Prevention of chemical contamination of groundwater by mine water

by C. Pamukcu* and F. Simsir*

Synopsis

In this paper, which is aimed to serve as a review article, first of all a breakdown of the earth's total water reserves is given. The usage areas of water in the mining industry are mentioned and these uses are briefly outlined, together with the main pollution potential of each. According to this, most of the water (almost 80% of it) is utilized in processing. Later on, probable damages that the mining would give to groundwater as a result of acid mine drainage, heavy metal pollution, euthrophication and deoxygenation is described. Finally, the measures and controls that should be taken against water contamination in mines are presented.

Introduction

Water is one of the earth's most abundant natural resources, and a resource that can be placed seriously at risk by the activities of the mineral industries. It is of particular importance that the overwhelming majority of the earth's water (some 99%) exists in forms that render it almost unusable directly for man's needs, either because of salinity, or its physical nature (ice) or location in the ground. A breakdown of water distribution is given in Table I, from which it is apparent that usable fresh water in lakes and rivers, upon which we mostly rely, comprises no more than 0.0161% of the earth's total water. It is this small fraction of the water resources of the world that are most immediately prejudiced by mining and many other human activities.

Water pollution in nature can be caused by two main types of action. These are:

- Introduction of substances (or certain forms of energy such as heat) into natural waters, causing physical or chemical changes
- Interception or diversion of all or part of a water resource.

Water in the mineral industries

Water is utilized in many stages of mining and mineral processing. A generalized picture of water in the mineral industries is given in Figure 1.

Processing utilizes by far the largest proportion of water, comprising 79% of all water used in US mines and similarly in other mines[2].

Water pollution problems in mining are seldom if ever attributable to any specific pollutant. It is general for several pollutants to be found in any single waste water stream. There are, however, four major problems: acid mine drainage, eutrophication, deoxygenation and heavy metal pollution—which are recognized as the most serious water pollution situations to be found in mining[3].

Control of water polllution

Controlled mining techniques

In surface mining, there are numerous ways in which water pollution can be lessened by the choice of an appropriate method of mining. Water almost inevitably enters the mine, and diversion ditches may be required to channel it

Table I

Distribution of the earth's water resources[1]

Location	Water volume (x 10^{15} litres)	Per cent of total
Oceans	1646000	94.2
Glaciers	28870	1.65
Lakes	275	0.016
Soil moisture	98	0.006
Atmospheric vapour	17	0.001
River waters	1-5	0.0001
Groundwater less than 0-8 km down	5270	0.28
Total groundwater	71800	4.13

* *Dokuz Eylul University, Mining Engineeing Department, Izmir-Turkey.*

 SA ISSN 0038–223X/3.00 + 0.00. Paper received Mar. 2007; revised paper received Apr. 2007.

