002, between the beginning and the end of the year, local piezometric lowered by 1 m, even though the relevant period can be more precisely subdivided into different time spans:

1) from the beginning of the year till the end of September 2002, the level rose by 1.1 m

2) from October 2002 to the end of January 2003, a drop in the piezometric level amounting to approx. 2.2 m was measured .

Pumping of underground water resources in 2002-2003 has therefore generated a drop in the groundwater's dynamic level, highlighted by the area's piezometric maps, followed by an uplift once the pumping itself ceased, so as to recover the logarithmic trend characteristic of the entire period of the analysis.

The San Marco shaft uplifting curve perfectly copies the trend of Campo Pisano. From 1998 until 2004 the piezometry maintains an unaltered logarithmic uplifting *trend*, from which it deviates markedly only on two occasions:

1) Between April and May 2001 the level rises faster than the characteristic trend, but already from June it returns to levels in line with the logarithmic trend.

2) Between the end of 2002 and the beginning of 2003 the modification induced by the Campo Pisano and Monteponi pumping can be detected, which can be detected in the lowering from 37.3 to 34.8 m a.s.l.

Also the curve relative to the Mount Agruxiau mine's Vittorio shaft (Fig. 13) presents a logarithmic trend common to the previous measuring points. Between the end of 2002 (November) and the beginning of 2003 (February) the level shows a drop as a result of the modification induced by the Campo Pisano and Monteponi pumping rates.

The monitoring of the San Giovanni mining shaft shows an uplifting that is not directly comparable with those described just above. An initial stage is evident until the end of 1997, during which the uplifting curve shows convexity in the upper part, and for almost all 1998 (until September) a turbulence can be detected, so that the piezometric level follows a trend that shows an approximate average increase with a velocity of 1 m per month. At the end of 1998 a considerable uplifting velocity is suddenly apparent, and in seven months the area's piezometry lifts on average in excess of 6.7 m per month (from –40.3 m b.s.l. to + 7 m a.s.l.). This anomalous behaviour constitutes sure proof of the subdivision in SERSEM of the IMD's hydro-structure: the S. Giovanni tank operates independently until the uplifting interconnects all the W SERSEM, adapting the lifting of the dynamic level according to a logarithmic trend. S. Giovanni shaft is therefore also impacted by the 2002-2003 pumping, decreasing from 37.3 to 34.8 m a.s.l. and subsequently returning to 37.4 m.

The measurements carried out in Nebida, from a purely qualitative viewpoint, faithfully copy the groundwater uplifting trend detected in the mine sites closest to the axis of the depression cone induced by the dewatering action. The trend of the uplifting curve is logarithmic, starting from levels which, historically, were already higher. Also in Nebida, the pumping from Monteponi and Campo Pisano generates a lowering from 47.2 m a.s.l. on 20/10/02 to 45.1 m a.s.l. on 1/2/03, to then rise up to 47.1 m a.s.l. on 1/5/03 and to resume the typical logarithmic trend with an actual rate of 0.16 m per month.

The data monitored in Masua mine start in March 1998 (DL = –10.6 m b.s.l.), therefore with over a year's delay compared with the other points of measurement. Nevertheless, from the observation of

Tab. 6: *Evolution of the aquifer's uplift in the IMD from 1996 to 2004*

Mine	Shaft	1996			1997			1998		
		ADL	AUV	ACC	ADL	AUV	ACC	ADL	AUV	ACC
Monteponi	**Vittorio &"T"**	-145.08	64.46	---	-80.62	61.92	848.97	-18.70	32.90	1746.29
Campo Pisano	**"1"& "2"**	-125.77	34.60	200.16	-91.17	71.47	254.54	-19.70	32.90	397.74
S. Marco	**S. Marco**	-105.00	22.30	---	-82.70	67.30	288.38	-15.40	29.50	454.84
Mt. Agruxiau	**Vittoria**	---	---	---	-50.30	35.10	1196.99	-15.20	30.01	648.09
S. Giovanni	**S. Giovanni**	-102.20	17.70	---	-84.50	44.30	3066.53	-40.20	51.60	5962.20
Nebida	**S. Margherita**	---	---	---	-34.10	33.60	368.39	-0.50	29.30	372.68
Masua	**Calligaris**	---	---	---	---	---	---	4.97	23.53	230.48
Scalittas	**GaribaDLi**	80.80	4.70	---	85.50	0.80	122.42	86.30	2.30	127.72

