Underground Mining Drainage. State of the Art

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ABSTRACT

The presence of groundwater in underground mining operations could produce very serious problems. Many of such problems are related with water inflow, sand-mud-water irruption, stability condition, subsidence, ... Groundwater increase the cost of mining operations, and dewatering can produce negative environmental impacts.

In such conditions it is necessary to establish the best technologies of mining drainage, from surface and/or underground, supporting any decision with the analysis of the best available technologies.

The authors presented the different technologies applied on mine drainage based on typical case histories. The discussion it is supported by its experiences and by the large bibliography produced by the International Mine Water Association through the papers published in its International Journal of Mine Water and on the Mine Water and the Environment as sources of the best available information.

The different methods employed and its efficiency are discussed on the framework of the hydrogeological behaviour and on the mine environments. A list of useful available references published in the IMWA journals is included.

INTRODUCTION

The water inflow in underground mining operations could produce very serious safety and economic problems. Some of this are related with:

- Miners security that can be affected requiring to implement special working cares to avoid serious injuries.
- Mining operations are delayed and the operating efficiency reduced with loss of time required by dewatering operations.
- Some explosives are de-sensitised in wet blast holes and special water proof packing or water resistant explosives are needed with consequent increases in blasting costs.

- Mining costs are increased due to the continual interruptions required to grouting or to implement specific installations to drainage the mining faces and to handling the water in-rushes.
- Maintenance costs rise with especial equipment required for the wet conditions, pumps, water transport channels or pipes required, and with the necessity to maintain operative such installations.
- High moisture content results in increased unit weight of material to be excavated and transported increasing costs.

In countries as Spain with very old mining tradition and very different geological conditions all hydrogeological problems exits (Fernández Rubio, 1986). Analyzing the water problems in a total of 59 Spanish coalfields we distinguish different categories of underground mines from an hydrological point of view:

- Mines with no water problems.
- Mountain mines with only seasonal flow-rates.
- Mountain mines intercepting perched aquifers in the unsaturated zone.
- Mines below piezometric table (with different subgroup).
  - Mines with rising inflows.
  - Recovery of flooded abandoned mines.

Three categories of inundations were established by Singh (1986). The first two types are mining induced inundation, whilst the third is a natural phenomenon:

- Event Controlled Inundation associated with caved mine workings below either a confined aquifer or surface bodies of water where the inflow is followed by main and periodic roof falls in the roof strata. The inflow rate of the water is suddenly increased from the background level to a peak rate within a short time and is then reduced exponentially to the background level over a period of time.
- Spontaneous Inrushes are a natural phenomenon associated with mining in the vicinity of karst aquifers.
- Accidental Inundation, due to working in the vicinity of large bodies of water such as lakes, ocean, large pool of water in an upper seam or water flooding the adjacent old workings.

Analyzing the last category during the period between 1851 and 1970 in the British collieries Job (1987, in Vutukuri and Singh, 1995) founded that the greatest risk was from abandoned flooded workings (16 again a total of 208 inrushes).

Such water inflow can cause more than flooding and production reduction: the loss of human life. 1026 people died in United Kingdom, USA and India mines between 1815 and 1985 as a result of water inundation accidents (Moebs and Sames, 1989, and Duckham, 1973, in Vutukuri and Singh, 1995). 235 Japanese coal miners lost their lives in 1915 when sea water broke through along a fault into the mine workings (Mohr, 1965 in Straskraba, 1984). 40 miners killed at Reding, Great Britain, in 1923 when water from an abandoned sump, not shown in maps, entered into the mine (Nelson, 1948 in Straskraba, 1984). 551 miners loose their life in water inflows in India related with rain, surface water and old workings flow during the period between 1954 and 1983, detaching the Chasnalla mine disaster in 1975 with 375 miners died (Singh and Singh, 1985). 14 miners killed by inrush of water from old workings at Ribolla colliery in Grosseto, Italy (Sammarco, 1986)...

Where the mining excavation is located below the groundwater table the amount of water that could appear at different depths depend on the hydrogeological and geomorphological conditions of the affected mined area. For example, in the coal mining district of Dorog (Hungary), 409 water inrushes have taken place since the beginning of the century, 95% out of which have been caused by flow through faults within the protective barriers (Schmeider, 1978, in Singh, 1986).

The underground mining may provoke changes on in-situ permeability and on underground and surface flow pattern (Singh and Atkins, 1983; Aston and Singh, 1983). The mining subsidence and sink holes, inside the called angle of draw, causes the increasing of both the amount of water inundation and the possibility of mine water and mud invasion (Yu, 1994). In this condition substantial costs were incurred at many mining projects for stream relocation, impermeabilization, and increased pumping of water from the mines. In order to reduce the subsidence and collapse problems the backfilling methods are employed with success. We know very good conducted applications in Neves Corvo Mine (Portugal) and in Reocín Mine (Spain), and also interested applications can be read on Straskraba and Abel (1993). The backfilling reduces ground movements in the rock overlying and adjacent to mine openings, and decreasing the number and size of fracture-controlled hydraulic flow paths into the mine. Straskraba and Abel (1993) present an very complete summary of this technologies, its advantages and the gained experience. With the introduction of backfill mining method the requirements for mine dewatering are reduced, however when hydraulic backfill is employ it is necessary to pump in addition the drain excess water.

The extension of the cone of depression provoked by the mine drainage is a function of many factors as depression required, hydrogeological behaviour, precipitation and infiltration rate, dewatering time, ...

Where the deposit itself is underlain by an aquifer under pressure then water may flood the mine due to either floor heave or to piping. Faults and tension cracks are often the ways that provide the hydraulic inter-connection. Such was the problems on the Berga coal mine (Barcelona, Spain), that finally obliged to abandon the mine.

Surface investigation boreholes can provide communication between aquifers and mine opening. In some mines large water inflows are provided through such old unsealed investigation boreholes. In Reocín Mine (Cantabria, Spain) water arrives from overlying aquifer crossed by the investigation holes and also from deep underlying confined aquifer reached by boreholes. Where this possibility exist it is desirable to seal the boreholes after drilling, with cement, clay or other impermeable material, unless a protected pipe piezometer is to be installed for monitoring purposes.

Frequently the ore body to be mined is an aquifer itself and require continuous dewatering operations. As an example, during the financial year 1992/93 the Zambian Consolidated Copper Mines Ltd pumped a total of 263 million cubic meters of water from its various mines operations (Naish, 1993). In other cases the mine is more or less isolated with relation to the aquifers by protective layers.

The amount of groundwater flow depends on many factors. Amongst them the most important include precipitation, morphology of the area, rocks permeability, formations water bearing potential... Also some anthropogenic aspect can determine the yield of water inflow, between this we can emphasise the mining method employed and the blasting that contribute to increase the rock permeability creating tension cracks.

Special research would be conducted to establish the different sources and rates of water inflows into the mine (Mulenga, et al., 1992). Water chemistry, temperature, isotopic and biological contents, tracers, and many other techniques can be employed in such investigations.

Frequently there is a direct relation between the amount of water inflow and the rainfall conditions, specially when the groundwater is encountered below very few meters but also in other places where it is encountered at some hundreds meters. Frequently the largest water inflows correspond with the areas of higher rainfall (Yu, 1988).

In cases of heterogeneous aquifers or when the aquifers themselves are compartmented by impervious dikes (as diabases) high water inflows can follow blasting operations.

The range of water problems change in a very large scale. For example, Gazizov (1983) summarise the data provided by 2600 coal faces inspected in 1979 in the former USSR, giving the following distribution of water inflows:

- 82 % small inflows (less than 5 m^3/hour);
- 10 % medium inflows (5-10 m^3/hour);
- 3-4 % heavy inflows (10-15 m^3/hour);
- 4-5 % very heavy inflows (over 15 m^3/hour).

The dangers of inrush of water must be eliminated or reduced by preplanning, based on systematic hydrogeological investigation and control measures (Atkinson and Dow, 1983).