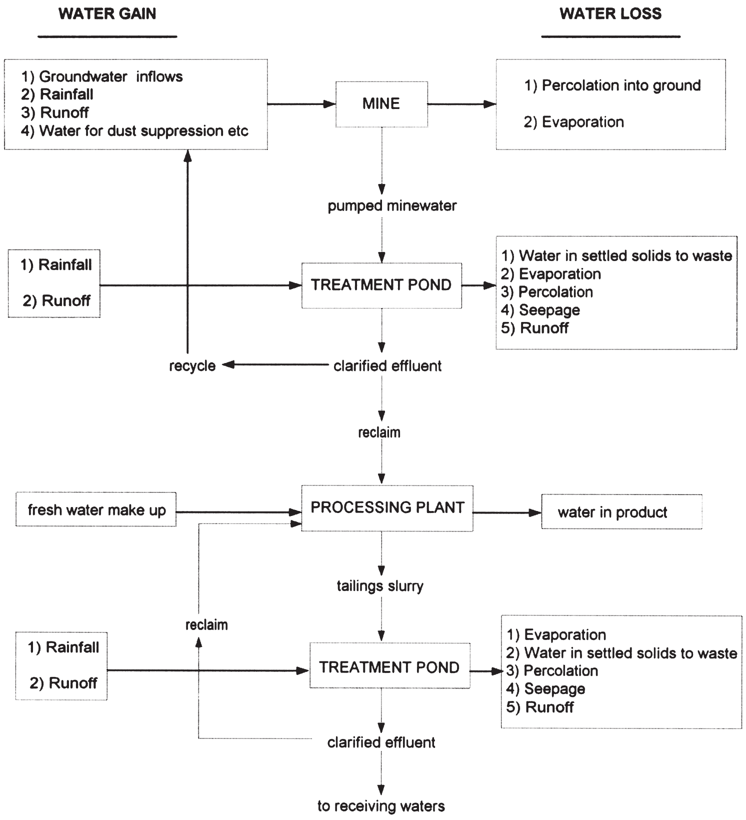

Figure 1—Basic water use flowsheet for a metal mine

to a sump. Here, settling can occur and (perhaps) oils can be removed, before pumping out for any further treatment. It may be possible to predrain the mine area; the water that is pumped from the boreholes thus remains uncontaminated.

A major source of surface-mine pollution in the USA is contour mining for coal[4]. Here, the mining method should avoid steep slopes, which are susceptible to erosion; should bury pyritic wastes promptly to avoid oxidation; and should maintain a barrier at the low wall to prevent uncontrolled run-off of water. Wherever possible, prompt backfilling can reduce the area of disturbed land and hence lessen polluted run-off. These techniques are all illustrated in Figure 2.

In underground mines, there is also some scope for prevention of pollution formation. In coalmining, a large part of water drainage is via roof joints opened as a result of caving. In shallow mines, subsidence may allow water ingress from surface sources. Consequently, any mining method that reduces the fracture of overlying strata can be advantageous; most methods, however, decrease the percentage of mineral extraction, or otherwise increase costs. In coalmining, working of the seam downdip rather than updip such that it can be flooded at the cessation of mining reduces acid formation due to the exclusion of oxygen. The design of seals or barriers must take account of the maximum water pressure that will be experienced[5].

Erosion and filtration control

Infiltration into wastes can result from subsurface water movements, 'leakage' from abandoned mines, or downward percolation of surface waters and rainfall. The outflows of waters that have percolated through contaminated material may be highly polluted. Control of infiltration therefore requires either that the wastes be isolated from the water supply or that their permeability is decreased. Erosion occurs as a result of rapid water flow over susceptible wastes, and regrading, compaction, diversion and revegetation are the usual techniques.

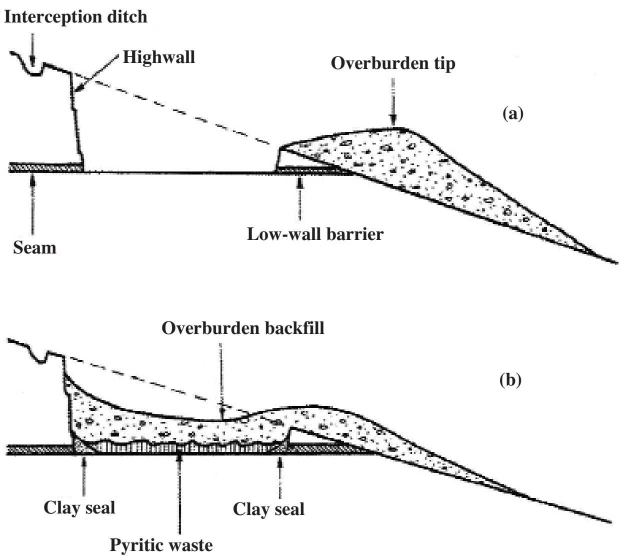

Figure 2—Design of contour mining method to minimize pollution: (a) by leaving a low-wall barrier to contain run-off; (b) in reclamation, the exposed coal seam is sealed with clay, pyritic wastes are backfilled and overburden is graded back[4]

Prevention of chemical contamination of groundwater by mine water

Permeability can be decreased by compacting the waste, or isolating it with concrete, asphalt, clay or other impervious seal. Clay is the cheapest material and the most practical one. An impermeable layer of material can be used as a seal over adit entrances or auger holes, prior to backfilling, to prevent water infiltration into the waste (Figure 2). An alternative is to divert surface waters before they reach the waste and convey them around the area. This reduces pollution and erosion, as well as reducing the volume of contaminated water subsequently produced[6]. Examples of these are given in Figures 3 and 4. The installation of underdrains can ease tip drainage and improve stability and lessen the residence time of water in the tip.