MINE	SHAFT	1999			2000			2001		
		ADL	AUV	ACC	ADL	AUV	ACC	ADL	AUV	ACC
Monteponi	**Vittorio &"T"**	14.20	12.90	1168.00	27.10	7.29	242.82	34.39	2.81	202.43
Campo Pisano	**"1"& "2"**	13.20	13.40	209.62	26.60	6.40	170.15	33.00	3.60	165.37
S. Marco	**S. Marco**	14.10	12.30	574.52	26.40	6.90	367.34	33.30	3.40	201.37
Mt. Agruxiau	**Vittoria**	14.81	11.59	1523.17	26.40	6.20	1958.13	32.60	2.50	853.91
S. Giovanni	**S. Giovanni**	11.40	14.60	1594.27	26.00	6.50	1070.11	32.50	4.10	800.36
Nebida	**S. Margherita**	28.80	10.30	409.97	39.10	5.30	416.83	44.40	2.30	411.27
Masua	**Calligaris**	28.50	3.83	296.20	32.33	9.07	256.64	41.40	0.00	230.46
Scalittas	**GaribaDLi**	88.60	-1.10	130.33	87.50	3.80	135.96	91.30	3.40	133.32

MINE	SHAFT	2002*			2003*			2004		
		ADL	AUV	ACC	ADL	AUV	ACC	ADL	AUV	ACC
Monteponi	**Vittorio &"T"**	37.20	0.20	181.56	37.40	1.78	193.24	39.18	---	195.72
Campo Pisano	**"1"& "2"**	36.60	0.20	156.20	36.80	2.90	153.66	39.70	---	156.01
S. Marco	**S. Marco**	36.70	1.00	193.24	37.70	1.40	161.33	39.10	---	106.37
Mt. Agruxiau	**Vittoria**	35.10	1.30	743.74	36.40	2.10	349.76	38.50	---	312.02
S. Giovanni	**S. Giovanni**	36.60	0.80	584.95	37.40	1.90	349.41	39.30	---	375.84
Nebida	**S. Margherita**	46.70	0.20	411.98	46.90	1.50	395.93	48.40	---	382.93
Masua	**Calligaris**	41.40	3.60	232.62	45.00	0.50	192.64	45.50	---	207.92
Scalittas	**GaribaDLi**	94.70	0.30	138.40	95.00	---	129.42	---	---	---

Abbreviation keys:

ADL = Average Dynamic Level (m a.s.l.); AUV = Average Uplift Velocity (m/y); ACC = Average Chlorine Content (mg/l)

* in the period from 18/10/2002 to 27/01/2003 altogether, approx. 1.3 Mm^3 were pumped from the Monteponi Sella, Monteponi T, Campo Pisano 1 shaft sites. Subsequently, in the two Monteponi sites the pumping was interrupted whereas it was continued in Campo Pisano (at least until 2004).

the levels recorded at this site we deduce that probably the uplifting takes place with an approximately logarithmic trend but with a "turbulent" water uplifting movement, proving a definite hydrostructural diversity of the synclinal, with E-W axis, which is actually a *tributary hydro-structure* of the IMD. The "turbulence" of this area's dynamic level reduces over a period, reaching an average uplifting rate of 0.15 m per month in 2004. The final level is 46.1 m a.s.l., considerably lower compared with Nebida (48.7 m a.s.l.).