In countries with very old mining history the abandoned workings may have existed for hundreds of year. Special care is necessary where abandoned mining flooded workings exist. Plans for such early workings are obviously non-existent and only a very rough estimation of the volume of water retained within them can be made. In such condition the ineffective barrier between unknown or known waterlogged and active workings can provoke the roof collapse and suddenly water irruption. To avoid such risk it is required to conduct in advance investigation and drainage works and to increase the mining pumping capacity. Under these condition an other complementary risk is the inflow of backfilled material. Similar possibilities exist under karstic condition with the risk of mud filled cavities.

Special water inflow risk appears mining below surface stored water accumulations such as sea, lakes, estuaries, rivers, streams, ponds, dams (Loveday, et al., 1983, Singh and Atkins, 1983, Sivakumar, et al. 1994, Vutukuri and Singh, 1995). However, in longwall coal mines in the United Kingdom, routine chemical analysis of mine water have indicated that water reaching undersea workings originated in aquifer strata rather than the sea itself (Whittaker and Aston, 1982, and Waston, 1979, in Singh, et al., 1986).

In New South Wales there are a number of examples whereby dams and reservoirs are underlain by coal seams of economic importance. In this conditions there are a number of hazards that are possible in the extraction of minerals from beneath stored water or the retaining structures (Loveday, et al., 1983):

- Dam structures.
  - Minor distortion - cracking and increased seepage.
  - Major distortion - rupture, failure, loss of life and property.
- Stored water.
  - Minor leakage - loss of safe yield.
  - Major leakage - total loss of supply.
- Mining operations.
  - Minor leakage - requires installation and operation of pumps.
  - Major leakage - loss of life, equipment and possibly the mine.

Together with this there are a loss of coal reserves due to the establish protection barriers (Sivakumar el al., 1994).

In such conditions and in order to regulate the potential hazards the New South Wales Government produced a very interesting "Dam Safety Act" (1978), after the experience gained applying the mining limitations set down by the Reynolds Inquire (in Loveday, et al., 1983), later change in 1960's (Sivakumar, et al., 1994) *(figure 1)*. Any proposed mining activity within the restricted zones needs to be submitted to the Dam Safety Committee for assessment. In the Bulli Colliery bellow the restricted zone of the Cataract Reservoir *(figure 2)* one of us (RFR) was requested to provide monitoring programme to predict or to identify any possible subsidence effect out of the expected limits. In such cases an under-estimated of the water risk can lead to serious inrushes.

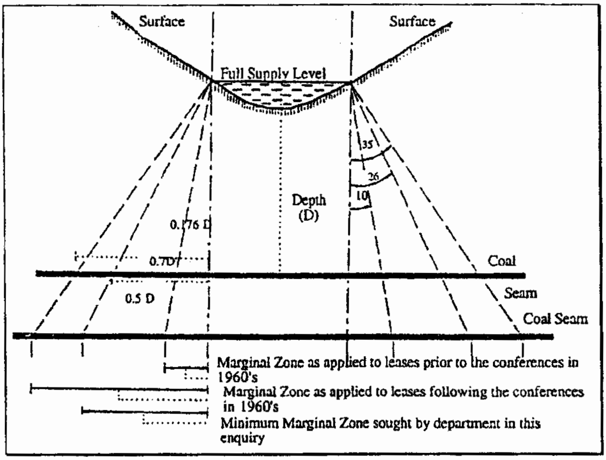

Figure 1. Effect of draw angle on the width of marginal zone (Loveday, et al., 1983).

From an environmental point of view the main consequences of mining dewatering are related with (Atkinson and Dow, 1983):

- Severe changes to the groundwater regime.
- Subsidence due to ground water extraction.
- Surface water drainage regime changes.
- Discharge of contaminated mine water.
- Erosion and sedimentation problems.

As past experience can provide accurate prediction of mine water inflow, the analysis of typical case histories is a good approach to evaluate the efficiency of each drainage method.

DEWATERING SYSTEMS

There is no universal methods for creating dry mining conditions. Several procedures can be used to dewatering the underground mining affected area reducing the water adverse effects. The methods include the surface exclusion of water, interception and drainage of water, dewatering drilling, grouting operations, ... The grouting methods can be described by reference to the mechanisms by which the groundwater flows are eliminated or reduced (Daw and Pollard, 1986):

permeation grouting, hydrofracture grouting, squeeze grouting, void-filling grouting and combined techniques.

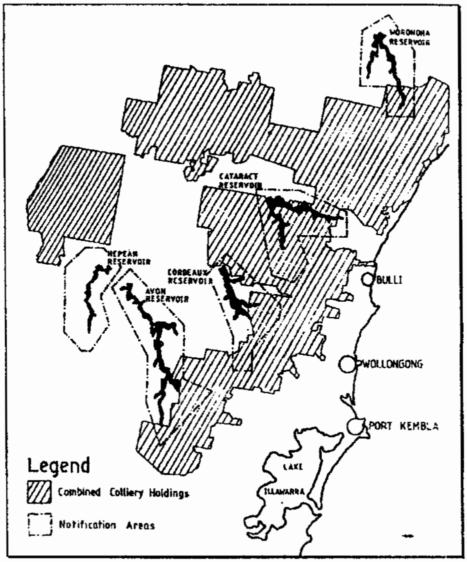

Figure 2. Restricted zone of the cataract reservoir.

The surface water exclusion or diversion includes the use of canals and pipelines to carry water over hydrological hazard zones, construction of herringbone ditches to speed up run-off, lined the river bed to avoid the surface water lost, judicious geological sitting of tailings dams and other surface water structures (Naish, 1993).

In any case advantage has to be taken of natural conditions, e.g. impervious layers, that could provide protection or reduction of water inflow (Atkinson and Dow, 1983).

If we are to apply any drainage methods an evaluation could be made of the cost of drainage versus the security provided and the economical benefit. The severity of the groundwater problem together with the environmental impact can determine the more appropriate method.

Some of the factors that define the selection of the dewatering system are the following (Morton and Mekerk, 1993):

- Hydrogeological conditions.
- Length of time dewatering is required.
- Volume of water to be removed.
- Whether drainage equipment can be installed in the operational area.
- Availability of dewatering equipment.
- Mine and/or contractor experience.

However the design of a dewatering system require a multi disciplinary approach, based on the following information (Morton and Mekerk, 1993):

- Dimensions of the area to be dewatered.
- Depth to which the water levels must be lowered.
- Whether the installation will be permanent or temporary.
- Quality of the water that has to be removed.
- Plans for disposal of the water removed.

We can classified as passive methods the gravity drainage on the working faces in shafts, ramps and galleries and as active methods the surface or underground in advance dewatering.

If large amount of water are to be pumped off-site then the natural watercourses occurring downstream of the mine may require widening, regarding and often diverting around the mining area itself (Norton, 1982). The hydrology of those streams and rivers will need to be fully investigated and monitored in order to avoid the re-infiltration of the drainage water. In some case the adopted solution was to concrete with impermeable lining the bed of the watercourse. Such solution was adopted with a great success on the Oeiras river over Neves Corvo complex sulphur mine (Portugal) avoiding the direct run-off infiltraticn (Fernández Rubio, et al., 1988; Fernández Rubio and Carvalho, 1993).

The diverted water require to cover the constraints and regulation related with surface mine water discharge quality standards. The employ of in advance dewatering techniques reduce the possibility of water quality affection. However this aspect is not a subject of this paper.

Drainage adits and tunnels

When the topography is suitable, adits may be driven as a self-draining level to dewater a mine or a group of mines (Vutukuri and Singh, 1993).

Such adit can be excavated on or under the ore body, as a drainage gallery from which collected water is disposed to the surface.

Such drainage system can be a very effective means of dewatering because of the high surface exposed for drainage.

In very heterogeneous rocks and in order to reduce the drainage uncertainty it is very important the position of such adits to intercept the faults and fractures water drainage systems. The hydrogeological heterogeneity of the host rocks was the problem of the low efficiency on the several kilometre drainage tunnel excavated on the La Carolina - Linares (Spain) lead district, on granite and metamorphic as country rocks.

However many drainage tunnels have been made in mining fields all over the world. Vutukuri and Singh (1993) describe the Graton tunnel in Casapalca copper-lead-zinc-silver mine in Peru. Two parallel tunnels one for haulage and one for drainage, totalling over 22,4 km in length was perforated. The project took some 10 years to complete. The highest inflow rate during construction was 11217 l/sec.