In underground mining there is only limited opportunity to reduce infiltration. The main methods are to seal and grout old boreholes and fissures, and to reduce water penetration through shaft linings.

Handling polluted water

If the formation of polluted water cannot be prevented, techniques must be devised to handle the contaminated flows. The single most important control technique is water reuse. If a closed-circuit system can be approached or attained, then discharge of effluent can be reduced or eliminated. The principal components of closed recycle systems are treatment ponds for mine water and mill effluent, with associated pumps. Reuse of effluent is mainly practised in drier areas, for in high-rainfall conditions discharge of surplus water may be inevitable. Provision is required for stormwater storage or diversion. Some mines can achieve 100% recycling during summer but discharge water in winter[8].

Reuse is also complicated by the quality of water required for mining and processing. In particular, multi-stage milling circuits, using floating and depressing agents in sequence, can suffer from reagent build-up interfering with the flotation process. Lagoons and impoundments function as settling areas to remove suspended solids, but chemical treatments are often required as well.

A technique restricted to arid regions is the use of evaporation ponds to reduce waste water volumes. Lagoons are deliberately constructed with large surface area and shallow depth if there is an excess of water (e.g. pumped minewater). It is therefore possible to evaporate much of it and lessen the volume to be treated by other means.

Regrading

The regrading of mined lands is an important pollution control technique, which can bury pollution-forming materials, reduce erosion and landslides, and eliminate ponding[9]. It is, however, a part of the wider topic of rehabilitation, the primary objective of regrading usually being land reuse rather than pollution control. The landforms that are created by regrading are controlled to a large degree by the desired after-use, but, from the water pollution viewpoint, regrading should achieve gentle slopes, which are neither susceptible to serious erosion, nor ponding of water, but which provide adequate conditions for revegetation.

Revegetation

The procedures for revegetating mined land are discussed. However, a vegetation cover can often be very effective in reducing water pollution. An herbaceous ground cover stabilizes disturbed surfaces, reduces the velocity of run-off and can more or less eliminate erosion. Vegetation removes large quantities of water from the soil by the process of transpiration; however, it does not always decrease the infiltration of water into spoil. In particular, trees are relatively ineffective, at least during the decade or so of initial growth. Revegetation is usually the cheapest and most satisfactory stabilizing method, but should be applied as part of an overall rehabilitation scheme if maximum benefits are to be achieved[10].

Mine sealing

Sealing of abandoned mine entrances, drainage levels, etc. is an important way of preventing water pollution, but can be difficult to apply. The usual objective is to prevent the outflow of polluted water, inundate the workings, and thus prevent oxidation of pyritic materials. Mine seals can be designed to withstand any likely head of water, but the seal

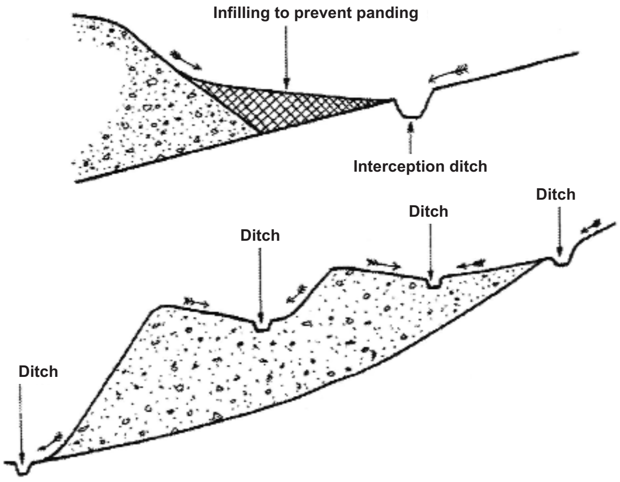

Figure 3—Control of run-off tips using interception ditches and grading to prevent ponding and percolation through tip[7]