The dynamic piezometry in Scalittas shaft (Fig. 13) shows a trend that is apparently unconnected to the *dewatering*. The hydrogeological complexity of the aquifer's SERSEM structure makes the course of the waters in this area particularly convoluted, so that the effect caused by the interruption of the Monteponi pumping is only visible in the long term and is identified by a slow and generally turbulent uplifting.

Discussion

The comparative piezometric analysis that can be highlighted on the basis of available data drawn from the former mining sites, shows that the recovery of the groundwater due to the cessation of mining activities (1995), which was then followed by the suspension of the pumping (1997), is characterised by a similar general trend. Actually, on the 1997 to 2004 timing scale, the recovery is on average logarithmic, i.e. initially rapid and then increasingly slower, even if the uplifting behaviour in Scalittas is decidedly different, since the groundwater level increases according to a broken linear trend.

Observing the curves (Fig. 13) more closely it can be noted how, in an increasing piezometric level order (from the most to the least depressed) in Campo Pisano (on average 15 m lower than in San Giovanni), San Marco (3 m lower than San Giovanni) and San Giovanni, the first recovery stage (from January to June 1997) is very sharp upwards, showing that the uplifting velocity of the free surface increases over a period while the relative part of drawdown cone was filled in . In July 1997 the curve of Campo Pisano and San Giovanni become sub-horizontal, whereas in San Marco, owing to the lack of data, it is impossible to evaluate any analogy; in Monteponi, instead, the groundwater recovers with an inclination trend practically constant for the whole of 1997, clearly (because of the pumping done in this mine) from a more depressed level than all the other sites.

As already mentioned, between June and August 1997, we can observe that in the Campo Pisano, San Marco and San Giovanni sites there is an inflection of the uplift curves, which trend perfectly correspond to the forecasting model: furthermore, the difference in height between the piezometric readings of these sites levels out in the first half of 1998.

At the beginning of 1998, San Giovanni deviates from the behaviour which characterises Campo Pisano, San Marco, Monte Agruxiau and Monteponi: in fact, the logarithmic trend (approx. 5 m per month) is replaced by a decidedly slower uplifting (approx. 1 m per month) which is characterised by an evident variability around an increasing average value.

This stage, probably due to the concomitance of several hydrogeo-

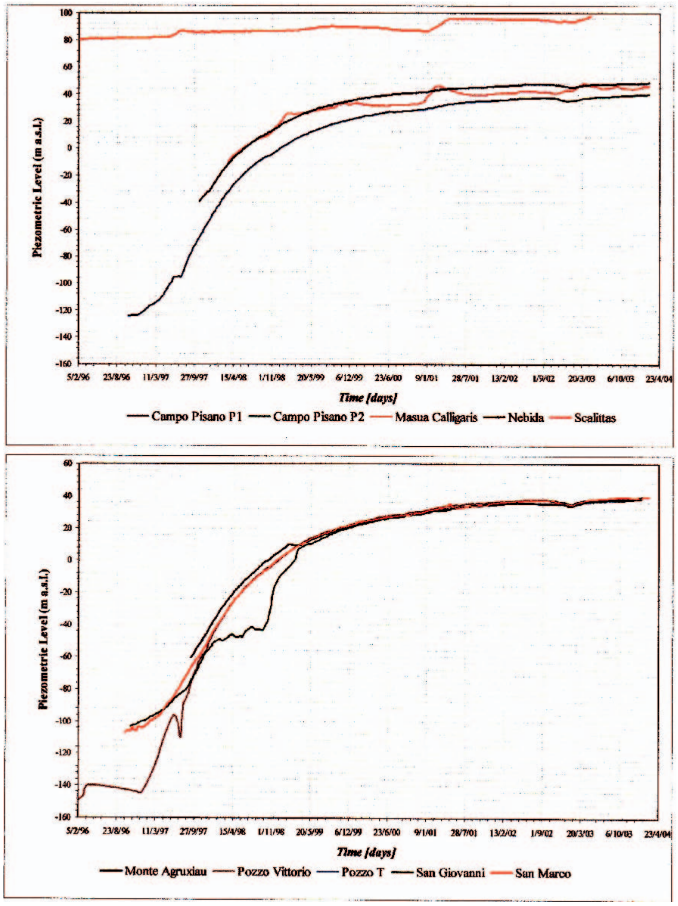

Fig. 13: *Recovery of the dynamic level in the various mines equipped with sensors.*