To increase the effectiveness of this drainage gallery, holes can be drilled on a fan or radiate pattern outward from the adit to increase the drainage diameter (Browner, 1982). Such holes can be drilled at the end of the gallery, or in intermediate places.

Other option is the gallery intersection of surface or underground holes. Using a down-the-hole survey instrument, it is possible to pinpoint the position of such boreholes along their length. On the negative side unplanned intersections of surface boreholes could cause operations problems.

As this drainage methods are initially expensive, a careful consideration of costs and benefits is required.

Surface vertical drainage wells

Where very heavy seepage is expected, pumping through down-the-hole hole on a deep wells system located in advance of the mining area can be the most practical and economical dewatering method. The large diameter wells locations are established according to mine planning requirements so that they can operate both prior and throughout the life of the mine.

Facilities of this type have been installed in many mines, in some case with hundreds of deep wells (Oruc, et al., 1993), and in excess of several hundreds meters deep. However the deep of the wells has a limitation related with the drilling cost, required diameter, pumping capacity, possibility of ground induced subsidence, ...

The design of vertical drainage wells for underground mines dewatering should always be preceded by an hydrogeological investigation supporting the knowledge of the groundwater behaviour of the different existing materials. If there are not enough available experience at the site, a moderately detailed field permeability testing program could be convenient.

The methods most commonly used to measure in situ permeability are the "pumping out" and the "pumping in" tests (Aston, et al., 1983); each one has its relative advantages and disadvantages depending upon the type of test strata. Also the first one require a vertical hole to install a submersible pump, and a sufficient diameter to allow the insertion of a pump and stable enough to prevent subsequent damage. The pumping in is an alternative mainly employed when the formations have either insufficient yield to pumping out or a low permeability; also this test is not restricted to vertical holes and does not require a large diameter to introduce the pump; however certain inherent problems do exist.

The pump wells construction technology (direct or reverse circulation drilling) and installation design depends upon the following interactive factors (Atkinson and Dow, 1983; Oruc, et al., 1993):

- Well location (temporary or permanent).
- Rock type (hardness, consolidation, cementation, ...).
- Depth and diameter required.
- Thickness of the pervious and "impervious" horizons.
- Sand particle size distribution on unconsolidated formations.
- Optimum pumping rate for groundwater control.
- Number of wells required in each location (single-well or multi-wells).
- Water quality/well screen corrosion factors.

Well diameter and depth must be decided from site conditions. Usually well diameter range from 0.30 m to 0.60 m, however diameter larger than 1 m are employed in some not consolidated formations. For the large diameter wells on middle hard formations reverse circulation drilling is more convenient. For hard rocks and for wells of less than 0.30 m diameter standard rotary methods are used. Depths can be higher than 500 to 700 m. A good discussion about constructional characteristics and features can be reed on Oruc, et al. (1993).

Drilling mud and fine sediments can seal and block the porous and channels through which water would flow (mainly in direct circulation drilling with bentonite mud fluid). To re-establish and to increase the permeability conditions around the well developments methods are commonly used. Amongst then the more frequent are:

- Surge plunger.
- Compressed air backwashing.
- Air lift pumping.
- Intermittent hight yield pumping.

Surge development using clay dispersants (as poliphosphates) or acid injection (hydrochloric acid with some additives) may improve significantly the well yield.

It is often difficult to accurately predict pumping rates required to drawn down the water table in advance of excavation. On behalf of pumping tests it is possible to establish the required pumping capacity, however the design of the dewatering systems using pump wells should not be based on single pump tests. Large-scale multi pump tests have to be carefully planned if they are to be successfully conducted to provide reliable measurements.

During the pumping tests it is very important to control flow-rate, water temperature and chemistry, water head as well as rainfall (Fernández Rubio, et al., 1983).

The duration of the test depends upon local condition. A single submersible pump test requires 2 or 3 days. A major multi-pump test should be continued for between 10 days and one month, including several control techniques as radioactive and chemical tracers, temperature profiling, hydrochemical information and conventional dynamic water mapping, based on piezometric observations. Both of then require measurements of the recovery of water levels. More details related to pumping rate, test duration and test arrangements can be found in Atkinson and Dow (1983).

Nowadays the availability of computer programmes provide the best tool to analyse the collected data. *Figure 3* (Atkinson and Dow) illustrates the typical procedure for the design of a pump well system.

It is an obvious fact, but sometimes overlooked, that the pumping rate must be compatible with the excavation rate. Too much pumping too early will merely waste money. However if the converse of too little pumping too late or if the wrong location of wells the following problems may arise increasing the costs (Norton, 1982):

- Possibility of dangerous water inrushes resulting in loss of production.
- Flooded excavations requiring expensive pumping in the working area.
- Increased blasting costs because of wet boreholes.
- Increased water quality impact due to the aggressive environment of the mining workings area.
- Increased moisture contents in the mineral and excavated rocks giving rise to handling problems in the transport system and preparation plant.

In any case the pumping system must be designed with reasonable over capacity so that if one pumping unit becomes inoperative there is sufficient excess capacity to prevent the development of local areas of hight water pressure.

It is useful to carry out the pumping wells in progressive stages to verify that it is enough to decrease the water table. The total drawn down corresponds to the incremental sum of the drawn downs provoked separately for each pumping well, according with to "principle of superposition" or interference effect (*figure 4*, in Atkinson and Dow). The effect of negative or positive barriers is often very important looking the water table depression. Pumping test can provide a good information about the occurrence of such barriers (Fernández Rubio, et al., 1983).

Once sufficient drawn down has been achieved, the pumping rate can revert to a capacity corresponding to the natural balance recharge conditions (Norton, 1982).

The cost of drilling, piping, maintenance and energy for the power to run the pumps can have a considerable effect on the financial success (Norton, 1982).

Where large numbers of pumps are in service, especially in remotely-located mines specialised pump maintenance is needed.

Often the wells drainage provoke a significant drawndown of the water table over large areas, producing significant changes on the natural regional hydrologic balance, that can oblige to modify the land usage.

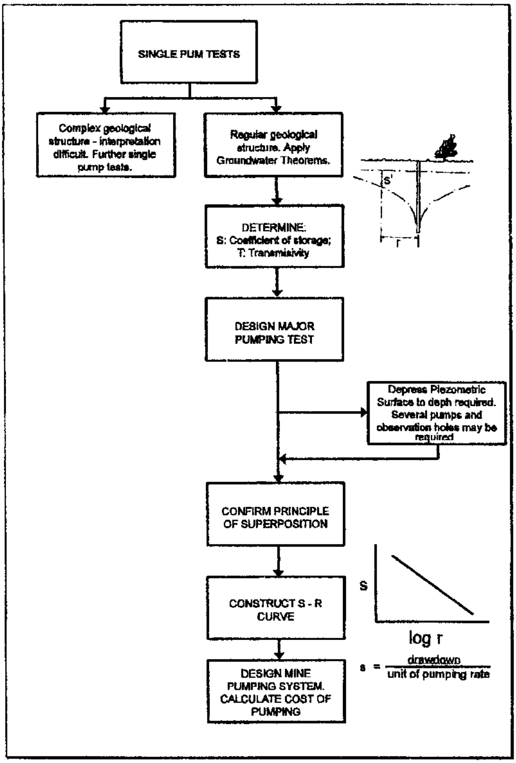

Figure 3. Pumping system design procedure (Atkinson and Dow, 1983).

In advance face drainage

In deep mines, when the ore body to be mined is an aquifer itself, an usual dewatering systems is through drain drives located on relatively low permeability strata with periodic dewatering crosscuts along the drives to intersect the aquifer and/or to provide diamond drilling access to the aquifers (Chileshe and Kulkarni, 1992). Underground dewatering boreholes is the most widely used method of dewatering on the Zambian Copper Belt (Naish, 1993) and in many other places.

The breakthrough methods (Naish, 1993) involves the mining o drives and crosscuts into the aquifers behind the protection of a water tight door or a "puddle pipe" installed in the drive or crosscut behind advanced. The water-tight door is normally accompanied by the provision of two 300 mm or one 600 mm pipes at drain-level, fitted with high pressure valves to permit sealing or drainage with the door closed. The water-tight doors will be designed to support the foreseeable water pressure. We designed the large water-tight door of Vazante mine (Minas Gerais, Brazil) useful for truck, heavy machinery and belt conveyors, which was proved in situ under a 300 m water pressure.