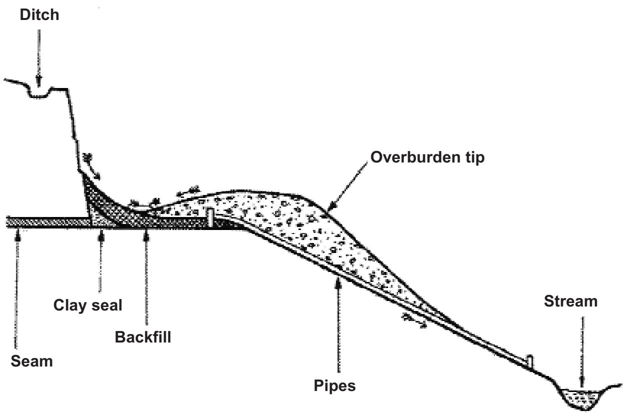

Figure 4—Use of buried pipe to achieve water control at a reclaimed contour strip mine[7]

Transaction Paper

is only a small part of the whole containment system. The major part is the perimeter of the mined-out area, the condition of which is often difficult. Sealing failures therefore usually occur because the pressure of the impounded water causes it to break out at weak points such as outcrops, fractures, subsided areas, etc. Many seals leak around their edges, due to problems of anchoring them to the strata.

There are considerable dangers in mine sealing, for the ultimate head may not be predictable or controllable. Sudden failures can (and have) cause major pollution destruction and indeed loss of life and property. It is usual therefore to install some form of pressure reduction system, to prevent the maximum designed head from being exceeded. Other methods of preventing oxidation include coating the pyrite with a chemical barrier to air and water, and antibacterial agents. Inundation is still the only practical method.

Water treatment

The complexities of surface and sub-surface hydrology are such that even the most careful application of the measures described above is unlikely to prevent entirely the formation of polluted water, which requires treatment before discharge. Mine drainage is most commonly treated to remove those pollutants that present a threat to aquatic life, but in some cases the treated effluent may have to form part of a public water supply and be treated to potable water standards.

Waste water for treatment is normally collected in impoundments. These may range from small ponds taking a few tons/day to major tailings dams covering several square kilometres and receiving tens of thousands of tons/day of slurry wastes. Settling ponds are often used in sequence, sometimes in conjunction with clarifiers or thickeners. The main object of all such ponds is to settle out and store the large proportion of the solids in the effluent. The relatively clear decanted liquid can then be passed to secondary facilities for any chemical treatment required. However, the larger tailings ponds also allow chemical changes such as oxidation to occur. Obviously the effectiveness of any pond varies according to the retention time of the effluent, which can range from as little as 4 h to several months. Commonly, a minimum retention time of 30 days is employed, plus the capacity to hold run-off from a predicted heavy storm event in order to reduce uncontrolled discharges[11]. The advantages and disadvantages of large tailing ponds are summarized in Table II. Below are discussed the major treatment processes normally applied to mine effluents.

Neutralization

Acidic effluents can be neutralized with any alkaline materials, by proper alkali selection. Neutralization can also effect precipitation of metals as hydroxides, as well as anions such as fluoride, phosphate and sulphate. The choice among the common alkalis (Table III) is determined by cost, reactivity, availability, convenience of handling, volume of sludge produced and desired effluent quality. The most commonly used alkalis are lime and hydrated lime.

Many metals precipitate out as insoluble hydroxides at particular pH Ievels. However, some metals, such as Zn and Al, will redissolve in very alkaline solutions, which can create difficulties if the effluent contains more than one metal. Precipitation of metals generally reduces their level in the effluent to 1 mg/litre or less. Removal of iron is hindered by the fact that, in fresh drainage, the ferrous ion predominates, which precipitates out at pH 9.5. If the iron can be oxidized to the ferric form before neutralization, the pH can be kept much lower. Calcium carbonate as limestone is the cheapest source of neutralizing capacity, but is not the most effective one.