logical causes, linked to the singular permeability due to fracturing and karst between –40 m b.s.l. and the average sea level of the San Giovanni area, is probably to be associated with the large cavities left by the intense mining activity being intercepted by the groundwater in the area in question. This deduction would seem to be confirmed by the strong uplifting which was measured in the ensuing period, between October 1998 and March 1999 (i.e. when any large cavities were filled), which could be interpreted as an attempt by the groundwater itself to find an hydraulic balance; furthermore, the fact that this anomaly in the uplifting of the San Giovanni waters was not found anywhere else, could prove this hypothesis.

The observation holes of Mount Agruxiau and Nebida copy the recoveries of the three above-mentioned sites from 1998 (there is no data available for the previous period) even though at higher levels (5-10 m a.s.l. on Mount Agruxiau and in excess of 20 m a.s.l. in Nebida). The deviation between the Mount Agruxiau curve and those of the central area of the Iglesiente area basin is destined to be reduced and to be zeroed at the beginning of 1999; similarly, the difference in height compared with the Nebida site will be reduced in time, but the clearly greater height of the latter won't allow the zeroing of the difference between the two observation holes until 2004.

The Masua piezometric measurements indicate a behaviour that can less easily be interpreted through logarithmic curves model; in fact the recovery deviates from the cyclically inverse exponential trend, overshooting it on the upper side, generally during the winter period, and on the lower side during summer. Probably this is due to the low permeability of the area, which in winter, owing to rainfall, shows a faster uplifting compared with the average logarithmic trend. In the following summer this already changes into a drop in the level or in a growth trend which is practically nil. Besides, it is important to note how the Masua piezometry, from 1999 until 2004 (Figures 8 and 9), turns out to be constantly lower than that of Nebida, apart from some exceptions, in any case ascribable to the precipitation trend.

However, it is necessary to highlight how the frequency of available data (3 piezometric measurements per month from 1997) is insufficient for evaluating the timing and modality of "response" by the groundwater table to the interruption of the Monteponi centralised dewatering. Unfortunately, for this reason it is impossible to assess the different hydrodynamic connection between the various sites and the characteristic intrinsic "sensitivity" of each of these, compared with the others, to the "dewatering switch off " event.

Similarly, no valid deductions can be made as to the consequences of the pumping carried out by Campo Pisano and Monteponi between October 2002 and January 2003, always due to the insufficient number of measurements in the period.

Conclusions

After almost 5000 years of exploitation, mining have ceased to be the Sardinia and, in particular, MDI preponderant socio-economic resource. Nowadays, the main problem facing the south western area of Sardinia is the supplying of water for human, agricultural and industrial consumption. Here, rainfall is unevenly distributed through the hydrological year, but is increasingly concentrated within short periods, thus alternating long periods of serious drought with periods of heavy rainfall.

The uplifting of the level of underground waters in the MDI central area has reached the level of the Great Spring (Gran Sorgente - +6.5 m a.s.l.) at the end of 1998. If the drainage tunnel hadn't been closed off to allow higher uplifting levels, useful for its drawing, the balancing function of the inflows/outflows would have been reinstated.

The utilisation of the underground water resources of the Iglesiente mines has, for a long time, represented a topic for important discussions linked to the potential advantages/disadvantages of their use. In the past, the heavy metal content such as Pb, Zn, Hg and Cd, has excluded their global utilisation, despite the fact that in areas like Campo Pisano and Nebida, water was produced for human consumption, of a quality ranging from poor to mediocre, but made use of only through the Ministry of Health's derogation, within the limits of the law. Currently, starting from the completion of a rapidly constructed pipeline measuring about 20 km, in compliance with Ordnance no. 307 dated July 2002, issued by the Commissioner for water emergencies in Sardinia, approx. 0.3 m^3/s are drawn from the Monteponi and Campo Pisano shafts. The water is partly destined for Cagliari and partially for Carbonia, for a total volume of 1.3 Mm^3. It must be emphasised that this is a volume that exceeds the average annual recharging of the aquifer, which was originally calculated at 0.23 m^3/s.