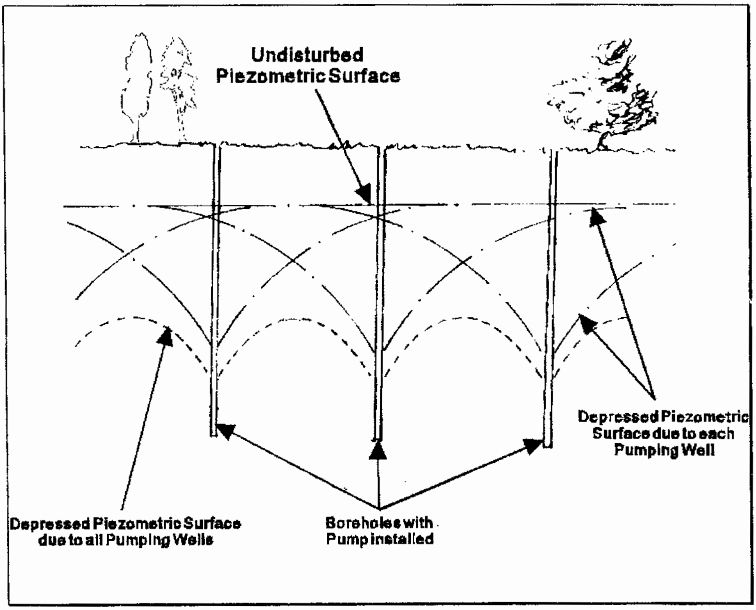

Figure 4. The principle of superposition (Atkinson and Dow, 1983).

The inflow of ground water in mine faces and specially at the extremities of the mining areas, can be fought by gravity drainage through the drive or with the help of portable pumps timely removed before the explosives detonation.

Such equipment require to pump an important amount of suspended solids, and usually plastic flexible pipes are required to facilitate the temporary removal from the face till a safe distance or protected place against rocks projection.

The water inflow quantity to the mine workings is controlled by the hydrogeology of the rock surrounding the mining excavation, aquifer characteristics, groundwater level, precipitation and surface water infiltration, mining methods and geometry and mining depths (Bridgwood, et al., 1983).

There are different modes of water inflow evolution (Bridgwood, et al., 1983; Fernández Rubio and Lorca Fernández, 1993):

- Constant rate of inflow over a long period.
- Occasional large inflow to a mine from a relative finite source of water.
- Gradually water inflow increasing.
- Gradually water inflow decreasing.

In general, the first one corresponds to a seepage under equilibrium condition, related with a constant source of water (e.g. river or lake).

The occasional large water inflow is characterised by a high initial stage, during which the rate of water inflow increases rapidly until a peak flow rate is observed. Following this, the flow gradually decreases till a normal flow rate consistent with the water recharge. This type is normally observed in karst condition or when natural or induced mining fractures connected with a water body are intercepted. This type of flow is also observed when a protective layer is crossed or/and an old flooded working is partially or totally connected. *Figure 5* shows the variation of pumping rates over a 6 years period to de-water a karst compartment in West Driefontein mine, South Africa (Wolmarans, et al, 1978).

The gradually water inflow increase is usually related with to the extension in size and depths of the mining working.

The last category is frequent when a confined groundwater system is intercepted by the mining workings.

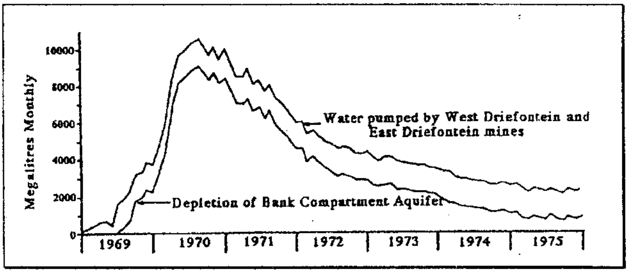

Figure 5. Progress made in depleting the aquifer in Driefontein mines (Wolmarans et al, 1978).

Underground inclined or sub-horizontal dewatering holes

Water occurrences during tunnels and galleries construction are frequently related with the holes drilled for rock bolts either on the roof or on the walls.

Frequently in face holes they are also employed to grout fissures in galleries or tunnels, in order to reduce the amount of water inflow (Akesson, 1983). When the fissures are sub-parallel to the drift the grouting results are often bad *(figure 6a)*; when the fissures are perpendicular to the grift the grouting sealing results are often good *(figure 6b)*.

On the other side and taking into account the difficulties to intercept vertical faults and fractures aquifer structures on behalf of vertical surface wells, the underground inclined or sub-horizontal drainage holes gained in interest (McKee and Hannon, 1985). Such holes are specially interested to drain the tension cracks (Akesson, 1983).

In this sense to reduce the underground water head surrounding the mining area one useful technique is through the installation of such horizontal or inclined diamond-drill holes, 50 to 80 cm in diameter drilled from the front or sidewalls of the galleries as mine development advances. In order to reduce drilling time and cost it is usual to fan several holes (3 to 5) from one drill location. Such drains are installed till a length up to 250 m (Browner, 1982) or even 300 to 400 m in Konkola mine (Chileshe and Kulkarni, 1992). Groundwater flow into the drain holes de-pressurating the aquifer and lowering its hydrostatic head.

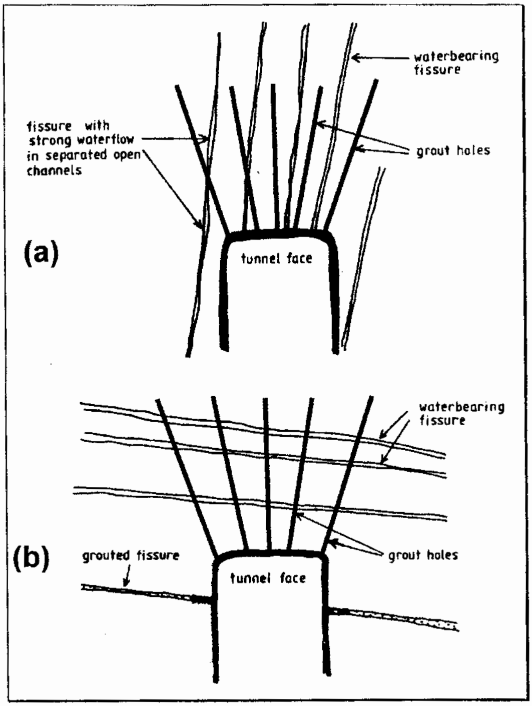

Figure 6. Grouting fisures in galleries (Akesson, 1983).

The technique was improved to permit installation of valves drains in areas of high pressure (more than 7 Mpa) and flows upper 65 l/s (McKee and Hannon, 1985). According to our personal experience in some underground mines highest pressure and yield was obtained (for example at Konkola mine, Zambia, and Vazante mine, Minas Gerais, Brazil). The technique requires frequently to drill a relatively long diameter hole (150 mm), some 5 to 10 m using a longhole machine. A flanged collared pipe (127 mm) is then inserted into the hole rockbolted, preco-plugged in place and injected by cement. A 100 mm diameter hole is then drilled inside. A flanged valve is then attached to the insert by one bolt, the valve opened and rotated through the water stream into position and firmly bolted in place *(figure 7)* (McKee and Hannon, 1985).

When it is necessary to prevent the risk of caving arriving to incompetent aquifer zones special cautions it is necessary to adopt. In Konkola Division the Ogram Method is employed (Naish, 1993). The borehole is drilled by conventional diamond drilling at NXC size until it just intersects the incompetent "sandy fissure" zone. Slotted casing with a casing shoe is then inserted into the hole, to the base of fissure zone, and kept free by constant turning. The diamond drilling machine is then swung off the hole and a bar mounted drifter equipped with cruciform m rock bit put in its place. Using the rock bit the hole is advanced, with the slotted casing being spun in behind the rock bit. The casing shoe effectively reams out the hole, to accommodate the casing. Once the rock bit intersects the competent strata, it is drilled approximately 1 metre into the competent rock, to give a firm foundation for the following casing. The casing is then pushed to the end of the hole. The casing prevents caving from blocking the hole and the slotting allows the passage of water. Other systems are employed on Rio Narcea Gold Mines and on Andorra Coal Mines, both of then in Spain.