Table II

Tailing ponds as treatment systems

Advantages	Disadvantages
1. Performs large number of processes, especially TSS reduction	Lacks responsive means of control, hard to optimize the process performed
2. Often high treatment efficiency	Large land area needed; major influence on hydrology
3. Often the only way of storing solids long-term	Severe rehabilitation problems; long-term safety hazard
4. Evens out effluent flows	Difficult to isolate from surface run-off
5. Little operating expertise required	Major design expertise required
6. Common and familiar method	High installation costs

Table III

Cost comparison of neutralizing agents[12]

Alkali	Basicity factor	Cost ($/ton)	Cost ($/ton basicity)
Quick lime (calcium oxide)	1.786	25.35	14.19
Hydrated lime (calcium hydroxide)	1.351	27.56	20.40
Crushed limestone (calcium carbonate)	1.000	8.82	8.82
Dolomite (calcium magnesium carbonate)	0.543	25.90	47.70
Magnesite (magnesium carbonate)	1.186	27.56	23.24
50% sodium hydroxide	1.250	83.77	67.02
50% sodium carbonate	0.943	39.68	42.08
Ammonium hydroxide	1.429	71.65	50.14

Until recently, its use was hampered by 'blinding' and slow reaction rates. It is effective mainly for ferric drainage, and a small particle size is advantageous. Limestone treatment is therefore still at the pilot plant stage. Lime neutralization is a routine process very widely employed. It comprises four steps. First the effluent is neutralized with lime (in slurry form usually) and mixed for 1–2 min. Aeration is then undertaken for 15–30 min., to oxidize iron to the ferric form. The drainage is then settled and classified, and the precipitated sludge is disposed of. Recent laboratory studies indicate that if lime treatment is combined with ozonation, better metal removal is achieved, and at lower pH.

There are two important points in connection with neutralization. First, unless all the acid-forming capacity is removed from the effluent, re-acidification may occur at distances remote from the point of discharge. The addition of excess alkali can obviate this, but the discharge of highly alkaline water can itself be damaging. Discharges should usually be in the range of pH 6–9.

Secondly, neutralization results in substantial quantities of precipitated sludge, often no more than 1–5% of solids by weight, which can present a difficult dewatering and disposal problem. Simple lagoons are the usual method currently used, sometimes alternately to allow air drying and subsequent tipping.

Flocculation

Some reagents, such as lime, ferric compounds and aluminium sulphate, are added to waters to promote settling of suspended solids. Flocculation is applied after easily settled solids have been removed, and is particularly useful for colloidal clays, etc., which settle naturally with great difficulty. Phosphate slimes in Florida are one waste type for which no successful treatment yet exists.

Precipitation

Although lime and limestone are the most common precipitating agents, as discussed above, other chemicals are also used. Sulphides are extremely effective in reducing metal concentrations—of mercury, for example—but limited to alkaline waters to avoid the generation of poisonous hydrogen sulphide.

Co-precipitation involves the removal of materials from solution by incorporating them within the particles of another precipitate. The standard method of removing radium, which is not easily precipitated, is co-precipitation with barium chloride in the presence of excess sulphate. In this way, almost all radium is removed as the sulphate.

Reduction

Reduction is applied in mining to only a limited extent at present, in the cementation of copper leachates. Possibly this method may also be applied to hexavalent chromium in waste waters, as it is in other industrial processes.

Oxidation

Aeration and oxidation are used for promoting the ferrous-ferric transformation, as already noted. Other applications are in cyanide removal, CN being oxidized to cyanates (CNO) and then to carbon dioxide and nitrogen. Excess chlorine and a pH of 10–11 are required[13]. Aeration is useful in removing a variety of other COD-producing pollutants from waste waters.

Biological

Biological treatment of effluent has been applied at one lead mine in Missouri. Eutrophic conditions are utilized to encourage algal blooms, the algae trapping and assimilating suspended and dissolved metals. Dead algae are collected in a final polishing pond before effluent is discharged. Such an ingenious system can only function in a climate that allows adequate algal growth throughout the year, which precludes its application at many mines.

Untried methods

There is a great variety of water purification methods that are used to obtain domestic water but which have not been applied to mining. They include adsorption on activated carbon, ion exchange, desalination, ultrafiltration, reverse osmosis, solvent extraction, evaporation, distillation, electrodialysis and freezing. Some of these are no more than laboratory trials, while most suffer from technical or economic limitations. However, considerable research is being devoted to their applications in mining and improvements may be anticipated.