As far as its use for irrigation is concerned, these same waters fall in class that is at the limit of acceptability, given the chlorides and dissolved solids content.

From the time of dismantling (1996) to date, prices for non-precious metals showed a trend which initially see-sawed until 2004. Subsequently they experienced a surge that more than tripled their value compared with 1996. On the London market (the London Metal Exchange), Pb reached 3.975 USD/ton to then stabilise on about

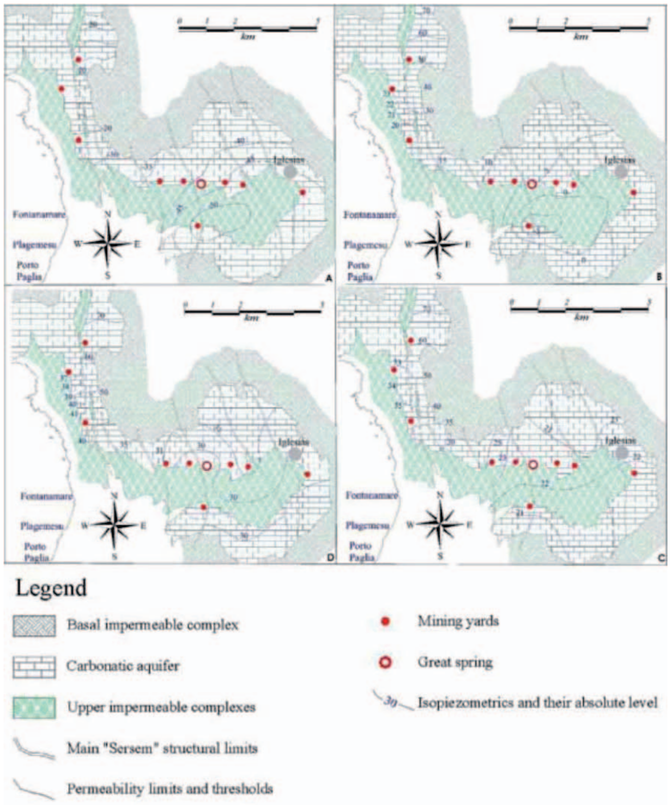

Fig. 14: *Changes in the aquifer's flow field over a period. A = 1997, B = 1998, C = 1999, D = 2000*