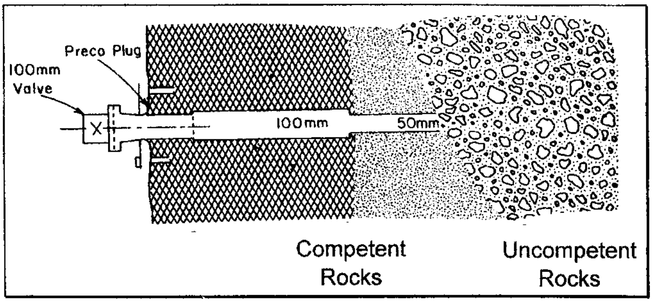

Figure 7. Underground dewatering well set-up (McKee and Hannon, 1985).

Such drains hole can be equipped with stopcock or gate valves providing the possibility to control the amount of water drained and, if necessary, to stop temporary or definitively the water outflow especially in the event of power or pump failure.

The intersection of surface exploration holes has also provided an excellent method for underground drainage, mainly when such possibility was take into account during the drilling operation to avoid the uncontrolled water flow.

The drained water can be collected throughout pipes in order to avoid the affection in its quality flowing directly on the gallery. These pipes require adequate handling and welding facilities, including valves manifolds, closure pieces, bends, "quick" couplings, etc. and in some cases intermediate pumps.

When there are the risk of water inrushes through intersection with abandoned old flooded workings, remedial measures to be taken include the provision of drilling advanced and flank bore holes ahead of an active development or mine working approaching such old mine workings. Continuous flow metering tests in open bore holes, together with temperature, hydrochemical parameters and water solid content can provide good information related with the cumulative water body.

Underground vertical drainage wells

When the ore body itself is the aquifer to be drained and when the dip is high there the possibility to drill underground vertical wells in advance.

A gallery is excavated on the hangingwall perpendicular to the ore body advancing some tens or hundreds meters (depending of the dip slope of the water bearing formation). In the front of such gallery is drilled vertical downward well to reach the aquifer some hundreds meter deep. In such condition through vertical submersible pumps the area to be mined can be drainage in advance.

OLD WORKINGS DEWATERING

When abandoned flooded mines are re-opening a great investment to dewater the mining openings is frequently required, mainly when the mined area appears as a honeycomb of old abandoned mine workings (Vutukuri and Singh, 1995).

A good example of this operation can be ready on Gillespie (1992) related with the Gympie gold mine (Australia) dewatering which was estimated on 2,000,000 cubic metres, using old mine plans and records of tonnage and gold grades mined. One of the difficulties was related with the estimation of the quantity of water versus depth.

Underwater T camera was employed to observe the obstacles and to dislodge such obstacles and raise them to the surface.

When the shaft was free of obstacles submersible pumps were used for dewatering, suspended from the surface by their own rising main.

Taking into account the weight of the pump, pipes and water were necessary to employ reinforced flanges, highly tensioned bolts and compressible stainless steel gaskets to handle the transient hydraulic bursting pressures and the weight of the rising main and pumps.

During the dewatering it is necessary to check the depth of water in the existing shafts, to monitor the water temperature and other physio-chemicals parameters on the pumped water and to register the cumulative pumped-out volumes. *Figure 8* provide the pumped water evolution on the Gympie gold mine (Australia) (Gillespie, 1992).

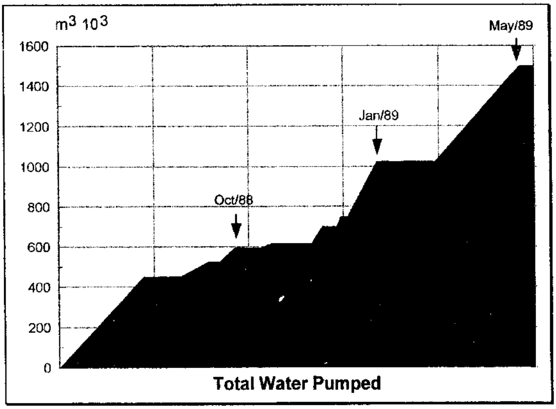

Figure 8. Pumped water evolution on the Gympie mine (Gillespie, 1992).

Flowmeter prove can be employed on the pumped and other existing shafts to identified the main water inter-connection.

Any pump and equipment must be protected against rocks and timber which may fall away from the sides of the shaft during he dewatering.

T camera equipment can be also employed to observe the shafts walls before any man direct observation.

DRAINAGE AND PUMPING SYSTEMS DESIGN

The basic requirements of a drainage and dewatering system are (Atkinson and Dow, 1983):

- To depress the piezometric surface to the require safe level. Over-depression at any point results in increased pumping costs.
- To have the facility to advance the dewatering as the mine excavation advance.

The optimum design of a mine pumping systems should be aimed to achieve effective mine dewatering together with high operational efficiency, low maintenance and overall costs (Bridgwood, et al., 1983).

In this sense, several factors should be taken into account for the selection and optimisation of a pumping system: quantity of water to be pumped, water quality, mine layout and developments.

The pumping systems should be designed to deal with variation of water head, seasonal inflow fluctuations, mechanical and electrical breakdowns, include power cuts and sudden increase in mine water inflow.

To cover such conditions it is convenient to guarantee additional dewatering capacity to cover any unexpected incidence and to have available stand-by pump and power to cover electricity supply outages. Diesel-generators are usually the most convenient to provide such supplies.

The intercepted water in the underground mining operations must be transported on behalf of Mono pump *(figure 9)* through galleries (Walker, 1988) and finally pumped out trough a pumping station or a staged pump system as the work progressed down.

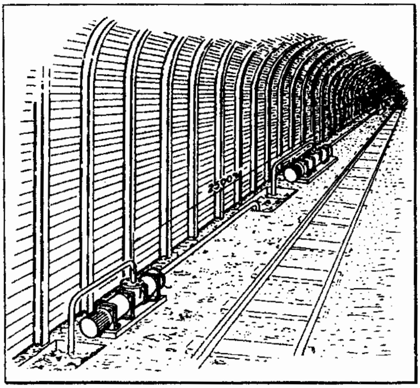

Figure 9. Inbye drainage (Walker, 1988).

The head requirement for a mine pump depends upon the static and dynamic water level, and the friction losses in the pump and pipes.

Mine water is characterised by the presence of impurities including suspended solids, mineral salts in subsaturated or supersaturated conditions, dissolved carbon dioxide, oxygen, hydrogen-sulphide and other gases, and acid or alkaline water. In any case is necessary to take into in account such conditions on the selection of the pumping equipment.

Water transported through channels or galleries usually is dirty water. To pump such water it is convenient to install sediment settlers or settling ponds to remove that deterious matter. This problem is further accentuated when service water is introduced to the mine for dust suppression or/and with hydraulic fill. *Figure 10* (Vutukuri and Singh, 1993) synthesise the sequence for suspended solids sedimentation and clear and dirty water pumping systems.

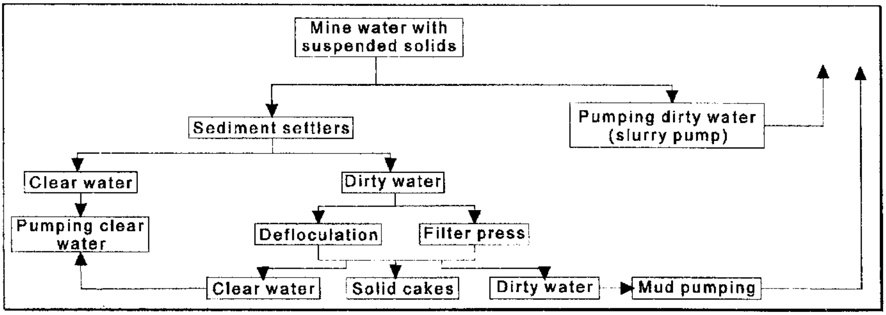

Figure 10. Dealing of mine water with suspended solids (Vutukuri and Sing, 1993. Modified).