The success or otherwise failure of pollution prevention and treatment measures can be judged only by reference to a standard, and such standards are widely applied by law in many countries.

Conclusions

Water in nature is polluted in many ways, one of which is mining, to a nonusable degree of it. The effects of contamination of usable waters are as follows:

- The quality of the water may be adversely affected, rendering it less suitable for human consumption or industrial use
- There may be ecological damage, altering the composition of (or eliminating) the natural biological communities inhabiting the water, and decreasing the diversity of organisms in it
- Water may cease to be available, in the required and accustomed quantities, at the points of use.

Water is utilized in many stages of mining and mineral processing. Mining pollutants in water can affect man as well as other organisms. Water pollution problems in mining are seldom if ever attributable to any specific pollutant. It is general for several pollutants to be found in any single waste water stream. There are however four major problems: acid mine drainage, eutrophication, deoxygenation and heavy metal pollution—which are recognized as the most serious water pollution situations to be found in mining[6].

The fundamental requirement for the successful control of water pollution is a knowledge of the quantities and qualities of all waters that may in any way be affected by mining, the quantities of water required during mining and processing, and the quality of these process waters after use. A properly designed monitoring programme and water treatment techniques, will result in the desired water control system at optimal costs.

References

1. Jarvis, A.P. and Younger, P.L. Passive treatment of ferruginous minewaters using high surface area media, *Water Research*, vol. 35, no. 15, 2001. pp. 3643–3648.
2. Newman, P., Hodgson, M., and Rosselot, E. The disposal of tailings and minewater sludge using geotextile dewatering techniques, *Minerals Engineering*, vol. 17, no. 2, 2004. pp. 115–121.
3. Banwart, S.A. and Malmström, M.E. Hydrochemical modeling for preliminary assessment of minewater pollution, *Journal of Geochemical Exploration*, vol. 74, no. 1–3, 2001. pp. 73–97.
4. Capewell, S. Environmental assessment of minewater pollution, Undergraduate Dissertation, Dept. of Civil and Environmental Eng., Univ. of Bradford, UK. 1996.
5. Wood, S.C., Younger, P.L., and Robins, N.S. Long-term changes in the quality of polluted minewater discharges from abandoned underground coal workings in Scotland, *Journal of Engineering Geology*, vol. 32, no. 1, 1999. pp. 69–79.
6. Robinson, J.D. and Robb, G.A. (1995). Methods for the control and treatment of acid mine drainage, *Coal International*, vol. 243, no. 4, 1995. pp. 151–156.
7. Younger, P.L. Coalfield closure and the water environment in Europe, *Mining Technology*, vol. 111 A, 2002. pp. 201–209.
8. Kroll, A. The example of environmental regulation of minewater in the European Union, Prospective Research and Policy Work, Spain. 2004.
9. Salmon, S.U. and Malmström, S.E. Geochemical processes in mill tailings deposits: modeling of groundwater composition, *Applied Geochemistry*, no. 19, 2004. pp. 1–17.
10. Sjoblöm, A., Hakanson, K., and Allard, B. River water metal speciation in a mining region: the influence of wetlands, tributaries and groundwater, *Water, Air and Soil Pollution*, vol. 152, 2004. pp. 173–194.
11. Höglund, L.O. Mitigation of the environmental impact from mining wastes, *Proc. Of the Intern. Conf. on Acid Rock Drainage*, Colorado, USA. 2000.
12. Skousen, J. Water management techniques for acid mine drainage control, *Green Lands Magazine*, 2000. pp. 1–8.
13. Pollard, S.A., Brookes, N., Lowe, J., Kearney, T., and Nathanail, C.P. Integrating decision tools for sustainable management of land contamination, *Science of the Total Environment*, vol. 325, no. 13, 2004. pp. 15–28.
14. Barry, D.L. The millennium dome contamination remediation, *Land Contamination and Reclamation*, vol. 7, no. 3, 1999. pp. 177–190.