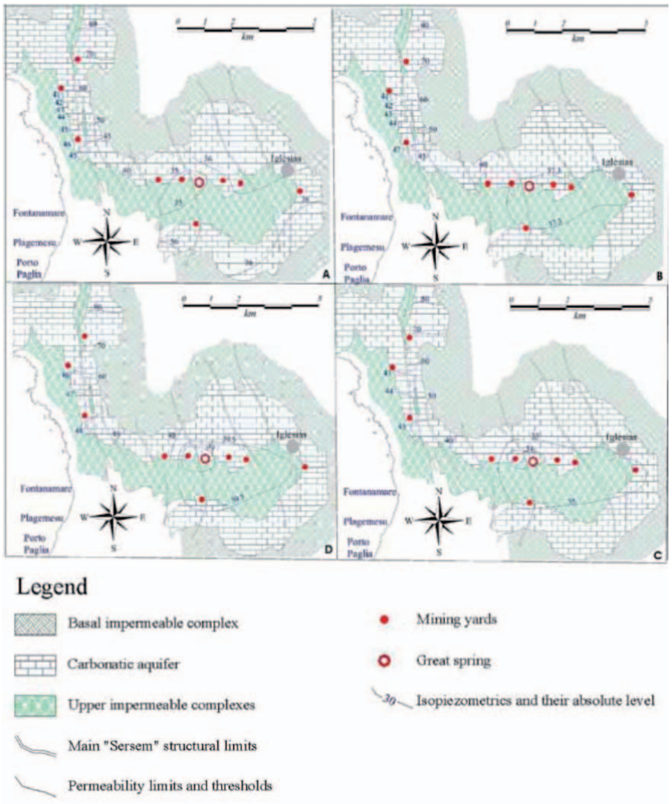

Fig. 15: *Changes in the aquifer's flow field over a period. A = 2001, B = 2002, C = 2003, D = 2004*

2.800 USD/ton. (Margiocco 2008 - Fig. 16).

According to ASSOMET, the Italian association of non-ferrous metal producers and re-cycling firms, *"Between 1976 and 1996, on yearly consumptions of 5 million tons of raw metal, the world demand for lead, in 7 years, i.e. in 2003, increased to 6 million, and in another two years to 7 and now is set at 8 million".*

Consumptions, which in the Western world are relatively stable at around 5 MTon/y, are increasing strongly in Asia, as proven by an ILZISG (International Lead and Zinc Study Group) research in Lisbon. Between January 2005 and 2008, the Reuters index (the non-precious metals prices index) has trebled: the price of lead (Pb) has increased by over 500 %, Zinc (Zn) by 150 %. The reasons for these increases are manifold but, basically, it is the constantly increasing need of raw materials by Asiatic economies, principally China and India, which is on a rise. According to the Berkley Capital, the mediumterm projections forecast an average Pb price of approx. 1.500 USD/ton, trebled since 2003. In the Western world, also mining production increases by 8.4 % thanks to the major producers (Australia, North America, Ireland). Nowadays, Italy only processes imported minerals for 34,000 ton (Margiocco 2008).

The DMI pumping plants (particularly those at -100 and -200) have been abandoned in a strictly conservative manner and could therefore be rapidly and economically reinstated. This could allow a return to mining in the area, by a prior and careful feasibility study which must take into account all socio-economic, technical, mining and hydrogeological aspects, together with the necessary estimates on the counter-value of the many still-to-be-mined minerals.

This study must take into account the manifold opportunities that resuming mining activities would bring about, apart from the intrinsic value of the minerals themselves. These opportunities, in a global planning context, consist in the following:

Utilisation of the water's temperature change for the generation of energy by means of constantly evolving, high-tech heat pumps available nowadays;

The energy generated could be used in a plant for the treatment of the water itself, at least within the scope of the water already in use today.

Utilisation of the mine cavities for storage of non-dangerous waste, with prior neutralising treatment having been done.Ending, the study herein presented, the authors hope it will be obviously usefulness for all the mine settings as that in Table 1 where now large dewatering plants works. But, what will occur in those zones when the dewatering will stop?

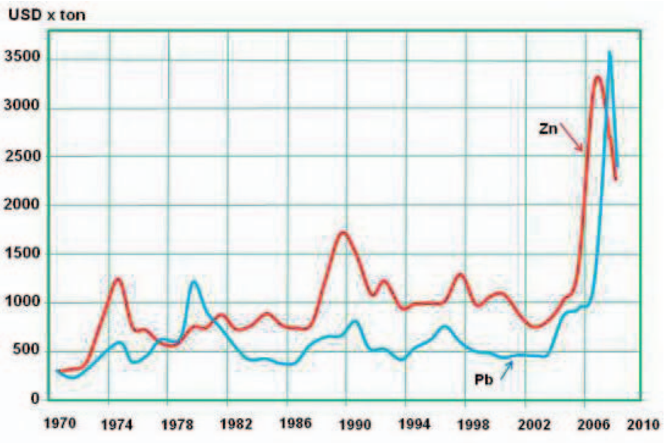

Fig. 16: *Lead and Zinc average prices. (Source: London Metal Exchange & ILZSG)*

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