There are two typical configuration of settling sumps (Vutukuri and Singh, 1993):

- Horizontal flow settlers (long shallow sumps) *(figure 11).*
- Vertical flow settlers without or with addition of flocculates agents *(figures 12 and 13).*

Some materials in solution can create greater difficulties in pumping. Water chemical quality knowledge and especially the corrosiveness of the mine water is required to decide on the employment of galvanised pipes and/or extensive earthing and sacrificial anodes to control stray current, which could prevent corrosion.

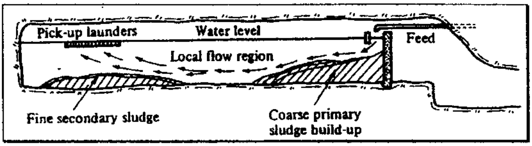

Figure 11. Horizontal flow settlers (Vutukuri and Singh, 1993).

Vutukuri and Singh (1993) describe in details the solutions adopted to combat the water quality problems, related with encrustation. Also an interesting discussion about selection and optimisation of mine pumping systems can be read in Bridgwood, et al. (1983).

The pumping system selection must be made both on the basis of specified technical parameters and according with economic criteria. A satisfactory solution is achieved when the technical requirement for high availability is in a viable relation to the total investment and operating costs (Helmann and Tams, 1986).

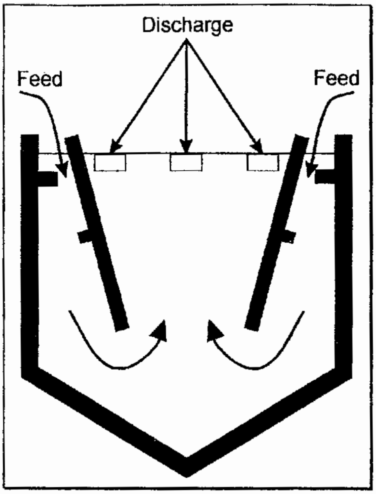

Figure 12. Vertical flow settlers without addition of flocculates agents (Vutukuri and Singh, 1993).

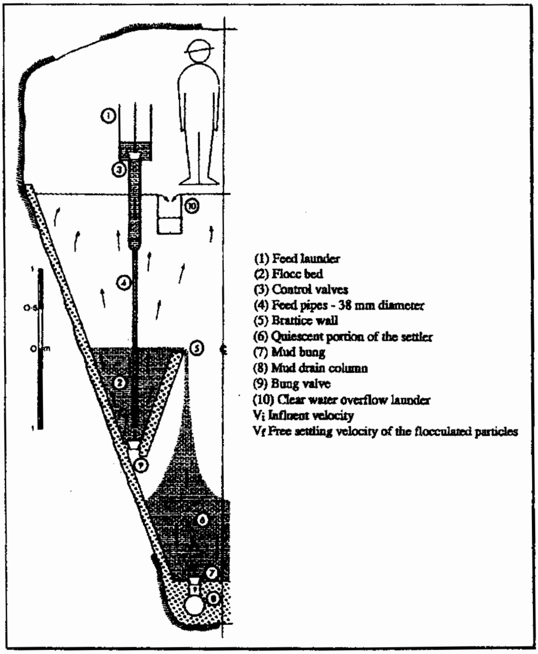

Figure 13. Vertical flow settlers with addition of flocculates agents (Vutukuri and Singh, 1993).

Basically two types of pumping systems are available:

- Direct pumping of run of mine water using slurry pump.
- Settling of run of mine water to produce clear water and thickened mud, with separate pumping facilities for each one of this two products.

Slurry pumps fall into to categories: low head-high volume flow rate centrifugal, and low volume flow rate-high head plunger pumps. Maintenance costs for slurry pumps are considerably higher than for clear water pumps.

Today centrifugal pumps, either single or multiple stage, are selected to provide a safe, reliable and economic solution to the vast majority of pumping needs within mines (Kinnear, 1988). There are three principal types of multiple stage centrifugal pumps *(figure 14)*: horizontal ring section, vertical turbine and electro-submersible. In practice, local conditions often limit the choice either because of access restrictions, risk of local flooding and/or the ability of the skilled maintenance personnel. Local experience in the subject to exacting demands in a hostile environment, frequently influence the pumpset chosen.

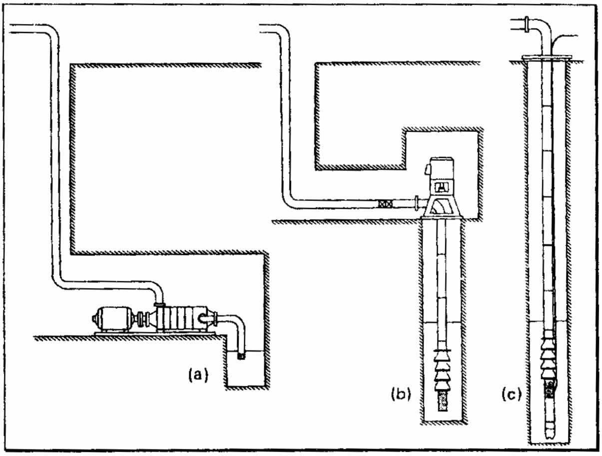

Figure 14. Principal types of multiple stage centrifugal pumps (Kinnear, 1988).

According with Kinnear (1988) the main characteristics of each one of this equipment are the following:

- *Horizontal Ring Section Type*

  This is the common style of pump, used world-wide for the primary requirement of mine dewatering. It has been developed to a high level of reliability by the main pump suppliers which serve the industry. These pumps can be specially engineered to permit the handling of mine waters which may be acid in nature and are often abrasive, through the suspension of sand and grit. Special attention is normally given to the designed of the sump and pump intake, to minimise the carry over of these abrasive particles into the pump, which otherwise will inevitably reduce both the operating efficiency of the unit and the time interval between major overhauls.

This type of pump has shown that can be readily installed and efficiently operated by the mine personnel, providing that due care is taken to ensure that the pump remains fully primed and that the shaft glands are adequately protected against loss of lubrication.

- *Vertical Turbine Type*
  It is less frequently used that the horizontal rig section type, mainly because of space restrictions at or access to the optimum sump site. However it is comparable in operating efficiency and offers the further advantage of being more suitable that the horizontal unit to automatic control, where the sump water is below the level at which the motor is to be mounted.
- *Electro-submersible Type*
  The water filled electro-submersible motor driven pump can satisfied the most severe pumping conditions in mine dewatering. It has to be provide that due care has been taken to match the pumpset to the system and to the conditions which exist in the particular dewatering location. The installation and the automatic control of this pump is very easy. Leading manufacturers have carefully studied the failure analysis data and have developed pumpsets reducing the likelihood of premature failure, achieving an higher degree of reliability.

A complete analysis of multistage mine dewatering pumpsets can be ready in Kinnear (1988).

When feasible the drawndown of the water table should be achieved through a combination of several dewatering systems. Adoption of the best technologies requires a considerable exercise of trial and error.

A comprehensive recapitulation about mine water inflows can be read in our paper published in IMWA Journal (Fernandez Rubio and Lorca Fernández, 1993). In such paper, and supported by many examples, we classified the mode of inflow of water to mine workings into the following categories:

- Variation of inflow rates as a gaussain distribution.
- Increasing inflow with time.
- Constant yield.
- Decreasing inflow with time.
- Mixed inflow rates.

CONTROL INSTRUMENTATION

Instrumentation should be installed to monitor the groundwater changes brought about by drainage and to evaluate the effectiveness of drainage.

The required equipment include the water discharge monitoring through V-notch weirs or other methods that provide records of the water yields.

At the same time it is necessary to control the drainage surrounding the mining area to ensure that the aquifers system is drainage efficiently and there are not the risk of water suddenly flow rate to the mine opening in uncontrolled conditions.

The simplest procedure is to install observation piezometers in boreholes located at key points where if possible they can continue to function through the life of the mine. Diameter of observation piezometers vary from 75 mm to 200 mm. The larger sizes being needed for automatic recorders or multi-piezometers. One single piezometer can be installed in an AX size hole and up to three can be installed in an NX size borehole. The advantage of installing double or triple piezometers is that it provides the possibility to analyse the flow water in three dimensions. However the corresponding installation of such piezometers requires an absolute guarantee of isolation of each intercepted aquifers.

We recommend that a maximum of the exploration holes drilled was cased and protected so they can be used at piezometers.

The locations for piezometers should be selected taking into account (Atkinson and Dow, 1983):

- Type of aquifers: confined aquifers react quickly to pumping and effects can be measured over a wide area. Unconfined aquifers react slowly due to storage yield effects and the cone of depression propagates slowly.
- Transmissivity: a highly-permeable aquifer will produce a vide flat cone of depression while an aquifer of low permeability will have a deeper smaller radius cone of depression.
- Geological conditions: lithological and mainly structural condition can react against changes in water pressure creating inter-communication in multi-layers systems.
- Planned pumping rates: the extent of the cone of depression is proportional to pumping rate on a log ratio.

It is convenient to install and monitoring the piezometers at least a year before to begin the dewatering process so that any seasonal fluctuation in the groundwater can be identified (Norton, 1982). However it is very useful to monitoring the piezometers several years before when a mathematical drainage model it is intend to develop.

Depending on the hydrogeological characteristics and on the water table depth, special piezometers could be more appropriated: air piezometer, vibrating wire piezometer, pore pressure system, ...

Each piezometer should be tested periodically in its full depth not only to determine that it is operating accurately but also to have the security that the water table evolution correspond with the original conditions. Water level should be recorded daily, weekly or monthly, and the data compared with rainfall and surface run-off. In many cases it will be adequate to read instrumentation with more frequency that usual, for example during run-off period, following heavy rains and when some variation in mine water inflow is observed.

Periodically it is also convenient to register the water temperature (thermo-logs) through the full length of each piezometer. Changes in water temperatures can reflect drainage flow at different depths and its direction (Hegedus-Konz, et al., 1992). This possibility is useful especially in karst systems where the mining drainage can disturbed the infiltration from river or other water bodies modifying the terrestrial heat flow distribution.

PUMPED WATER TREATMENT

Frequently the pumped water has not the required quality to discharge directly to the surface water courses or to employ in industrial, agricultural or domestic uses.

The more frequent problem it is related with the amount of suspended solids on the dirty pumped waters. The coarse suspended solids can be reduced in settling ponds. Further reduction of suspended solids to achieve the required values, required large sedimentation basins.

In Vazante underground zinc mine (Minas Gerais, Brazil), the largest amount of suspended solids is related to the existing clay in karstic cavities, and require a very large sedimentation ponds before diverting to the river.

The size of sedimentation ponds should provide a real water retention time within a range of 3 to 8 hours.

In some cases sedimentation ponds can be not enough to remove the colloidal suspended material contained in the mine water drainage. Coagulation processes with appropriated flocculant can be required.

Flocculation processes can be examined in laboratory and field scale employing anion, cation and non-ion poly-electrolytes, and controlling flocculants dosage, mixing methods retention time, ...

The use of additional grass filter on such ponds co-operate to reduce the suspended matter. On *figure 15* (based on Janiak, 1992) a sedimentation pond with grass filter is represented. The depth of water in the vegetation part can be 0.2 and 0.4 m. Different types of vegetal species can be employed. Mixed bog plants have shown a favourable effect on the reduction of suspended solids, turbidity and other impurities (Janiak, 1992).

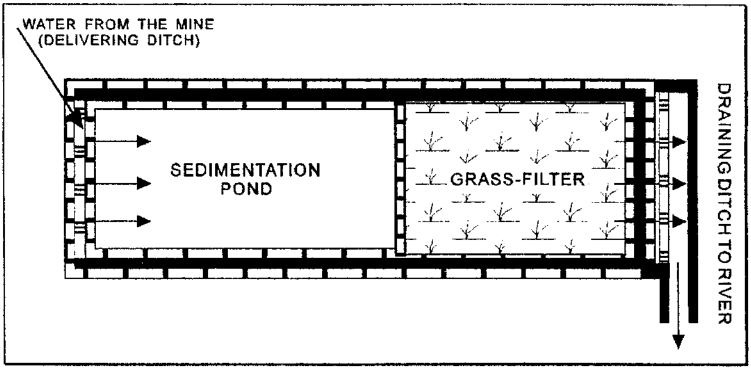

Figure 15. Sedimentation basin (based in Janiak, 1992).

The filter vegetation can be developed from seeds and rhizomes introduced to the basin along with the peat soil.

When the pumped water present chemical problems, special treatment plant can be required to improve its quality.

The favourable effect of vegetation on the reduction of some chemical impurities could be mainly seen for iron, manganese and other metals.

GROUNDWATER REBOUND

On underground mines dewatered through surface vertical wells or mine shaft, water levels return more or less to the pre-mining original level, once the pumping ceased, flooding mining openings.

During this not-dewatering period it is very important to follow the monitoring of water level evolution both in the mine openings and on the installed piezometers.

Monitoring of water quality parameters is also very convenient mainly as a tool for taking action to reduce potential environmental future problems.

Convenience and viability to implement a tight door or a bentonite/concrete barrier should be analyzed before definitive or temporary abandonment of any section of the mine. Such barriers should confine the accumulated water on the abandoned mining work. The implementations of such operations in a latter stage could have a very hight cost or even could be impossible to be constructed efficiently.

CONCEPTUAL MODELS

From the very first beginning in any action related with mine dewatering operations, or even when it is required to adopt any decision we recommend to establish an full conceptual model able to explain all the existing lithological, structural, metalogenetic and hydrogeological information.

According with our experience such model will be more realistic when more easily can explain the full available information.

A good geological and hydrogeological background and a large experience it is required to guarantee that the adopted scheme is the more realistic.

Such models have to be exposed and discussed with the mine operation responsible, geologists, hydrogeologists and other technical persons that could provide useful complementary information. Once adopted any decision will be considered in the full context of its influence over the hydrogeological behaviour.

MATHEMATICAL MODELS

Accurate predictions of the water inflow rates associated with different mining circumstances are highly desirable for reasons of safety, health and economy (Singh, et al., 1986). To this effect the ability to predict water flows rates is an important aid to mining planing (Fawcett, et al., 1984).

Based on permeability test results, seepage volumes and probable inflows can be computed. However, taking into account the geological complexities, it is more appropriate to analyse the mine water drainage on behalf of mathematical models. Analytical and numerical models are the best tools to predict the quantities of water flowing into underground mines and to consider the effect of any drainage system designed. Singh, et al. (1986) describe the analytic calculations of hydraulic conductivities on longwall panels on the basis of stress determination. failure analysis and an assessment of the consequent fracture hydraulic conductivity induced by longwall mining (the last one by means of finite element analyses).

To implement confident mathematical models, it is extremely important to have sufficient hydrogeological data and hydraulic parameters. Some of them can be obtained through pumping tests, where groundwater is pumped from a well and water levels are recorded in observation holes located in the surrounding area. Methods of test pumping analysis include Theis, Jacob, Hantush and Walton equations among others.

Other practical and economical type of test to estimate the range of rock permeability, is the packer permeability tests in diamond drilling holes (constant or variable head). An expanding packer is used, sealed off and water is pumped into the section under pressure. Usually such tests are performed at numerous depths on different boreholes to obtain average permeability values in different areas (Lloyd, et al, 1983). However the obtained data it is only an approach to the real datums.

In low permeability environments especial tests, as slug or pulse tests, could be required.

The use of mathematical models enables the planning engineers to optimised the dewatering system by simulating the effects of varying pump well patterns and rates of pumping, or other dewatering underground techniques (drainage galleries, horizontal or inclined holes, ...).

The mathematical models require a periodic review introducing the new acquired data and information. Today all the family of MODFLOW models are the most usual taking into account the gained experiences and the relatively easy operation on the hand of models experts.

CONCLUSIONS

Underground mining dewatering requires considerable research and engineering design, if they are to be economically effective, safe and environmentally acceptable.

The adopted drainage system must be compatible with the full mining exploitation project and must be fully integrated with mining operations.

In any case the organisation of this operations requires high level of technical competence.

BIBLIOGRAPHY

Akesson, J.A. 1983. A study of geohydrological and rock engineering environment at Lappvattnet experimental mine. *International Journal of Mine Water*, 2 (3): 25-38. Granada, Spain.

Aston, T.R.C., Singh, R.N. 1983. A reappraisal of investigations into strata permeability changes associated with longwall mining. *International Journal of Mine Water*, 2 (1): 1-14. Granada, Spain.

Aston, T.R.C., Singh, R.N. Whittacker, B.N. 1983. The effect of test cavity geology on the in situ permeability of coal measures strata associated with longwall mining. *International Journal of Mine Water*, 2 (4): 19-34. Granada, Spain.

Atkinson, T., Dow MPhil, R. 1983. Surface mine drainage using large diameter pumpwells. *International Journal of Mine Water*, 1 (4): 1-26. Granada, Spain.

Brawner, C.O. 1982. Control of groundwater in surface mining. *International Journal of Mine Water*, 1 (1): 1-16. Granada, Spain.

Bridgwood, E.W., Sing, R.N., Atkins, A.S. 1993. Selection and optimization of mine pumping systems. *International Journal of Mine Water*, 2 (2): 1-19. Granada, Spain.

Chileshe, B.C., Kulkarni, R.V. 1992. Konkola deep mining project: concept and planning. *Mine Water and the Environment*, 11 (3): 1-15.

Davies, A.W. 1982. Protection against inrushes in the United Kingdom. *1st Int. Mine Water Congress*, Proc. B. Budapest, Hungary.

Fawcett, R.J., Hibberd, S., Singh, R.N. 1984. *International Journal of Mine Water*, 3 (2): 33-54. Granada, Spain.

Fernández Rubio, R. 1886. Water problems in Spanish coal Mining. *International Journal of Mine Water*, 5 (3): 13-28. Madrid, Spain.

Fernández Rubio, R., Botín, J.A., Lavandeira, A. 1983. Hydrogeological investigation and drainage infrastructure at underground zinc and lead Troya Mine. *International Journal of Mine Water*. 2 (3): 39-56. Granada, Spain.

Fernández Rubio, R., Carvalho, P. 1993. Surface water inflow reduction at the underground Neves-Corvo Mine, Portugal. *Mine Water and the Environment*, 12: 11-20. Wollongong, New South Wales, Australia.

Fernández Rubio, R., Carvalho, P., Real, F. 1988. Mining-hydrological characteristics of the underground copper mine of Neves-Corvo, Portugal. *Third International Mine Water Congress Proceedings*. 15 pp. Melbourne.

Fernández Rubio, R., Lorca Fernández, D. 1993. Mine water drainage. *Mine Water and the Environment*, 12: 107-130. Wollongong, New South Wales, Australia.

Gazizov, M.S. 1993. Water regime control in mines and quarries in the USSR coal industry. *International Journal of Mine Water*, 2 (1): 43-48. Granada, Spain.

Gillespie, R. 1992. Gympie gold mine dewatering. *Mine Water and the Environment*, 11 (1): 1-14. Nottingham, England.

Hegedus-Koncz, M., Nandori, G., Gaspar, L. 1992. Hydrogeological and geothermal changes in karstic reservoirs due to mine dewatering. *Mine Water and the Environment*, 11 (1): 45-54. Wollongong, New South Wales, Australia.

Hellman, D.-H., Tams, D. 1986. Submersible motor pumps for mine drainage applications. *International Journal of Mine Water*, 5 (1): 33-44. Granada, Spain.

Janiak, H. 1992. Mine drainage treatment in Polish Lignite Mining. *Mine Water and the Environment*, 11 (1): 35-44. Wollongong, New South Wales, Australia.

Kinnear, W.J. 1988. High reliability multistage mine dewatering pumpsets. *International Journal of Mine Water*, 7 (2): 7-18. Granada, Spain.

Lloyd, J.W., Rushton, K.R., Jones, P.A. 1983. An assessment of groundwater into a proposed shaft and drift in the Warwickshire coaldfield using packer test data in an electrical analogue model. *International Journal of Mine Water*, 2 (4): 1-18. Granada, Spain.

McKee, D.M., Hannon, P.J. 1985. The hydrological environment at the Gays River Mine. Nova Scotia, Canada. *International Journal of Mine Water*, 4 (2): 13-34. Granada, Spain.

Loveday, F.P., Atkins, A.S., Aziz, N.I. 1983. The problems of Australian underground coal mining operations in water catchment areas. *International Journal of Mine Water*, 2 (3): 1-15. Granada, Spain.

Morton, K.L, van Mekerk, F.A. 1993. A phased approach to mine dewatering. *Mine Water and the Environment*, 12: 27-34. Wollongong, New South Wales, Australia.

Mulenga, S.C.; Fernández-Rubio, R., León, A., Baquero, J.C. 1992. Estimation of quantitative water inflow from different sources in Konkola Mine, Zambia. *Mine Water and the Environment*, 11 (4): 1-22.

Naish, E.J. 1993. Dewatering concepts at Zambian Copperbelt mines. *Mine Water and the Environment*, 11 (3): 35-45.

Norton, J.P. 1982. Groundwater problems in surface coal mining in Scotland. *International Journal of Mine Water*, 1 (1): 17-24. Granada, Spain.

Oruc, E., Jahic, I., Balta, K. 1993. Construction and production features of dewatering wells in the "Kreka" lignite basin. *International Journal of Mine Water*, 12: 41-52. Wollongong, New South Wales, Australia.

Sammarco, O. 1986. Spontaneous inrushes of water in underground mines. *International Journal of Mine Water*, 5 (2): 29-42. Granada, Spain.

Singh, R. N. 1986. Mine inundations. *International Journal of Mine Water*, 5 (2): 31-28. Granada, Spain.

Singh, R.N., Atkins, A.S. 1983. Design considerations for mine workings under accumulations of water. *International Journal of Mine Water*, 1 (4): 35-56. Granada, Spain.

Singh, R.N., Atkins, A.S. 1984. Application of analytical solutions to simulate some mine inflow problems in underground coal mining. *International Journal of Mine Water*, 3 (4): 1-27. Granada, Spain.

Singh, R.N., Hibberd, S., Fawcett, R.J. 1986. Studies in the prediction of water inflows to longwall mine workings. *International Journal of Mine Water*, 4 (3): 1-10. Madrid, Spain.

Singh, T.N., Singh, B. 1985. Model simulation study of coal mining under river beds in India. *International Journal of Mine Water*, 4 (3): 1-10. Granada, Spain.

Sivakumar, M., Singh, R.N. Morton, S.G.S. 1994. Mine water management and controls in an environment sensitivity region. *Mine Water and The Environment*. 13 (1). 27-40. Wollongong, New South Wales. Australia.

Straskraba, V. 1984. Ground-water as a nuisance. *International Journal of Mine Water*, 3 (1): 25-49. Granada, Spain.

Straskraba, V., Abel, J.F. Jr 1994. The differences in underground mines dewatering with the application of caving or backfilling methods. *Mine Water and the Environment*. 13 (2): 1-20. Melbourne, New South Wales, Australia.

Vutukuri, V.S., Singh, R.N. 1993. Recent developments in pumping systems in underground metalliferous mining. *Mine Water and the Environment*. 12: 71-94. Melbourne, New South Wales, Australia.

Vutukuri, V.S., Singh, R.N. 1995. Mine inundation-Case histories. *Mine Water and the Environment*. 14: 107-130. Melbourne, New South Wales, Australia.

Walker, S.C. 1988. An introduction to screw-type pumps within the mining industry. *International Journal of Mine Water*, 7 (2): 19-32. Granada, Spain.

Wolmarans, J.F., Guise-Bround, F.H. 1978. The water hazards in deep gold mining in the far Witwatersrand, South Africa. *Water and Underground Works, SIAMOS*. 1: 329-346. Granada, Spain.

Yu, P. 1988. The main hydrogeological characteristics of mineral deposits in China. *Third International Mine Water Congress*. AIMM, 93-101. Melbourne, Australia.

Yu, P. 1994. Surface subsidence in the karst mining area in China. *Mine Water and the Environment*. 13 (2): 21-26. Melbourne, New South Wales, Australia.